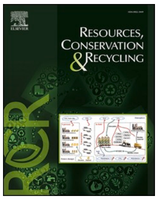
Resources, Conservation & Recycling 212 (2025) 107958

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling



Inequities blocking the path to circular economies: A bio-inspired network-based approach for assessing the sustainability of the global trade of waste metals

Filippos K. Zisopoulos [a,b,*], Brian D. Fath [c,d,e], Susana Toboso-Chavero [a,b], Hao Huang [f], Daan Schraven [g], Benjamin Steuer [h], Alexandros Stefanakis [i], O.Grant Clark [j], Serban Scrieciu [k], Simron Singh [l], Dominik Noll [m], Martin de Jong [a,n,o]

[a] Rotterdam School of Management, Erasmus University Rotterdam, Rotterdam, the Netherlands
[b] Integral Design and Management, Department of Materials, Mechanics, Management & Design, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands
[c] Department of Biological Sciences, Towson University, Towson, United States
[d] Advancing Systems Analysis Program, International Institute for Applied Systems Analysis, Laxenburg, Austria
[e] Department of Environmental Studies, Masaryk University, Brno, Czech Republic
[f] Department of Electrical and Computer Engineering, Princeton University, Princeton, United States
[g] Faculty of Architecture & the Built Environment, Delft University of Technology, Delft, the Netherlands
[h] The Hong Kong University of Science and Technology, Division of Environment and Sustainability, Hong Kong, China
[i] Laboratory of Environmental Engineering and Management, School of Chemical and Environmental Engineering, Technical University of Crete, Chania, Greece
[j] Department of Bioresource Engineering, McGill University, Ste-Anne-de-Bellevue, Canada
[k] Bartlett School of Environment, Energy and Resources, University College London, London, United Kingdom
[l] School of Environment, Enterprise and Development, University of Waterloo, Waterloo, Ontario, Canada
[m] MED – Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, University of Évora, Évora, Portugal
[n] Erasmus School of Law, Erasmus University Rotterdam, Rotterdam, the Netherlands
[o] Institute for Global Public Policy, Fudan University, Shanghai, China

ARTICLE INFO

Keywords:
Resilience
Resource-use efficiency
Ecological network analysis
Ascendency analysis
Bio-inspired design
Waste trade

ABSTRACT

Considering the importance of waste metals for the transition to circular economies, this study follows a bio-inspired approach to evaluate their material and monetary global trade patterns for sustainability and equity. Between 2000 and 2022, the global trade grew by 5 % in trading countries, by 37 % in trade links, by 71 % in material flows, and by 569 % in economic flows. Driven by indirect effects, the average circulation of material and monetary flows ranged between 21.8–34.9 % depending on the demand or supply perspective but showed a declining trend. Due to homogenization, high network redundancy, and low network efficiency the trade remained robust yet outside the *"window of vitality"* characterizing natural ecosystems. A few, mostly high-income countries dominated the market, consolidating imports of high-value metal waste mostly from low- and middle-income exporters. Policies should address circularity and trade inequities, accounting for environmental and social ramifications throughout the lifecycle of products and materials.

1. Introduction

With a strong industrial and business emphasis, the circular economy (CE) has in some cases been compared to a techno-economically optimized machine (Fromberg et al., 2023) streamlined for extracting latent economic value from a growing demand for commodified socio-metabolic waste (Savini, 2023). The predominant focus on end-of-pipe solutions has led many to conceptualize a CE as an advanced form of waste management for maximizing recycling and energy recovery from incineration when in fact those are only patches on current linear systems (Webster, 2021). This becomes evident when considering that most policies related to CE roadmaps and strategies identified

---

* Corresponding author.
E-mail address: zisopoulos@rsm.nl (F.K. Zisopoulos).

https://doi.org/10.1016/j.resconrec.2024.107958
Received 9 August 2024; Received in revised form 3 October 2024; Accepted 3 October 2024

between 1976 and 2024 (see supplementary material: Appendix A), have been addressing mainly waste management and recycling (Chatham House and The Royal Institute of International Affairs, 2020). Likewise, the corpus of publications on the CE issued by various institutions and bodies in the European Union since 2015 (when the first Circular Economy Action Plan was released) has also been focusing heavily (though not exclusively) on recycling activities (Baldassarre and Saveyn, 2023). Even EU Member States considered as frontrunners in CE, such as the Netherlands, have been targeting mainly improvements in recycling and energy recovery processes which are at the bottom of the waste hierarchy principles (PBL, 2022).

The current global patterns of increasing resource extraction, production, consumption, and waste generation have been identified as the main drivers of climate change, biodiversity loss, and pollution (United Nations Environment Programme, 2024a). The CE emerged as a response but instead of fundamentally rethinking the structure of economies, it has been materializing across the world by attaching substantial weight towards recycling and end-of-life strategies mostly at the macro level (Stefanakis and Nikolaou, 2021), and often on top of existing business models trapping organizations in the linear patterns which they have built over time (Stucki et al., 2023). In this regard, several authors have argued that not everything *"circular"* should be considered as sustainable by default (Corvellec et al., 2021; Schaubroeck, 2020), and that the CE still lacks an evidence-based theoretical framework and an economic theory for pragmatic transition towards sustainability which resonates with politicians (Velenturf and Purnell, 2021).

While much of the CE discussion has been centred on resource efficiency gains, there are yet various angles to the concept. To facilitate understanding among the readership, Table 1 lists a set of key concepts that capture some perspectives related to the CE's extended impact (highlighted in **bold**). It has been proposed that a transition to a CE may enhance the resilience of economic actors towards shocks (e.g., natural disasters, pandemics, price volatility etc.), albeit not in a straightforward way as it may bring both congruences and contestations across scales i.e., at the firm level, at the industry level, and at the socio-ecological level (Kennedy and Linnenluecke, 2022). Interestingly, previous research on the network properties of the global commodity trade suggests that countries may improve their economic resilience without hindering their economic growth by seeking to expand the number of trade links between them (e.g., diversification of import sources for strategic commodities), for reduced economic losses and fast recovery from economic shocks (Kharrazi et al., 2017). However, an excessive number in trade connections may also facilitate shockwave transmission and/or risk resource drainage in parts of the network due to insufficient consolidation ability (i.e., inadequacy in bringing different sources of inputs together into a more coherent flow), undermining resilience, and resulting in node *"necrosis"* from limited cross-scale circulation and distribution of resources (Fath et al., 2019). In some cases, stability in resilience may even be undesirable, for example, when it comes in direct conflict with sustainability values such as with the perpetuation of inequities in socio-economic systems (e.g., the introduction of well-intended CE policies may benefit some actors but it may also create unintended lock-in effects at the disadvantage of others) or with eutrophication in natural ecosystems (Kharrazi et al., 2018). Other undesired side-effects may include the displacement of criticality risks from one country to another (Schaubroeck, 2020), the potential of increasing the *"circularity divide"* (i.e., the gap of competitive advantage) between countries (Barrie et al., 2022), and the accumulation of **socio-metabolic risk** in space and time (Singh et al., 2022).

Evidently, further research is necessary to explore whether the current mechanistic understanding of a CE as an efficient recycling engine may reduce or increase risks through trade-offs and avoid any potential lock-ins of socio-economic systems into unsustainable resilience. In

Table 1
Key concepts and terms.

Capacity to develop: is a network property in ascendency analysis and process ecology describing the upper bound of a system's potential to grow and develop when studied as a network of nodes and links, the mathematical expression (and main assumption) of which is the sum of its network efficiency and its network redundancy (Ulanowicz, 2001). Since the method is based on information theory, the capacity to develop, along with its corresponding complementary variables (ascendency and overhead), are expressed in bits and can be scaled by the total system throughput of the corresponding flow medium to impart physical meaning (Ulanowicz, 2001).

Circular resource nationalism: is a policy approach where *"a country prioritizes sovereign control over its secondary material resources (at all stages of their lifecycle) and asserts this control through the principles of the circular economy"* (Schröder and Barrie, 2024).

Network efficiency (or degree of order): is a (unitless) network property in ascendency analysis and process ecology capturing how well articulated, constrained, or ordered the (conceptually reduced and modelled) system is due to its network structure (Ulanowicz et al., 2009).

Network non-locality: When the rate of (indirect) cycle paths is increasing (i.e., where *"one species affects another through a "shared contact" species"*), then pathway proliferation occurs due to the tendency of indirect paths to grow geometrically and dominate (Albert et al., 2000; Borrett et al., 2007; Dunne et al., 2002; Dunne et al., 2002; Layton, 2014; Patten, 1985; Patten et al., 1982). This is considered to lead to a phenomenon called network non-locality whereby high indirect effects of asymmetric network structures may endow the system with high cyclicity of retained resources and to increased robustness towards random node deletion due to shocks (Albert et al., 2000; Borrett et al., 2007; Dunne et al., 2002a,b; Patten, 1985; Patten et al., 1982; Layton, 2014).

Network redundancy (and network resilience): Resilience has various definitions with a popular one being *"the ability of a system to maintain its structure and patterns of behavior in the face of disturbance"* (Holling, 1986). In panarchy theory, it is *"the capacity [of a system] to successfully navigate all stages of the complex adaptive cycle"* (Fath et al., 2015). In ascendency analysis and process ecology, network redundancy is a (unitless) network property capturing the *"disordered"* part of a network which endows it with flexibility through redundancy in connections between nodes (Ulanowicz et al., 2009). It is expressed as flow path diversity which is sufficient for maintaining the system's function during shocks (Ulanowicz, 2020). In this context, network redundancy is a prerequisite for network resilience to emerge, and therefore, these two terms may not be fully interchangeable.

Number of roles: The analogy with natural ecosystems is that the number of roles relates to the number of trophic levels (Ulanowicz et al., 2009) describing specialized functions of some nodes (e.g., species) in receiving, transforming, and transferring flows over to other nodes in the network (Zorach and Ulanowicz, 2003).

Planetary boundaries: This framework describes nine processes [1) climate change, 2) novel entities, 3) stratospheric ozone depletion, 4) atmospheric aerosol loading, 5) ocean acidification, 6) biogeochemical flows, 7) freshwater change, 8) land system change, and 9) biosphere integrity] all of which are crucial for the stability and resilience of the Earth by taking as a reference state the Holocene i.e., the interglacial state characterized by warm planetary conditions which allowed human civilization to evolve (Richardson et al., 2023).

Robustness: is a (unitless) network property in ascendency analysis and process ecology describing a balance between network resilience against disturbances and network efficiency for streamlining resource throughput, a balance which is theorized to characterize sustainable natural ecosystems, at least the ones which have managed to survive and persist over time (Ulanowicz, 2020, 2009; Zorach and Ulanowicz, 2003). It has been proposed that it is the variable in least supply which is expected to impact a system's robustness the most, meaning that in over-redundant networks robustness is determined more by changes in network efficiency whereas in over-efficient networks robustness is determined more by changes in network redundancy (Kharrazi et al., 2017).

Socio-metabolic risk: It is a *"systemic risk associated with the availability of critical resources, the integrity of material circulation, and the (in)equitable distribution of derived products and societal services in a socio-ecological system"* (Singh et al., 2022).

Sustainability: Being a contested concept, sustainability is often perceived from a *weakly coupled* perspective where the dimensions of economy, society, and the environment are assumed to be independent from each other (Pelenc et al., 2015). Here, by sustainability we mean the ability of a socio-economic system to sustain itself over time from a *strongly coupled* perspective where the economy is understood as a social construct embedded in society which in turn is embedded within the natural environment (Pelenc et al., 2015).

Window of vitality: is a concept describing the theoretical upper and lower boundaries of network properties within which natural ecosystems are theorized to exist, due to a balance in network constraints (allowing for the efficient streamlining of resources among species across trophic levels) and redundancy in network connections (for enhanced resilience against shocks) (Ulanowicz et al., 2009; Zorach and Ulanowicz, 2003).

other words, CEs which are solely built on *"business cases"* to maximize efficiencies for boosting the ratio of gross domestic product (GDP) per unit of resource used without considering their contribution and impact on systemic resilience and inequities, may compromise global sustainability by increasing simultaneously both its numerator and denominator. This can be a precarious situation in a world of finite resources, especially when six out of the nine identified **planetary boundaries** have already been transgressed with evidence showing that the Earth is *"leaving its Holocene-like state"* (Richardson et al., 2023), entering *"uncharted territory"* (Ripple et al., 2023).

The points above highlight an urgent need for identifying relevant methods and indicators which can capture the complex interdependencies of socio-economic and socio-ecological systems, particularly in relation to their transitions towards CEs. During the past decade a bio-inspired approach has been gaining traction in the CE discourse focusing on the study of feedback loops of resources and information by using a plethora of indicators from network-based methods to capture properties of socio-economic systems which may not be directly measurable (Brehm et al., 2020; Chatterjee et al., 2021a, 2021b; Chatterjee and Layton, 2020; Fath et al., 2019; Johnson and Webster, 2021; Layton, 2022; Layton et al., 2015; Lietaer et al., 2010; Panyam and Layton, 2019; Reap and Layton, 2017; Ulanowicz et al., 2009; Webster, 2021). Each one of these properties addresses a different aspect of the underlying system function where information is contained in the connections of the network, and in combination they have the potential to reveal deep structures which may not otherwise be obvious (Fath et al., 2019; McNerney et al., 2013). For example, it has been proposed that it is neither efficiency nor resilience but their balance (i.e., **robustness**) which may be an important indicator for the sustainability of socio-economic systems (Johnson and Webster, 2021; Layton, 2014; Ulanowicz et al., 2009; Webster, 2021). The applications of network-based methods have been numerous, and indicatively they have been used to assess the resilience of cities (Galychyn et al., 2022), of supply chains (de Souza et al., 2019), of economic systems (Huang and Ulanowicz, 2014), and of large complex systems of systems (Chatterjee et al., 2023).

The aim here is to explore the potential of network-based indicators not only for assessing the sustainability of complex socio-economic systems by benchmarking them against natural ecosystems but also for illuminating systemic inequities which may emerge during their transition to CEs – an aspect that represents the novel contribution of this work. The global trade of waste metals is selected as a case study by using publicly available time series data from the Chatham House Circular Economy Trade Database (Chatham House and The Royal Institute of International Affairs, 2020). Studying global trading patterns for the potential existence of systemic inequities is important because they may hinder the transition of countries towards circular economies, particularly the ones in the Global South.

The paper is structured as follows: In Section 2 the methodology is described. In Section 3 the results of network-based methods (i.e., ecological network analysis and ascendency analysis) are presented. In Section 4 the findings are discussed along with implications for sustainable circular economies and the limitations of the study. Section 5 concludes the paper.

2. Methods

2.1. Case study

The focus of this paper is on the international trade of metal waste between 2000 and 2022 (Fig. 1) because relative to all other types of waste this stream had the largest market share (~30 %–48 %) it was traded in substantial amounts (~22 %–33 %), and it contained critical raw materials, specialty metals, and rare earths which can be of strategic importance. The global trade is studied as two distinct networks of annual material and monetary flows (Fig. 2).

2.2. Data preparation

The dataset was downloaded from the Chatham House Circular Economy Trade Database (Chatham House and The Royal Institute of International Affairs, 2020) on the 15th of May 2024. The time series data were formatted in tables where each year would have two corresponding tables: one of annual material flows and one of annual monetary flows. Any missing nodes in the raw dataset were identified and inserted as additional rows or columns with elements of zero value to ensure that the generated matrixes were symmetric. The rows i and columns j of the matrixes corresponded to the export and import countries, respectively, whereas their elements corresponded to the annual trade flows of waste metals between countries and were symbolized with T_{ij} (in million tonnes per year for the material flows or billion USD per year for the economic flows). Due to the nature of the data, the network was closed meaning that any other boundary input flows z_i and output flows y_i were not accounted for. The datafile along with all calculations is available in the supplementary material.

Following the notation at the Chatham House database, it is stressed that some of the network nodes were termed as *"special categories"* or *"areas not elsewhere specified"* (Chatham House and The Royal Institute

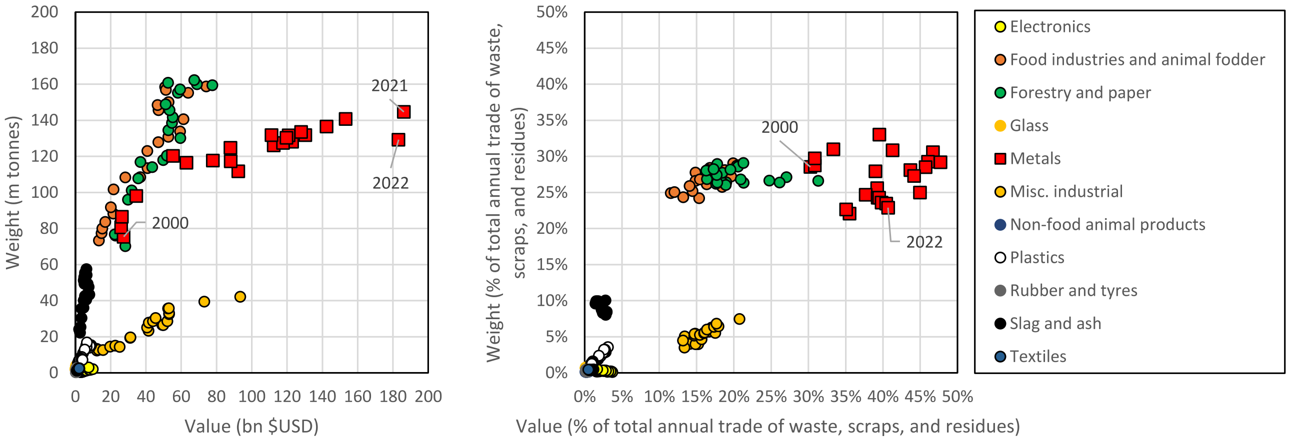


Fig. 1. The annual material and economic flows in the global trade of different types of waste, scrap, and residues between 2000 and 2022 (Chatham House and The Royal Institute of International Affairs, 2020) juxtaposed *left:* in absolute numbers, *right*: in relative terms (as shares of the total annual value of traded waste, scrap, and residues i.e., the sum of the individual waste streams listed). Waste metals are shown as red squares. The various categories and sub-categories of metal waste trade flows (considered here in an aggregate manner) and the list of trading countries are shown in the supplementary material (Appendixes B and C, respectively).

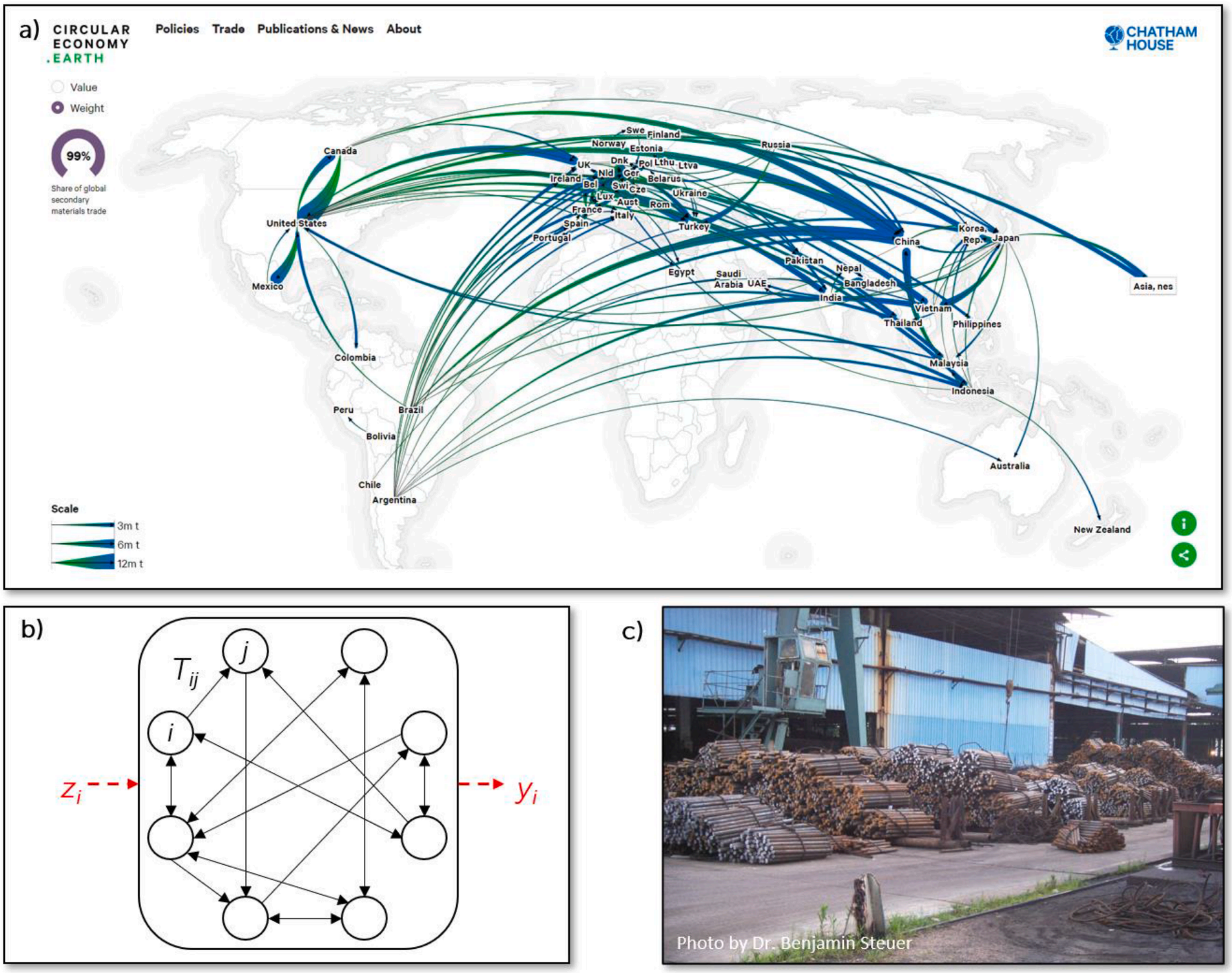


Fig. 2. a) Screenshot from the online database Chatham House Circular Economy Trade database (Chatham House and The Royal Institute of International Affairs, 2020), b) system boundary of the global trade of waste metals, analysed as a network of countries (i.e., nodes) where T_{ij} represents the annual material or monetary flow from country i to country j (i.e., edge or link), and where z_i and y_i are boundary input and output flows, respectively (which are not considered here). c) Example of waste metals: reprocessed metal from dismantled End-of-Life ships.

of International Affairs, 2020). The former term *"is used by countries reporting trade flows if they do not want the trading partner breakdown to be disclosed. The distinction between an 'unknown partner country' and an 'undisclosed partner country' can sometimes be mixed up when recorded"* (Chatham House and The Royal Institute of International Affairs, 2020). The latter term covers *"unknown trading partners, recorded when the reporting country does not submit the details of their partner. This occurs (a) for low value trades and (b) if the partner designation is unknown to the reporting country, or if an error is made in assigning the trading partner. Reporting countries sometimes withhold partner details to protect company information. Different categories of areas not elsewhere specified are associated with the world as a whole, with continents, and (prior to 2006) with regions"* (Chatham House and The Royal Institute of International Affairs, 2020).

The formatted tables with the raw data were then analysed with ascendency analysis and ecological network analysis, the results were plotted on figures, and were interpreted.

2.3. Network-based methods

Common network-based indicators such as link density, connectance, degree centrality, and cumulative degree distribution were used to study the global trade of waste metals as a network of m nodes (i.e., number of countries) and l edges (i.e., number of trade flows between countries).

The link density of the network k and its connectance K were calculated as $k = \frac{l}{m}$ and $K = \frac{l}{m^2}$, respectively. The former describes the links per node, and the latter captures the number of trade flows occurring in the network over all possible trade flows which could theoretically occur if all countries would trade with each other.

The degree centrality of the network (a measure of trade relationships between countries) was calculated for each country by accounting for its imports (in-degree centrality $d_{in-degree}$ as the sum of all its incoming flows), exports (out-degree centrality $d_{out-degree}$ as the sum of all its output flows), and total trade flow ($d_{total\ degree} = d_{in-degree} + d_{out-degree}$).

The degree distribution $P(d_i)$ was defined as the fraction of nodes having in-, out-, or total degree d_i over the sum of in-degree nodes, out-degrees, and total nodes m, respectively. The cumulative degree distribution function is useful for identifying whether the data follow a power law when plotting them against the degree distribution on a log-log scale, and it was calculated by adding the proportion of nodes with a certain degree and higher. For example, for nodes of degree one the cumulative distribution would be the proportions of all nodes since all of them considered in the analysis had at least one trade flow.

2.3.1. *Ascendency analysis*

Here, indicators from ascendency analysis are presented (Ulanowicz, 2002, 2009, 2020). The total system throughput $T_{..}$ describes the annual global trade activity (million tonnes per year or billion USD per year) and it was calculated by:

$$T_{..} = \sum z_i + \sum T_{ij} + \sum y_i \tag{1}$$

Considering that this trade network was studied as a closed system:

$$T_{..} = \sum T_{ij} \tag{2}$$

The capacity of the network for development H (bits) was calculated by:

$$H = -\sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) \log_2 \left(\frac{T_{ij}}{T_{..}}\right) \tag{3}$$

The average mutual information of the network X (bits) was calculated by:

$$X = \sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) \log_2 \left(\frac{T_{ij}}{T_{i.}} \frac{T_{..}}{T_{.j}}\right) \tag{4}$$

Here, $T_{i.}$ represents the sum of trade flows exported from country i, and $T_{.j}$ represents the sum of trade flows that are imported by country j during the same period (Ulanowicz et al., 2009). Assuming that the network was at steady state, the sum of nodal imports and of exports were considered equal (Fath, 2012):

$$\sum T_{i.} = \sum T_{.j} = T_{..}$$

The network's capacity to develop H (bits) and its redundancy H_c (bits), were calculated by:

$$H = X + H_C \tag{5}$$

$$H_c = -\sum_{i,j} \left(\frac{T_{ij}}{T_{..}}\right) \log_2 \left(\frac{T_{ij}^2}{T_{i.} T_{.j}}\right) \tag{6}$$

The scaled properties (with $T_{..}$) have units of million tonnes-bits per year or billion USD-bits per year. The ascendency A, overhead Φ, and the total (scaled) capacity of the network to develop C, were:

$$\mathrm{A} = \mathrm{T}_{..}\mathrm{X} \tag{7}$$

$$\Phi = \mathrm{T}_{..}\mathrm{H}_c \tag{8}$$

$$C = A + \Phi \tag{9}$$

The degree of order a was calculated by:

$$a = \frac{\mathrm{X}}{\mathrm{H}} \tag{10}$$

The robustness R was calculated by:

$$R = -\alpha \ln(\alpha) \tag{11}$$

The number of roles n was calculated by:

$$n = 2^X \tag{12}$$

The number of links per node c was calculated by:

$$c = 2^{\left(\frac{H_c}{2}\right)} \tag{13}$$

2.3.2. *Ecological network analysis*

Here, indicators from ecological network analysis are presented (Fath, 2018; Fath et al., 2007; Fath and Scharler, 2018). The elements of the original data matrixes which represent the direct trade flows between two countries i and j, were normalized in an input-driven perspective ($g_{ij,input}$) and in an output-driven perspective ($g_{ij,output}$) while considering the absence of boundary flows:

$$g_{ij,input} = \frac{T_{ij}}{T_{.j}} \quad \text{or} \quad g_{ij,output} = \frac{T_{ij}}{T_{i.}} \tag{14}$$

The direct flow intensity matrix G was constructed in both cases:

$$G = \left(g_{ij}\right) \tag{15}$$

G was raised to n powers and the produced matrixes were summed up to form the integral flow matrix N with elements n_{ij} in both cases:

$$N = \left(n_{ij}\right) = G^0 + G^1 + G^2 + \dots G^n = (I - G)^{-1} \tag{16}$$

Each n_{ij} element in each one of those n matrixes represents the probability of a trade flow to reach other countries in the network in n steps.

The indirect effects DI were calculated in both cases by:

$$DI = \frac{\sum_{i,j=1}^{n} \left(n_{ij} - g_{ij} - \delta_{ij}\right)}{\sum_{i,j=1}^{n} g_{ij}} \tag{17}$$

where δ_{ij} takes the value of one if and only if $i = j$ or zero otherwise.

Finn's Cycling Index (FCI) required the calculation of the total system throughput for system cycling (TST_{ci}) to capture the cycling of flows through each one of the nodes.

$$TST_{cj} = \frac{(n_{ii} - 1)}{n_{ii}} T_{.j} (\text{input} - \text{driven}) \quad \text{and} \quad TST_{ci} = \frac{(n_{ii} - 1)}{n_{ii}} T_{i.} (\text{output} - \text{driven}) \tag{18}$$

$$FCI_{.j} = \frac{\sum TST_{cj}}{T_{..}} (\text{input} - \text{driven}) \quad \text{and} \quad FCI_{i.} = \frac{\sum TST_{ci}}{T_{..}} (\text{output} - \text{driven}) \tag{19}$$

Network homogenization (Fath and Patten, 1999) was calculated as the ratio of the coefficient of variation of the G matrix $CV(G)$ over the coefficient of variation of the N matrix $CV(N)$. This required the calculation of the sum of squared deviations (SSD) of all elements of the direct (or the integral) matrix from their mean value, and of their standard deviation (s):

$$CV(G) = \frac{s(G)}{\bar{g}} \quad \text{and} \quad CV(N) = \frac{s(N)}{\bar{n}} \tag{20}$$

$$s(G) = \sqrt{\frac{SSD(G)}{\#elements\ in\ G - 1}} \quad \text{and} \quad s(N) = \sqrt{\frac{SSD(N)}{\#elements\ in\ N - 1}} \tag{21}$$

$$SSD(G) = \sum \left(\bar{g} - g_{ij}\right)^2 \quad \text{and} \quad SSD(N) = \sum \left(\bar{n} - n_{ij}\right)^2 \tag{22}$$

3. Results

3.1. *Ascendency analysis*

Between 2000 and 2022, the total system throughput (i.e., sum of all trade flows for a given year) of the global trade of waste metals grew by about 71 % in terms of materials and by 569 % in terms of economic value (Fig. 3a). The amount of waste metals traded in 2000 was 75.5 million tonnes with a total value of 27.4 billion USD which peaked in 2021 to 144.7 million tonnes worth 186.2 billion USD. During these 22 years, both the economic and material network of the global metal waste trade expanded also by about 5 % in terms of size (i.e., number of nodes) and by 37 % in terms of trade links (i.e., number of trade flows). This quantitative growth and structural development of both networks explains the increase in their corresponding total **capacity to develop** (i.

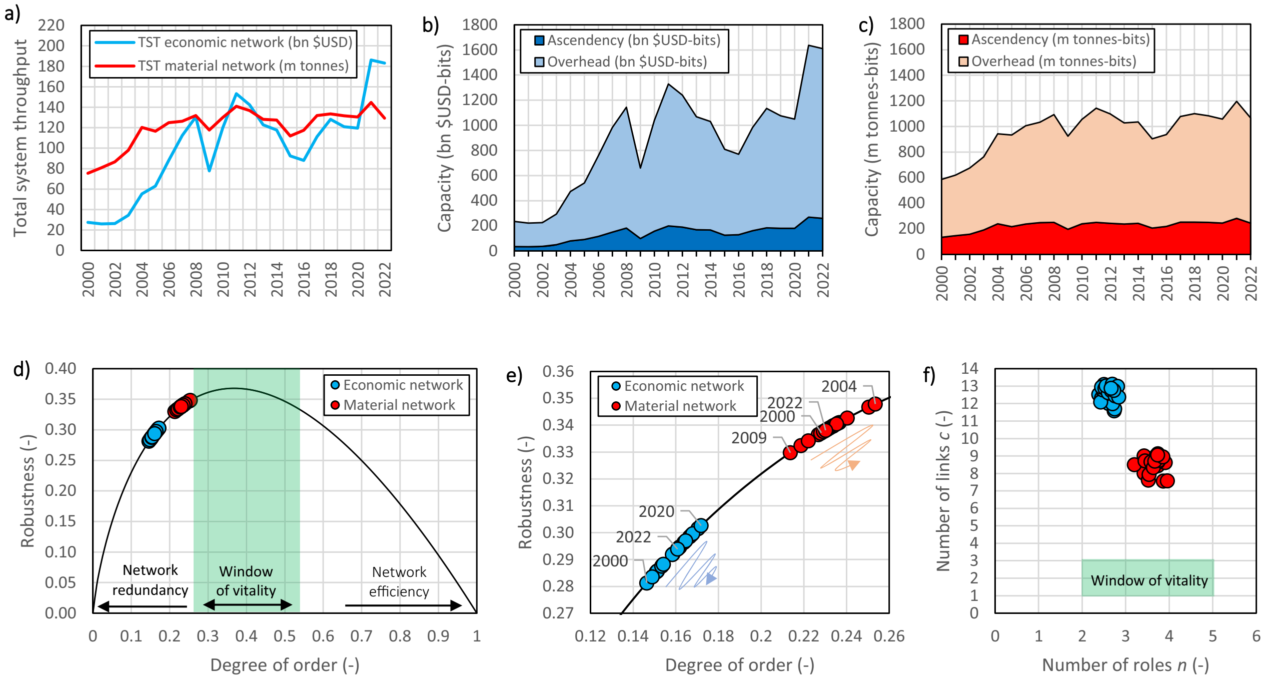


Fig. 3. Results of ascendency analysis of the global metal waste trade between 2000 and 2022 showing a) the total system throughput, b) the capacity to develop for the economic network and c) for the material network. The *"window of vitality"* (Ulanowicz, 2009; Ulanowicz et al., 2009) is shown as: d) a range of the degree of order (i.e., network efficiency) (Borrett and Lau, 2014; Ulanowicz, 2009), e) with zooming-in of the data on the robustness curve, and f) as an area formed when the number of links per node is plotted against the number of roles (Ulanowicz et al., 2009; Zorach and Ulanowicz, 2003).

e., sum of **network efficiency** and **network redundancy**) from 587.1 m tonnes-bits and 234.1 bn $USD-bits in 2000 to 1067.3 m tonnes-bits and 1610.1 bn $USD-bits in 2022, or by about 82 % and 588 %, respectively (Fig. 3b and c).

The connectance for both networks remained on average around 0.11 for all years studied. In other words, only 11 % of material and monetary flows materialized from all possible *m* x *m* combinations (where *m* is the number of nodes in the corresponding trade network) which could theoretically manifest if all countries would trade with each other. However, this sparsity is elusive since both networks had on average about 229 nodes with about 5800 trade connections which provided them with considerable **network redundancy** and consequently, with high **network resilience.** This redundancy contributed on average about 84 % and 77 % to the total **capacity to develop** of the economic and the material network, respectively (Fig. 3b and c). The remaining ~16 % and ~23 % were due to structural constraints indicating that both networks had limited **network efficiency** in streamlining material and monetary flows. This stable balance between **network resilience** and **network efficiency** suggests that the overall structure of the global trade of waste metals was sustained at a relatively high **robustness** (Fig. 3d) which converged around a narrow range of values over the years (Fig. 3e).

Yet, despite the relatively high **robustness**, neither of the two networks were within the region of the ***"window of vitality"*** which is the theoretical characterization of sustainable natural ecosystems (Ulanowicz, 2009; Ulanowicz et al., 2009). This is possibly due to the relatively large number of links per node in both networks (Fig. 3f) which was three to four times higher than what was proposed for networks of robust (i.e., sustainable) natural ecosystems (Ulanowicz, 2009; Ulanowicz et al., 2009; Zorach and Ulanowicz, 2003). Additionally, the material network had a larger **number of roles** than the economic network, suggesting that it exhibited more *"trophic levels"* (i.e., where trading countries are analogous to *"species"* with different *"functions"*).

3.2. Ecological network analysis

The values of the Finn Cycling Index (FCI) for both networks showed a decreasing trend and a converging pattern both from an input-driven and an output-driven perspective (Fig. 4a). The former captures the demand side (i.e., studying the fractions of direct trade flows normalized by the sum of all imports per country) and the latter the supply side (i.e., studying the fractions of direct trade flows normalized by the sum of all exports per country). This convergence was much more pronounced for the economic network which also exhibited higher FCI values than the material network. More specifically, the average FCI for the economic network was 33.8 % from an input-driven perspective and 34.9 % from an output-driven perspective whereas the average FCI for the material network was 21.8 % from an input-driven perspective and 26.8 % from an output-driven perspective. This is consistent with **network redundancy** being higher for the economic network. The observable drops in the FCI values of the material network in 2007 and 2020 were likely due to the impacts of the global economic crisis and of the COVID-19 pandemic, respectively. Interestingly, the FCI values of the economic network during both periods were seemingly unaffected.

An interesting outcome of the analysis is that the direct trade flows contributed on average only 5 % to the total trade activity (Fig. 4b, c, d, and e) which suggests that material and monetary cycling was largely due to dominance of indirect effects, a phenomenon coined as **network non-locality** (Fath, 2012). Additionally, the values of indirect effects were very similar both from an input- and an output-driven perspective which is in line with theory for systems at steady state (Borrett et al., 2011). Moreover, both networks were homogeneous since the coefficient of variation (i.e., relative dispersion) of their direct flows was on average about three times greater than the coefficient of variation of their indirect flows (Fig. 4f).

3.3. A joint outlook on the indicators

The FCI values for the economic network were relatively higher and

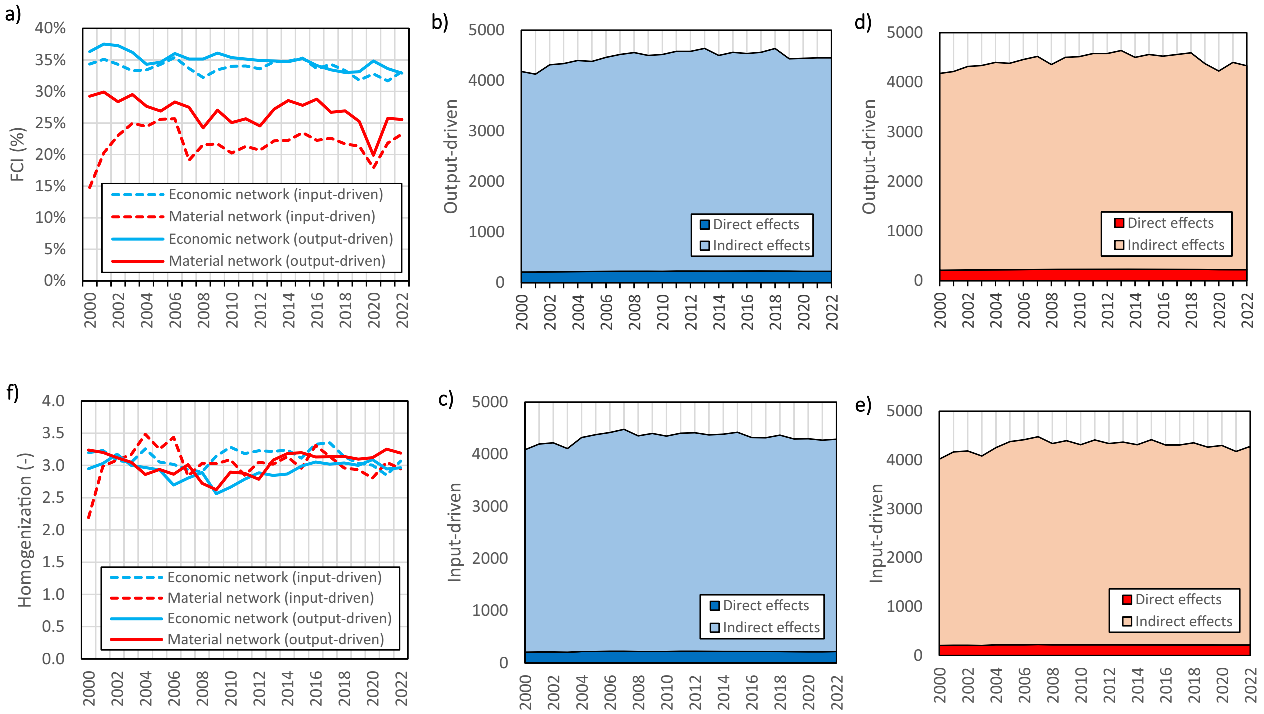


Fig. 4. Results of ecological network analysis of the global metal waste trade between 2000 and 2022 showing: a) the FCI (truncated at 20 steps), b) the indirect effects for the economic network (blue) from an output-driven perspective, and c) from an input-driven perspective, d) the indirect effects for the material network (red) from an output-driven perspective, and e) from an input-driven perspective, and f) the degree of homogenization for both networks expressed as the ratio of the coefficient of variation of direct flows over the coefficient of variation of indirect flows (%).

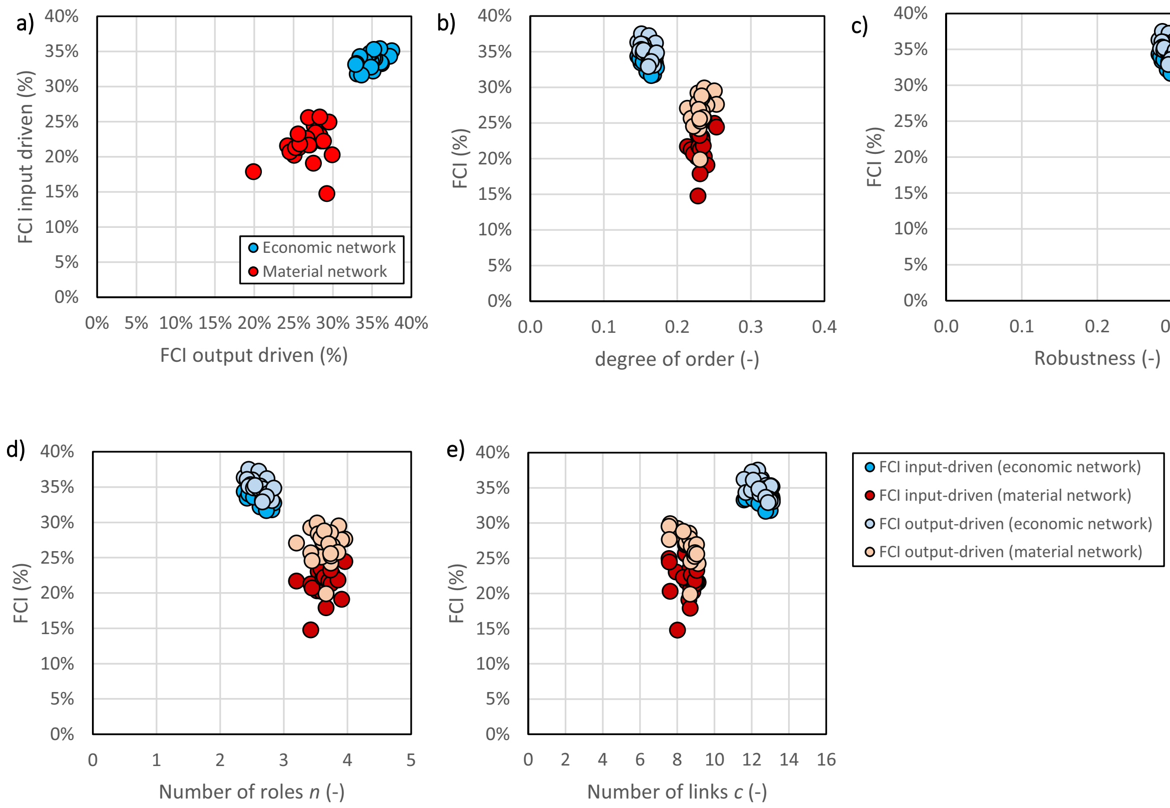


Fig. 5. The FCI of both networks juxtaposed a) from an input-driven with an output-driven perspective, b) with the degree of order, c) with robustness, d) with the number of roles, and e) with the number of links.

more uniform than the FCI values of the material network both from an input and an output perspective (Fig. 5a). This suggests that circulation of monetary flows was more intense than of material flows, but it showed a decreasing trend over the years despite an observed growth in total trade value. The lower variability in the FCI values of the economic network compared to those of the material network (Fig. 5b, c, d, and e) may be due to its relatively larger number of trade links resulting to a higher **network redundancy** and consequently to a higher **network resilience** which remained stable over the years. The material network exhibited higher yet more dispersed values of **network efficiency** (Fig. 5b) and **robustness** (Fig. 5c) than the economic network suggesting that it had a more articulated structure. This may also explain its more pronounced sensitivity to the shocks of the global economic crisis and the COVID-19 pandemic.

The homogenization values for the material network were similar both from an input- and an output-driven perspective (Fig. 6a). They also seemed to not be affected much by the degree of order (i.e., **network efficiency**) (Fig. 6b), the **robustness** (Fig. 6c), the **number of roles** (Fig. 6d), or the number of links (Fig. 6e). A weak positive relation between homogenization and the FCI was observed mainly for the material network from an input-driven perspective (Fig. 6f).

A visual inspection of the cumulative frequency distributions of in-, out-, and total-degrees of nodes in both networks for all the years studied (supplementary material: Appendixes D and E), gave the impression of power-law distributions where a few countries had the role of central hubs with many trade links while the largest share of countries were at the periphery of the network having few trade links. This was observed mainly for regions of the networks including high-degree nodes (i.e., countries with more than 100 trade connections such as China, the US, the Netherlands, Germany, France, and others), and it was more pronounced from an in-degree (import) perspective.

4. Discussion

4.1. Robust circulation due to redundancy, network non-locality, and homogeneity

Between 2000 and 2022, the global trade for waste metals grew mainly in terms of complexity (i.e., number of links) and of size in terms of total system throughput (i.e., size of material and monetary flows) but less so in terms of the number of countries participating in the trade. Interestingly, the circulation of the trade flows was substantially higher than estimations of previous studies on other types of trade networks (Iskrzyński et al., 2021) but showed a decreasing trend. We theorize that the combination of an increasing total annual economic value with a decreasing *Finn Cycling Index* may imply a growing dependence of the economic network on a few highly connected countries responsible for sustaining a growing trade activity for waste metals. However, it is also noted that the interpretation of the FCI is context dependent as it merely captures the proportion of flow from the total system throughput which recirculates back into the nodes of the network without accounting for residence time or storage (May, 1981), and in some cases high cycling may even indicate a system under stress (Fath, Asmus, et al., 2019). Also, the FCI should not be confused with other circularity indicators (e.g., the circular material use rate of Eurostat). Due to the aggregate nature of analysed trade data, it is not possible to clarify which types of metal waste have been recirculating without resorting to manual filtering of individual trade flows on the online database of Chatham House. Whereas the FCI quantifies the flow activity due to the presence of feedback loops and cyclical structures in the network, a closer analogue to the multiplier effect in economics is the *average path length (APL)*. This indicator quantifies how many units of flow activity are generated per unit of input flow, and in economic context it would capture *"how many times a unit of currency entering a market will be*

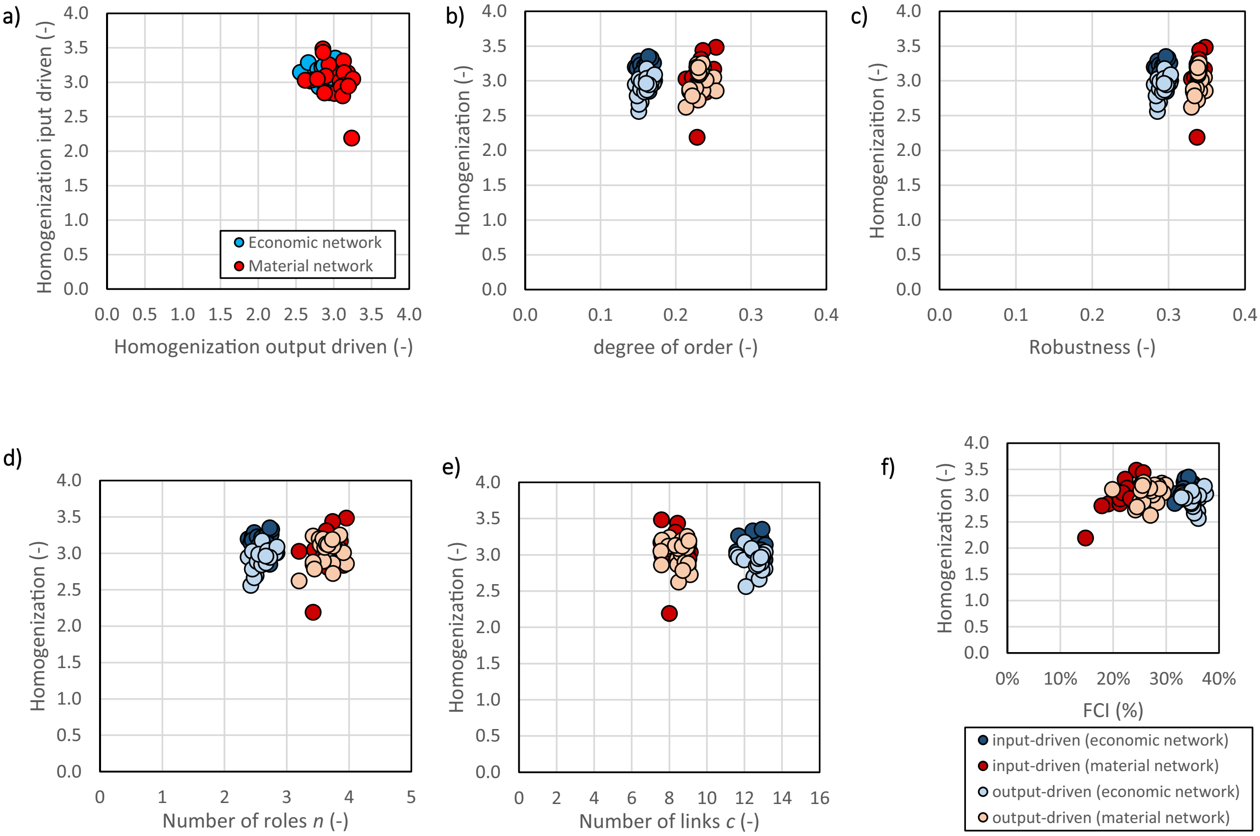


Fig. 6. The degree of homogenization for both networks juxtaposed a) from an input-driven with an output-driven perspective, b) with the degree of order, c) with robustness, d) with the number of roles, e) with the number of links, and f) with the FCI.

exchanged before exiting that market" (Fath et al., 2019). However, the calculation of the *APL* was not possible because both studied networks were closed (i.e., not accounting for any input or output flows).

Even though both networks were outside the ***"window of vitality"***, their **robustness** values were relatively high and stable. This was likely the combined result of a high **redundancy** in trade flows, of **network non-locality**, and of homogeneous (i.e., similarly valued) indirect flows. While the stabilizing effect of high **network redundancy** on **robustness** may be intuitively straightforward, this may not the case for the effect of homogeneous indirect flows. A plausible explanation can be found in research on the operation of resilient power systems where it was proposed that between two power grids of equal total system throughput and of the same structure (i.e., **network efficiency**), the one where the flows between its nodes are of equal size is expected to exhibit higher **robustness** and **network resilience** than the one where the same connections have unequally distributed flow sizes (Huang et al., 2022, 2024). This reasoning may help explain the contribution of indirect flow effects (i.e., unobservable network of asymmetric connections) to the stability in the **robustness** of the global metal waste trade network since they were more evenly distributed (i.e., *"well-mixed"*) than the direct flows (i.e., observable network) (Fath and Patten, 1999). Also, it is not unlikely that the indirect flows may have also been of lower economic value than the *"first-pass"* direct flows.

Interestingly, the *"ecosystem"* of countries in the material network was more *"species"*-rich than the economic network in terms of **number of roles**. The analogy with natural ecosystems here is that countries may be adopting roles analogous to *producers* (i.e., exporting countries of metal waste), *primary consumers* (i.e., importing countries of metal waste), *secondary consumers* (i.e., importing countries of processed metal waste as secondary raw materials), and *decomposers* (i.e., importing countries of relatively low value metal waste which may or may not reenter the formal or the informal economy or which may end up in controlled or uncontrolled landfills).

It is also important to note that, following theory (Ulanowicz et al., 2009), it was proposed that natural ecosystems *"can be either strongly connected across a few links or weakly connected across many links, but configurations of strong connections across many links and weak connections across a few links tend to break up or fall apart, respectively (May, 1972)"*. If this theory holds also for socio-economic systems, then the large number of trade links between countries in combination with the annual *"shuffling"* of trading partners (which is visually observed on the Sankey diagrams in Appendix F of the supplementary material), implies that the global trade of waste metals was a highly connected but volatile network.

The above points highlight that network-based indicators need to be considered simultaneously for obtaining a more holistic understanding of systemic network properties rather than being considered individually. For example, a network which is very robust for one type of resource may not necessarily be the most robust for another type of resource or more equitable otherwise.

4.2. *Inequity aspects in the trade of waste metals*

It is reasonable to expect a further increase in waste generation (United Nations Environment Programme, 2024b) along with an intensification of recycling efficiencies with reduced specific impact (per kg) and a fiercer competition between countries for different resources (Harpprecht et al., 2024). This concerns, in particular waste metals, in anticipation of an increasing future demand and volatile supply of metals (Harpprecht et al., 2024) and potentially of other critical raw materials which are necessary for achieving carbon neutrality. For copper, for example, it has been proposed that circularity strategies complementary to improved recycling will need to be deployed to reduce its rising future demand while mitigating the negative impacts of primary metal production (Born and Ciftci, 2024). In the case of the Japanese steel sector, research suggested that its decarbonization will depend on its ability to shift its current steel scrap downcycling practices towards improving material efficiency and upcycling to avoid overdependence on innovative production technologies (Watari et al., 2023b). Another issue pertains directly to the smelting process and maximum input of metal scrap. For example, blast furnaces can take a maximum of only 25 % scrap steel load while electric arc furnaces can use 100 % scrap steel yet require six times more energy (Steuer et al., 2021). In China, the focus was originally set on developing the former (which has also higher emissions) impairing the scale of recycling and creating a backlog to large-scaled generating sources such as End-of-Life ships (Steuer et al., 2021). The impending future scarcity of scrap metals, and the lack of technological means to reprocess these, may further exacerbate the disparity in the accessibility and distribution of waste metals as secondary raw materials between countries of the Global North (having abundant access) and countries of the Global South (lacking access), a phenomenon which was coined as *"scrap endowment"* (Watari et al., 2023a). This global inequity could also worsen the situation of low-income countries facing financial crisis such as Lebanon where it was reported that armed gangs affiliated with political parties have taken control of the scrap metal industry (Saleh, 2024).

Previous research on the global waste metal trade showed that it is a highly complex and hierarchical network shaped over decades by geopolitics and economic unrest (Hu et al., 2020). The researchers identified scale-free properties where a small number of countries from three identified groups (East Asia-America-Oceania, Europe, and South Asia-Middle East) were found to dominate the export market, monopolizing most of the trade flows and most of the total value, while importing countries were found to be competing (Hu et al., 2020). In our case, the deviation of the global waste metal trade network from a strict power law may be due to a variety of reasons such as preferential node attachments (i.e., where highly connected nodes are more likely to form new links) as well as growth mechanisms in sub-distributions of the network or systemic constraints (e.g., as a direct or indirect result of international trade agreements or national policies).

Interestingly, when the raw data were examined in terms of economic value per kg traded (i.e., sorted in a descending order where the first hundred largest annual trade flows were illustrated on Sankey diagrams on Appendix F of the supplementary material), it became visually evident that a relatively small number of (mostly) high-income countries have been consolidating imports of high-value metal waste in low quantities from many (mainly but not exclusively) low- and middle-income exporting countries. Such an example is that of Switzerland which, over the years studied, has been accumulating high-value waste metals in small amounts by diversifying its imports from Indonesia, Malaysia, Lebanon, Armenia, and Chile among many others. A further search on the online database revealed that for several of the years studied, a very large part of the imported value from scrap metals by Switzerland was due to their content in gold, platinum, or other precious metals. The observed disparity in the accumulation of economically valuable waste metals may have been due to a selective bias of some countries for securing critical raw materials and for increasing their circularity rates, a phenomenon which was coined as **circular resource nationalism** (Blot et al., 2024; Schröder and Barrie, 2024). Perhaps this was not the case for less valuable scrap metals which may have ended up leaking to the environment (mainly but not only) in countries of the Global South.

From a socio-metabolic point of view, material circularity is of primary relevance considering that higher circularity rates lower the input and output pressures on the environment. When material circularity is accompanied with high connectivity between different actors for improved circulation of resources and resilience, one may rush to conclude that it is a well-functioning CE. In this regard, **network resilience** and **robustness** (i.e., balance between efficiency and resilience) resulting from emerging **network non-locality** have already been proposed to be considered as public goods based on the assumption of non-excludability and non-rivalry, as well as on the expectation of generating positive externalities (Kharrazi et al., 2020). Yet, any perceived beneficial role of **network resilience** (or of **robustness** and circularity for that matter) as a driver and as an outcome of CE transitions may not hold automatically (Perramon et al., 2024). This may be the case particularly when inequities in the accessibility of primary resources and secondary raw materials (such as waste metals) persist or even become exacerbated over time, increasing the **socio-metabolic risk** of countries.

It is proposed that a bio-inspired approach has the potential to inform CE policies in the following two ways. Firstly, network-based methods can extend the toolkit of policy makers with an eco-mimicry perspective for examining the global distribution patterns of waste metals and for improving their effective cross-scale circulation by benchmarking against natural ecosystems. These methods can build upon and complement socio-metabolic research by identifying **socio-metabolic risks**. They do so by offering a dashboard of indicators which can provide a more holistic overview of systemic network properties including the proportion of resources cycling (i.e., FCI), **network resilience, robustness**, and **network non-locality** among others. Secondly, nature-based solutions (Stefanakis et al., 2021) can complement this effort by offering a set of practical and scalable strategies for restoring, conserving, and protecting natural ecosystems and biodiversity (Tsalis et al., 2022) with applications ranging from the embeddedness of constructed wetlands as detrital actors within steel industrial ecosystems (Malone et al., 2018) to the remediation of contaminated soil, water, and leachate in landfills (Abiriga et al., 2021; Hale et al., 2022).

4.3. Limitations

The analysis should be considered only in the context of the downloaded dataset at the obtained date (since the online database is experimental and subject to periodic updating). Moreover, the analysis focuses on the trade of metal waste which is only but a subset of a global CE. This means that it omits any other relevant flows in the total life cycle of the studied material streams which typically includes the processes of extraction/mining, production, fabrication and manufacturing, use, waste management, and landfilling (Kullmann et al., 2021). Furthermore, the aggregation of the material and monetary flows in the downloaded dataset misses the level of detail on the exact type of materials traded. Additionally, both networks are studied under a steady state assumption representing *"static pictures"* of the total volumes traded over a year, overlooking any in-between dynamics. In natural ecosystems shocks are absorbed in a seemingly static manner but which may occur via dynamic processes over long periods of time as the result of natural cycles and of the diversity of internal mechanisms of a vast number of species. In human-made systems, the evolution of post-shock modulation of material, energy, monetary, and information flows for tolerating disturbances may be too fast to capture. Future work could focus on obtaining spatio-temporal data of higher granularity to enable a more comprehensive analysis of socio-economic robustness across various levels, sectors, and actors.

Since all relevant structural information which may affect the results of our analysis is contained in the network flows, it is also important to note the following limitations due to data issues similar to the work of McNerney et al. (2013): a) any possible conflation of prices and quantities of waste metals may mean that any changes in their sizes may be due to various indistinguishable mechanisms, and b) quantities smaller than a minimum cutoff value may have been reported by countries as zeros due to country reporting requirements leading to an impression of incomplete network topology. The collective size of all those non-reported small flows of metal waste may be substantial considering that in both types of networks studied the flows of zero value represent on average about 89 % of all possible m x m links between countries. Typically, analyses focus on mapping and quantifying only the large flows, but the small ones that are missed or that fall below the detection threshold (reporting), could eventually (singly or cumulatively) have important systemic repercussions.

Finally, it is stressed that the two types of networks assessed are in fact two different viewpoints of the same system. No complex system can be observed in its entirety or at a resolution that captures all the detail of all types of flows. Perhaps the inability to generate a complete description is inherent in the definition of a complex system. Hence, these systems are unpredictable by their very nature, since it is assumed that their dynamics are sensitively dependent on initial conditions (or arbitrarily small fluctuations).

5. Concluding remarks

Network-based indicators are valuable for obtaining a comprehensive overview of the sustainability of socio-economic systems. Here, ascendency analysis and ecological network analysis have been employed to explore their potential for studying trading patterns of the global metal waste trade and for identifying inequities in resource accessibility of countries between 2000 and 2022. Results show that during this period, the global trade of waste metals has been stable at relatively high levels of **network resilience**. This was likely due to the synergistic effect of high **network redundancy, network non-locality** (i.e., dominance of indirect effects), and homogenization of indirect flows. The values of **robustness** (representing the balance between network efficiency and network resilience) were also relatively high and stable, but they remained outside the ***"window of vitality"*** characterizing sustainable natural ecosystems. Within these 22 years, waste metals became progressively a more valuable resource where material and monetary circulation was considerable but with a decreasing trend and in a market dominated (mainly but perhaps not exclusively) by a small number of countries from the Global North. Additionally, the trade links in the network of countries may have been volatile as suggested by the large number of links and the annual *"switching"* of trading partners.

Addressing inequities in the accessibility of primary resources and secondary raw materials such as waste metals is important because if they persist over time, they may worsen the **socio-metabolic risk** of countries with weak economies. Therefore, besides boosting circularity rates, CE policies for waste metals will also need to address global inequities in their accessibility while accounting for environmental and social implications occurring throughout the complete lifecycle of related products and materials. To this end, a bio-inspired approach which builds on network-based methods for improved decision making and nature-based solutions for practical, regional, and scalable actions, can be invaluable for supporting countries' transition towards regenerative circular economies. It is reasonable then to expect that the adoption of such bio-inspired CE policies by socio-economic actors will be easier and faster if they are developed and presented as opportunities rather than as constraints.

Author contributions

F.K.Z. conceived the idea of the research, compiled the document structure, conducted the quantitative analysis, and wrote the text as the main author. The order of authors is arbitrary as all of them contributed at different parts and across different times or versions of the manuscript with their expertise on different aspects which are highlighted in parentheses following their initials: B.D.F. (network methods, circular economy), S.T-C. (circular economy, waste management), H.H. (network methods), D.S. (circular economy), B.S. (circular economy, waste management, metal waste), A.S. (circular economy, ecological engineering, nature-based solutions), O.G.C. (circular economy, ecological engineering), S.Sc. (circular economy, economics), S.S. (circular economy, socio-metabolic research, industrial ecology), D.N. (circular economy, socio-metabolic research, industrial ecology), M.d.J. (inclusion/exclusion/inequity aspects, funding acquisition). All authors contributed significantly to this work by reading, knowledge-sharing, providing constructive criticism, editing, and reviewing the text. 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, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Brian D. Fath:** Writing – review & editing. **Susana Toboso-Chavero:** Writing – review & editing. **Hao Huang:** Writing – review & editing, Funding acquisition. **Daan Schraven:** Writing – review & editing. **Benjamin Steuer:** Writing – review & editing, Visualization, Resources. **Alexandros Stefanakis:** Writing – review & editing. **O.Grant Clark:** Writing – review & editing. **Serban Scrieciu:** Writing – review & editing. **Simron Singh:** Writing – review & editing. **Dominik Noll:** Writing – review & editing, Funding acquisition. **Martin de Jong:** 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.

Data availability

The Word file with the Appendixes and the Excel file with the data and the analysis are included as supplementary materials.

Acknowledgments

F.K.Z. is 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 Princeton University's School of Engineering and Applied Science (SEAS). D.N. acknowledges funding under the research contract 2022.05039.CEECIND/CP1734/CT0001 (https://doi.org/10.54499/2022.05039.CEECIND/CP1734/CT0001) through the Portuguese Foundation for Science and Technology (FCT) with MED (https://doi.org/10.54499/UIDB/05183/2020) and CHANGE (https://doi.org/10.54499/LA/P/0121/2020). The authors are grateful for the constructive comments of the editor and two anonymous reviewers.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107958.

References

Abiriga, D., Jenkins, A., Vestgarden, L.S., Klempe, H., 2021. A nature-based solution to a landfill-leachate contamination of a confined aquifer. Sci. Rep. 11. https://doi.org/10.1038/s41598-021-94041-7.

Albert, R., Joeng, H., Barabasi, A.-L., 2000. Error and attack tolerance of complex networks. Nature 406, 378–382.

Baldassarre, B., Saveyn, H.G.M., 2023. A systematic analysis of EU publications on the circular economy - JRC133158. Luxambourg. https://doi.org/10.2760/36203.

Barrie, J., Anantharaman, M., Oyinlola, M., Schröder, P., 2022. The circularity divide: what is it? And how do we avoid it? Resour. Conserv. Recycl. 180. https://doi.org/10.1016/j.resconrec.2022.106208.

Blot, E., Bergeling, E., Watkins, E., Marchetti, E., 2024. Circularity Strategies and Sustainable Resource Management to Safeguard the Clean Energy Transition.

Born, K., Ciftci, M.M., 2024. The limitations of end-of-life copper recycling and its implications for the circular economy of metals. Resour. Conserv. Recycl. 200. https://doi.org/10.1016/j.resconrec.2023.107318.

Borrett, S.R., Fath, B.D., Patten, B.C., 2007. Functional integration of ecological networks through pathway proliferation. J. Theor. Biol. 245, 98–111. https://doi.org/10.1016/j.jtbi.2006.09.024.

Borrett, S.R., Freeze, M.A., Salas, A.K., 2011. Equivalence of the realized input and output oriented indirect effects metrics in ecological network analysis. Ecol. Modell. 222, 2142–2148. https://doi.org/10.1016/j.ecolmodel.2011.04.003.

Borrett, S.R., Lau, M.K., 2014. enaR: an R package for ecosystem network analysis. Methods Ecol. Evol. 5, 1206–1213. https://doi.org/10.1111/2041-210X.12282.

Brehm, C., Chatterjee, A., Layton, A., 2020. Mimicking the nested structures of ecosystems in the design of industrial water networks. Procedia CIRP. 90, 361–365. https://doi.org/10.1016/j.procir.2020.01.104.

Chatham House, The royal institute of international affairs, 2020. Waste, scraps, and residues [WWW Document]. www.circulareconomy.earth. URL https://circulareconomy.earth/trade?year=2020&category=6&units=value&autozoom=1 (accessed 1.16.24).

Chatterjee, A., Brehm, C., Layton, A., 2021a. Evaluating benefits of ecologically-inspired nested architectures for industrial symbiosis. Resour. Conserv. Recycl. 167. https://doi.org/10.1016/j.resconrec.2021.105423.

Chatterjee, A., Helbig, C., Malak, R., Layton, A., 2023. A comparison of graph-theoretic approaches for resilient system of systems design. J. Comput. Inf. Sci. Eng. https://doi.org/10.1115/1.4062231.

Chatterjee, A., Layton, A., 2020. Mimicking nature for resilient resource and infrastructure network design. Reliab. Eng. Syst. Saf. 204, 107142. https://doi.org/10.1016/j.ress.2020.107142.

Chatterjee, A., Malak, R., Layton, A., 2021b. Exploring system of systems resilience versus affordability trade-space using a bio-inspired metric. J. Comput. Inf. Sci. Eng. 21, 050905. https://doi.org/10.1115/1.4050288.

Corvellec, H., Stowell, A., Johansson, N., 2021. Critiques of the circular economy. J. Ind. Ecol. 1–12. https://doi.org/10.1111/jiec.13187.

de Souza, V., Bloemhof-Ruwaard, J., Borsato, M., 2019. Towards regenerative supply networks: a design framework proposal. J. Clean. Prod. 221, 145–156. https://doi.org/10.1016/j.jclepro.2019.02.178.

Dunne, J.A., Williams, R.J., Martinez, N.D., 2002a. Network structure and biodiversity loss in food webs: robustness increases with connectance. Ecol. Lett. 5, 558–567. https://doi.org/10.1046/j.1461-0248.2002.00354.x.

Dunne, J.A., Williams, R.J., Martinez, N.D., 2002b. Food-web structure and network theory: the role of connectance and size. Proc. Natl. Acad. Sci. u S. a 99, 12917–12922. https://doi.org/10.1073/pnas.192407699.

Fath, B.D., 2018. Systems ecology: ecological network analysis. In: Encyclopedia of Ecology (Second Edition), 1, pp. 643–652. https://doi.org/10.1016/B978-0-12-409548-9.11171-6.

Fath, B.D., 2012. Overview of network environ analysis - a systems technique for understanding complex ecological systems. Ecol. Quest. 16, 77. https://doi.org/10.12775/v10090-012-0008-0.

Fath, B.D., Dean, C.A., Katzmair, H., 2015. Navigating the adaptive cycle: an approach to managing the resilience of social systems. Ecol. Soc. 20. https://doi.org/10.5751/ES-07467-200224.

Fath, B.D., Asmus, H., Asmus, R., Baird, D., Borrett, S.R., de Jonge, V.N., Ludovisi, A., Niquil, N., Scharler, U.M., Schückel, U., Wolff, M., 2019a. Ecological network analysis metrics: the need for an entire ecosystem approach in management and policy. Ocean Coast. Manag. 174, 1–14. https://doi.org/10.1016/j.ocecoaman.2019.03.007 (July 2018).

Fath, B.D., Fiscus, D.A., Goerner, S.J., Berea, A., Ulanowicz, R.E., 2019b. Measuring regenerative economics: 10 principles and measures undergirding systemic economic health. Glob. Transit. 1, 15–27. https://doi.org/10.1016/j.glt.2019.02.002.

Fath, B.D., Patten, B.C., 1999. Quantifying resource homogenization using network flow analysis, Ecol. Modell.

Fath, B.D., Scharler, U.M., 2018. Systems Ecology: Ecological Network Analysis, 2nd ed, Encyclopedia of Ecology. Elsevier Inc. https://doi.org/10.1016/B978-0-12-409548-9.11171-6.

Fath, B.D., Scharler, U.M., Ulanowicz, R.E., Hannon, B., 2007. Ecological network analysis: network construction. Ecol. Modell. 208, 49–55. https://doi.org/10.1016/j.ecolmodel.2007.04.029.

Fromberg, E.H.E., Bakker, C.A., Peck, D., 2023. Conceptualising a circular economy—an enquiry into circular economy conceptual metaphors. Circ. Econ. Sustain. https://doi.org/10.1007/s43615-023-00325-7.

Galychyn, O., Fath, B.D., Buonocore, E., Franzese, P.P., 2022. Ecological network analysis of a metabolic urban system based on input–output tables: model development and case study for the city of Vienna. Clean. Prod. Lett. 3, 100019. https://doi.org/10.1016/j.clpl.2022.100019.

Hale, S.E., Folde, M.S., Melby, U.H., Sjødahl, E.U., Smebye, A.B., Oen, A.M.P., 2022. From landfills to landscapes—nature-based solutions for water management taking into account legacy contamination. Integr. Environ. Assess. Manage. 18, 99–107. https://doi.org/10.1002/ieam.4467.

Harpprecht, C., Miranda Xicotencatl, B., van Nielen, S., van der Meide, M., Li, C., Li, Z., Tukker, A., Steubing, B., 2024. Future environmental impacts of metals: a systematic review of impact trends, modelling approaches, and challenges. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2024.107572.

Holling, C.S., 1986. The resilience of terrestrial ecosystems: local surprise and global change. Sustainable Development of the Biosphere. Cambridge University Press, Cambridge, UK, pp. 292–320.

Hu, X., Wang, C., Lim, M.K., Koh, S.C.L., 2020. Characteristics and community evolution patterns of the international scrap metal trade. J. Clean. Prod. 243. https://doi.org/10.1016/j.jclepro.2019.118576.

Huang, H., Mao, Z., Layton, A., Davis, K.R., 2022. An ecological robustness oriented optimal power flow for power systems' survivability. IEEE Trans. Power Syst. 38, 447–462. https://doi.org/10.1109/TPWRS.2022.3168226.

Huang, H., Poor, V., Davis, K., 2024. Inclusion of reactive power into ecological robustness-oriented optimal power flow for enhancing power system resilience. In: Proceedings of the 57th Hawaii International Conference on System Sciences.

Huang, J., Ulanowicz, R.E., 2014. Ecological network analysis for economic systems: growth and development and implications for sustainable development. PLoS. One 9. https://doi.org/10.1371/journal.pone.0100923.

Iskrzyński, M., Janssen, F., Picciolo, F., Fath, B., Ruzzenenti, F., 2021. Cycling and reciprocity in weighted food webs and economic networks. J. Ind. Ecol. 1–12. https://doi.org/10.1111/jiec.13217.

Johnson, C., Webster, K., 2021. ABC&D: Creating a Regenerative Circular Economy for All. TerraPreta Publishing.

Kennedy, S., Linnenluecke, M.K., 2022. Circular economy and resilience: a research agenda. Bus. Strategy. Environ. 1–12. https://doi.org/10.1002/bse.3004.

Kharrazi, A., Kudo, S., Allasiw, D., 2018. Addressing misconceptions to the concept of resilience in environmental education. Sustainability (Switzerland) 10. https://doi.org/10.3390/su10124682.

Kharrazi, A., Rovenskaya, E., Fath, B.D., 2017. Supporting Information S1. Theoretical resilience as a function of efficiency and redundancy. PLoS. One 12. https://doi.org/10.1371/journal.pone.0171184.

Kharrazi, A., Yu, Y., Jacob, A., Vora, N., Fath, B.D., 2020. Redundancy, diversity, and modularity in network resilience: applications for international trade and implications for public policy. Curr. Res. Environ. Sustain. 2, 100006. https://doi.org/10.1016/j.crsust.2020.06.001.

Kullmann, F., Markewitz, P., Stolten, D., Robinius, M., 2021. Combining the worlds of energy systems and material flow analysis: a review. Energy Sustain. Soc. https://doi.org/10.1186/s13705-021-00289-2.

Layton, A., 2022. Using biological inspiration to guide the design of human networks for resilienS. Climate Resilience Academy UM. URL https://www.youtube.com/watch?v=sPobHdq_wsI (accessed 1.16.23).

Layton, A., 2014. Food Webs: Realizing Biological Inspirations for Sustainable Industrial Resource Networks (PhD Thesis). Georgia Institute of Technology.

Layton, A., Bras, B., Weissburg, M., 2015. Ecological robustness as a design principle for sustainable industrial systems. In: Proceedings of the ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 4: 20th Design for Manufacturing and the Life Cycle Conference; 9th International Conference on Micro- and N. Boston. https://doi.org/10.1115/DETC2015-47560.

Lietaer, B., Ulanowicz, R.E., Goerner, S.J., McLaren, N., 2010. Is our monetary structure a systemic cause for financial instability? Evidence and remedies from nature. J. Futures Stud. 14, 89–108.

Malone, S.M., Cohen, A.R., Bras, B., Weissburg, M., 2018. The application of detrital actors in industrial systems. Procedia CIRP. Elsevier B.V., pp. 867–871. https://doi.org/10.1016/j.procir.2017.11.091

May, R.M., 1981. A cycling index for ecosystems. Nature 292, 105, 00280836/81/280105-01501.00.

McNerney, J., Fath, B.D., Silverberg, G., 2013. Network structure of inter-industry flows. Phys. A: Stat. Mech. Appl. 392 (24), 6427–6441. https://doi.org/10.1016/j.physa.2013.07.063.

Panyam, V., Layton, A., 2019. Bio-inspired modelling approaches for human networks with link dissipation. In: ASME 2019, International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE2019. Anaheim, CA, USA, pp. 1–10. DETC2019-98171.

Patten, B.C., 1985. Energy cycling in the ecosystem. Ecol. Modell. 28, 1–71.

Patten, B.C., Richardson, T.H., Barber, M.C., 1982. Path analysis of a reservoir ecosystem model. Can. Water Resour. J. 7, 252–282. https://doi.org/10.4296/cwrj0701252.

PBL, 2022. Circular economy progress report 2022 (summary).

Pelenc, J., Ballet, J., Dedeurwaerdere, T., 2015. Weak sustainability versus strong sustainability: brief for GSDR.

Perramon, J., Bagur-Femenías, L., Alonso-Almeida, M., del, M., Llach, J., 2024. Does the transition to a circular economy contribute to business resilience and transformation? Evidence from SMEs. J. Clean. Prod. 453. https://doi.org/10.1016/j.jclepro.2024.142279.

Reap, J., Layton, A., 2017. Lessons from living systems for the development of sustainable industrial resource networks. J.Energy Challenges and Mech. 4, 1–10.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., Von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., Rockström, J., 2023. Earth beyond six of nine planetary boundaries.

Ripple, W.J., Wolf, C., Gregg, J.W., Rockström, J., Newsome, T.M., Law, B.E., Marques, L., Lenton, T.M., Xu, C., Huq, S., Simons, L., King, S.D.A., 2023. The 2023 state of the climate report: entering uncharted territory. Bioscience 73, 841–850. https://doi.org/10.1093/biosci/biad080.

Saleh, E., 2024. Guns, gangs and metal: the double-edged sword of protection inside Beirut's scrap economies. Anthropol. Today 40. https://doi.org/10.1111/1467-8322.12863.

Savini, F., 2023. Futures of the social metabolism: degrowth, circular economy and the value of waste. Futures. 150. https://doi.org/10.1016/j.futures.2023.103180.

Schaubroeck, T., 2020. Circular economy practices may not always lead to lower criticality or more sustainability; analysis and guidance is needed per case. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2020.104977.

Schröder, P., Barrie, J., 2024. What is circular resource nationalism? [WWW Document]. Chatham House. URL https://circulareconomy.earth/publications/what-is-circular-resource-nationalism (accessed 6.11.24).

Singh, S.J., Huang, T., Nagabhatla, N., Schweizer, P.-J., Eckelman, M., Verschuur, J., Soman, R., 2022. Socio-metabolic risk and tipping points on islands. Environ. Res. Lett. 17, 065009. https://doi.org/10.1088/1748-9326/ac6f6c.

Stefanakis, A., Nikolaou, I., 2021. Circular Economy and Sustainability, 1st ed. Elsevier Publishing, Amsterdam, The Netherlands.

Stefanakis, A.I., Calheiros, C.S.C., Nikolaou, I., 2021. Nature-based solutions as a tool in the new circular economic model for climate change adaptation. Circ. Econ. Sustain. 1, 303–318. https://doi.org/10.1007/s43615-021-00022-3.

Steuer, B., Staudner, M., Ramusch, R., 2021. Role and potential of the circular economy in managing end-of-life ships in china. Resour. Conserv. Recycl. 164. https://doi.org/10.1016/j.resconrec.2020.105039.

Stucki, T., Woerter, M., Loumeau, N., 2023. Clearing the fog: how circular economy transition can be measured at the company level. J. Environ. Manage. 326. https://doi.org/10.1016/j.jenvman.2022.116749.

Tsalis, T., Stefanakis, A.I., Nikolaou, I., 2022. A framework to evaluate the social life cycle impact of products under the circular economy thinking. Sustainability (Switzerland) 14. https://doi.org/10.3390/su14042196.

Ulanowicz, R.E., 2020. Quantifying sustainable balance in ecosystem configurations. Curr. Res. Environ. Sustain. 1, 1–6. https://doi.org/10.1016/j.crsust.2019.09.001.

Ulanowicz, R.E., 2009. The dual nature of ecosystem dynamics. Ecol. Modell. 220, 1886–1892. https://doi.org/10.1016/j.ecolmodel.2009.04.015.

Ulanowicz, R.E., 2002. The balance between adaptability and adaptation. Biosystems 64, 13–22. https://doi.org/10.1016/S0303-2647(01)00170-8.

Ulanowicz, R.E., 2001. Information theory in ecology. Comput. Chem. 25, 393–399. https://doi.org/10.1016/S0097-8485(01)00073-0.

Ulanowicz, R.E., Goerner, S.J., Lietaer, B., Gomez, R., 2009. Quantifying sustainability: resilience, efficiency and the return of information theory. Ecol. Complex. 6, 27–36. https://doi.org/10.1016/j.ecocom.2008.10.005.

United Nations Environment Programme, 2024a. Global resources outlook 2024 - Bend the trend - pathways to a liveable planet as resource use spikes. Nairobi.

United Nations Environment Programme, 2024b. Global waste management outlook 2024: beyond an age of waste - Turning rubbish into a resource. Nairobi. https://doi.org/10.58117/20.500.11822/44939/.

Velenturf, A.P.M., Purnell, P., 2021. Principles for a sustainable circular economy. Sustain. Prod. Consum. 27, 1437–1457. https://doi.org/10.1016/j.spc.2021.02.018.

Watari, T., Giurco, D., Cullen, J., 2023a. Scrap endowment and inequalities in global steel decarbonization. J. Clean. Prod. 425. https://doi.org/10.1016/j.jclepro.2023.139041.

Watari, T., Hata, S., Nakajima, K., Nansai, K., 2023b. Limited quantity and quality of steel supply in a zero-emission future. Nat. Sustain. 6, 336–343. https://doi.org/10.1038/s41893-022-01025-0.

Webster, K., 2021. A circular economy is about the economy. Circ. Econ. Sustain. 1, 115–126. https://doi.org/10.1007/s43615-021-00034-z.

Zorach, A.C., Ulanowicz, R.E., 2003. Quantifying the complexity of flow networks: how many roles are there? Complexity. 8, 68–76. https://doi.org/10.1002/cplx.10075.