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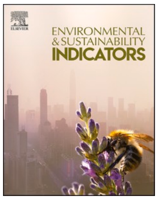

Network properties of the global waste trade

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ABSTRACT

The network properties of the global waste trade were assessed by using time series data of material and monetary flows between 2000 and 2022 from the online experimental database of Chatham House. More specifically, indicators from ecological network analysis and ascendency analysis were used to identity patterns which may not otherwise be directly identifiable, and to compare the network properties of the global waste trade to those of natural ecosystems. Focus was given on the distribution of monetary and material flows, on policy recommendations, and on future research avenues which we think are relevant for obtaining a more comprehensive understanding of socio-economic systems such as trade networks. This work provides a solid example of the application of network-based methods as an eco-mimicry approach for assessing the sustainability and fragility of socio-economic systems which can be of relevance to researchers and policy makers interested on transitions towards regenerative circular economies.

1. Introduction

Despite past efforts to transition to a circular economy, the global circularity rate dropped from 9.1% in 2018 to 7.2% in 2023 (Circle Economy Foundation and Deloitte, 2024). Meanwhile, it has been estimated that the global resource use in 2060 could increase by 60% compared to the levels of 2020 if production and consumption patterns remain unchanged (United Nations Environment Programme, 2024). This is unsurprising when considering that since 1971, humanity has been progressively exhausting Earth's annual biocapacity to sustain its ecological footprint (Global Footprint Network, 2024). Evidently, the global socio-economic metabolism has been geared towards consuming unsustainably increasing amounts of non-renewable flows for creating more flow-demanding structures (Hagens, 2020). But having already transgressed six out of the nine identified planetary boundaries (Richardson et al., 2023) we are now entering unknown climatic territory (Ripple et al., 2023), a development which warrants urgent further investigation on global socio-metabolic patterns.

Here, in line with a recent call for more research demonstrating the potential of circularity metrics on case studies (Shevchenko et al., 2024), a dashboard of indicators from ascendency analysis (Ulanowicz, 2009) and ecological network analysis (Fath et al., 2007) was deployed. The synergistic application of these two methods simultaneously is in assessing the sustainability of socio-economic systems by revealing patterns which may not be otherwise apparent (Fath et al., 2019; Mcnerney and Kryazhimskiy, 2009). The global trade of waste, scraps, and residues was selected as a case study due to their important contribution as secondary raw materials in the transition of countries to circular economies, and it was analysed as two distinct networks of trade flows: one of material flows and one of their corresponding monetary flows. The aim was to examine whether there are any identifiable patterns in changes in their sizes and complexity over time.

Section 2 describes the methods while section 3 presents and discusses the results, future research directions and policy recommendations, and chapter 4 highlights the conclusions.

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2. Methods

Time series data of annual trade flows of waste, scraps, and residues between 2000 and 2022 were obtained from the publicly available experimental database of Chatham House (Chatham House and The Royal Institute of International Affairs, 2020). The time series data were formatted in tables where each year would have two corresponding tables: one of annual material flows and one of their corresponding annual monetary flows. The rows *i* and columns *j* of the matrixes refer to the export and import countries, respectively. T_{ij}, $T_{i.}$, $T_{.j}$, and $T_{..}$ represent the trade flow from country *i* to country *j*, the sum of trade flows exported by country *i*, the sum of trade flows imported by country *j*, and the total system throughput (i.e., the global annual trade in terms of material flows or economic flows which here excludes boundary input or output flows due to the nature of the data), respectively. Any missing nodes (countries) 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. Table 1 lists the indicators used from ascendency analysis (Ulanowicz, 2002, 2009, 2020) and ecological network analysis (Fath, 2018; Fath et al., 2007; Fath and Scharler, 2018). Other indicators which were calculated include link density, connectance, degree centrality, and degree distribution. The datafile along with all calculations is available in the supplementary material.

3. Results & discussion

In the context of this analysis, complexity relates to the qualitative development of the networks in their structure (i.e., depending on the number of links and on how they are connected) whereas size has two interpretations. The first interpretation refers to the total system throughput which is the sum of annual trade flows. This sum typically accounts also for any input and output boundary flows but here they could not be considered due to the nature of the analysed data. The second interpretation is related to the total number of countries participating in the trade each year which form the nodes of the network.

When examining the data between 2000 and 2022, a considerable growth in the global trade activity for waste becomes evident (Fig. 1a). The total system throughput in 2000 was 264.4 million tonnes of waste worth 90.5 billion $USD whereas in 2022 it increased to 564.4 million tonnes of waste worth 450.5 billion $USD. Even though the annual growth rate of trade activity fluctuated both in terms of material and monetary flows it showed an overall increasing trend where there was a particularly noticeable expansion of the total economic value traded between 2002 and 2012 (i.e., by 277%) and between 2020 and 2022 (i.e., by 34%). The observed drops in global trade activity in specific years (i.e., in 2009, 2016, and 2020) may be due to shock effects such as the covid-19 pandemic and the financial crisis of 2007–2008 [e.g., see a study on modelling the implications of the *"great trade collapse"* for the declining imports of the United States during that period (Yilmazkuday,

Table 1
List of indicators used.

Method	Indicator	Symbol or Formula	Meaning
Ascendency analysis	Ascendency	$A = T_{..}\sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)\log_2\left(\frac{T_{ij}}{T_{i.}}\frac{T_{..}}{T_{.j}}\right)$	The *"ordered"* part of the trade network due to structural constraints responsible for streamlining trade flows efficiently (scaled with the total system throughput to impart physical meaning).
	Overhead	$\Phi = -T_{..}\sum_{i,j}\left(\frac{T_{ij}}{T_{..}}\right)\log_2\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right)$	The *"redundant"* part in the trade network responsible for sufficient flow path diversity and, consequently, network resilience (scaled with the total system throughput to impart physical meaning)
	Capacity to develop	$C = A + \Phi$	The ability of a trade network to grow and develop calculated as the sum of its *"ordered"* part and its *"redundant"* part
	Degree of order	$a = \frac{A}{C}$	The ability of the network for streamlining/consolidating trade flows (i.e., network efficiency)
	Robustness	$R = -\alpha\ln(\alpha)$	The balance between network efficiency and network redundancy
	Number of roles	$n = 2^X$	The distinct roles of countries in attracting, transforming, and distributing trade flows or, in other words, the number of transfers of a trade flow
	Number of links	$c = 2^{\left(\frac{H_c}{2}\right)}$	The number of trade links per country
Ecological network analysis	Normalized flows	$g_{ij,input} = \frac{T_{ij}}{T_{.j}}$ and $g_{ij,output} = \frac{T_{ij}}{T_{i.}}$	The normalized trade flows for an input-driven (demand side) and an output-driven (supply side) perspective (here excluding boundary flows)
	Direct flow intensity matrix	$G = \left(g_{ij}\right)$	Matrix which considers all (normalized) direct trade flows g_{ij} (constructed both for an input-driven and an output-driven perspective)
	Integral flow matrix	$N = \left(n_{ij}\right) = G^0 + G^1 + \ldots G^n$	Matrix where each element n_{ij} represents the probability of a trade flow to reach other countries in the network in *n* steps (constructed both for an input-driven and an output-driven perspective)
	Indirect effects	$DI = \frac{\sum_{i,j=1}^{n}\left(n_{ij} - g_{ij} - \delta_{ij}\right)}{\sum_{i,j=1}^{n} g_{ij}}$	The degree of indirect effects in the trade network where δ_{ij} takes the value of one if and only if $i = j$ or zero otherwise (calculated both for an input-driven and an output-driven perspective)
	Finn Cycling Index	$FCI_{.j} = \frac{\sum TST_{cj}}{T_{..}}$ where $TST_{cj} = \frac{(n_{ii} - 1)}{n_{ii}}T_{.j}$	The proportion of flows circulating in the network due to the presence of cycling structures and feedback loops from an input-driven perspective
		$FCI_{i.} = \frac{\sum TST_{ci}}{T_{..}}$ where $TST_{ci} = \frac{(n_{ii} - 1)}{n_{ii}}T_{i.}$	The proportion of flows circulating in the network due to the presence of cycling structures and feedback loops from an output-driven perspective
	Homogenization	$Homogenization = \frac{CV(G)}{CV(N)}$ where $CV(G) = \frac{s(G)}{\overline{g}}$ $s(G) = \sqrt{\frac{SSD(G)}{\#elements\ in\ G - 1}}$ $SSD(G) = \sum\left(\overline{g} - g_{ij}\right)^2$ $CV(N) = \frac{s(N)}{\overline{n}}$ $s(N) = \sqrt{\frac{SSD(N)}{\#elements\ in\ N - 1}}$ $SSD(N) = \sum\left(\overline{n} - n_{ij}\right)^2$	The ratio of the coefficient of variation of the *G* matrix $CV(G)$ over the coefficient of variation of the *N* matrix $CV(N)$ which considers 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*) (calculated both from an input-driven and an output-driven perspective).

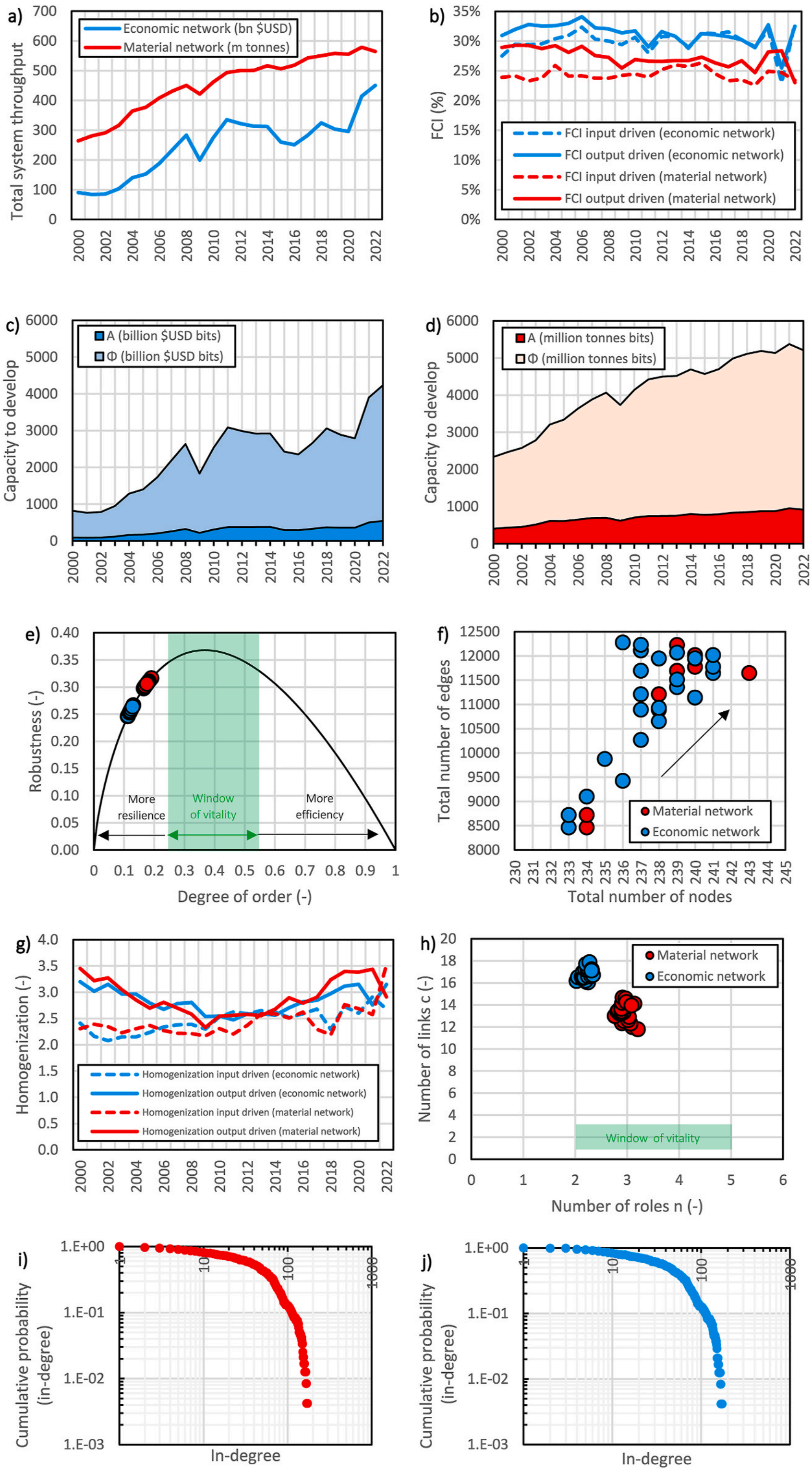

Fig. 1. Assessing the network properties of the global trade of waste with network-based methods (Fath et al., 2007; Ulanowicz, 2009) by using time series data from Chatham House (Chatham House and The Royal Institute of International Affairs, 2020) downloaded on the May 16, 2024. The analysis was done on the (aggregate) annual trade flows: i.e., economic flows (blue) and material flows (red) to calculate the following indicators: a) total system throughput (excluding boundary input and output flows), b) Finn Cycling Index (20-step), c) capacity to develop expressed by the sum of ascendency (A) and overhead (Φ) for the economic network, and d) similarly for the material network, e) robustness where each data point represents a network for one full year (the blue points correspond to the economic flow network, and the red points to the material flow network), f) number of nodes juxtaposed with number of edges, g) degree of homogenization (ratio: $\frac{CV(G)}{CV(N)}$), h) number of roles (n) juxtaposed with number of links per node (c), i) cumulative probability distribution of in-degree nodes for the material network in 2022, and for j) the economic network for the same year. The values characterizing the range of the *"window of vitality"* have been reported elsewhere (Ulanowicz et al., 2009; Zorach and Ulanowicz, 2003).

2019)]. Other reasons may include the adoption of extended producer responsibility (EPR) schemes (Compagnoni et al., 2024) and of waste related policies with stricter standards and a reportedly global impact such as China's initiatives *Operation Green Fence* and *Operation National Sword* which were implemented to improve the monitoring and the quality of its imported recyclables, and which led many countries to seek either for alternative markets to export their waste or for other ways to manage them domestically (Li and Mu, 2024; Meng, 2019; Tran et al., 2021).

The proportion of waste, scraps, and residues that have been circulating annually between countries due to the existence of network cycles in the global trade activity can be tracked by the Finn Cycling Index (*FCI*). Despite the observed increase in the total system throughput during these 22 years, the *FCI* showed a relatively stable and converging pattern in terms of demand and supply in both networks, an effect which was more pronounced in the economic network (Fig. 1b). The *FCI* for the material network was on average 27% from an output-driven (supply) perspective and 24% from an input-driven (demand) perspective. The corresponding average *FCI* values for the economic network were higher, at 31% and 30%, respectively. Disruptions in the annual cycling of trade flows are evidenced from the observed decline of the *FCI* of the economic network in 2021 and its consecutive recovery in 2022, along with a corresponding lag in its drop in 2022 for the material network. These recent fluctuations of the *FCI* for both networks could be the consequence of side-effects of the covid-19 pandemic such as the reduced demand for secondary raw materials in countries like China (Mahyari et al., 2022; Zhou et al., 2021). Other minor drops observed in the *FCI* in 2009, 2011, 2014, and 2017 may be related to the ripple effects in the waste market due to the global economic crisis and the implementation of EPR schemes and of waste related policies.

The ability of the global trade to self-organize and evolve in complexity can be described by information-based indicators from process ecology (Ulanowicz, 2006, 2009; Ulanowicz et al., 2009). In this regard, a network's *capacity to develop* is the sum of its *"ordered"* part due to structural constraints (i.e., the *"ascendency"*) and its *"redundant"* part due to residual network connections offering flexibility for resources to flow through diverse pathways (i.e., its *"overhead"*) (Ulanowicz, 2006, 2009; Ulanowicz et al., 2009). In the studied period, the material and economic networks grew their *capacity to develop* (i.e., the scale of the overall waste trade operation) by 123% and 417%, respectively (Fig. 1c and d) where ascendency contributed on average with 13% and 17%, respectively. This suggests that there was only a mild articulation in the configuration of both networks, in other words, there was limited network efficiency (e.g., between specialized bilateral partners) for consolidating waste trade flows (Ulanowicz, 2009; Ulanowicz et al., 2009). The remaining 87% and 83%, respectively, were due to overhead, indicating that there was sufficient flow path diversity in trade connections for enhanced resilience against shocks (Ulanowicz, 2009; Ulanowicz et al., 2009).

The excess overhead skewed the balance of the global trade of waste outside the *"window of vitality"* (Fig. 1e), a range which is theorized to characterize sustainable natural ecosystems (Ulanowicz, 2009; Ulanowicz et al., 2009). Nevertheless, the robustness of both networks was maintained throughout the studied period within a narrow range of relatively high and stable values. This stability may have been the combined result of two reasons. Firstly, due to a growth both in the number of countries participating in the trade and in the trade connections between them (Fig. 1f). Secondly, due to the dominating indirect effects which accounted for approximately 95% of the total flow activity (data not shown) and which were largely homogeneous (i.e., more similar) compared to the more heterogeneous direct (i.e., *"first pass"*) flows. This becomes evident from the coefficient of variation of the direct flow intensity matrix was about three times larger than the coefficient of variation of the integral flow matrix (Fig. 1g). The main benefit of homogenization as an indicator is that it measures how resources are shared among network nodes (Fath and Patten, 1999; Fath and Scharler, 2018) where more evenly distributed flows are presumed to lead to more resilient systems (Huang et al., 2024). In other words, even though the robustness values of both networks were lower than those of sustainable natural ecosystems due to higher flow pathway redundancy, it is plausible that their observed stability was mainly due to evenly distributed (homogenized) indirect flows. Yet, it remains unclear why there was a convergence and consecutive divergence of homogenization in 2013 both from a demand and a supply perspective for both networks.

In previous research it has been proposed that the *"window of vitality"* can also be described by the area enclosed when plotting the minimum and maximum values of the (average logarithmic) number of roles against the minimum and maximum values of the (average logarithmic) number of links per node which have been hypothesized to characterize the network structures of natural ecosystems (Ulanowicz et al., 2009; Zorach and Ulanowicz, 2003). Following this eco-mimicry perspective, countries in the trade market may be regarded as analogues of *"effective trophic levels"* or *"species"* having different roles in an *"ecosystem"*, an analogy which may allow for the examination for structural resemblances with natural ecosystems. Results showed that the structures of both studied networks were different than those of natural ecosystems in terms of their relatively higher number of links per node (Fig. 1h). Interestingly, the material network exhibited more roles on (logarithmic average) over the years studied than the economic network, but it also had a lower (logarithmic average) number of links per node. In other words, the countries participating in the trade may have had higher diversity in socio-economic processes (or *"effective trophic levels"* at an aggregate level) for streamlining material flows of traded waste than their accompanying monetary flows. In contrast to natural ecosystems where different species may be taking more distinct roles (e.g., primary producers being different from detritivores), in trade networks countries may be adopting multiple roles simultaneously (since they may include several diverse socio-economic actors as collectors, processors, traders, recyclers etc.) which may also differ per material traded and perhaps even across different years. Here, it is noted that due to the format of the downloaded (aggregated) data, it was not possible to distinguish the composition of each individual trade flow without resorting to manual filtering on the website of the online database of Chatham House.

Moreover, it was shown that the material network was less redundant in trade connections than the economic network, suggesting that it had lower network resilience (also in line with Fig. 1c and d). It may seem counterintuitive to observe a difference in network redundancy when studying a single interconnected system (here, the global trade of waste) as two overlayed networks of material and monetary flows. Besides, if one of the two networks collapses so will the other. For example, the breaking of partnerships between countries due to tariffs or other policies will have a cascading effect on the material flow network, and vice versa, if the material network fails for some reason (e.g., due to a pandemic) it will also affect monetary transactions. Yet, this observed discrepancy in network redundancy is likely due to the probabilistic approach of ascendency analysis for studying the information contained in the structure of a network as well as in the magnitudes of its flows, since it is largely based on information theory (Ulanowicz, 2009; Ulanowicz et al., 2009). An example which highlights such disparity is the trade of waste metals which is a subset of the global trade of waste in the same database (Chatham House and The Royal Institute of International Affairs, 2020; Zisopoulos et al., 2025). On the one hand, some types of waste metals may be traded in very small amounts, but they may have high economic value due to their content in valuable resources such as critical raw materials. On the other hand, some scrap metals may be traded in large quantities but have very low economic value. This suggests that the corresponding probabilities of material and monetary flows for the same type of waste metals that are traded between two countries may be dissimilar since they are calculated by division with their associated total system throughput (the values of which may also differ). This also explains why the numerical values of ascendency and overhead may also differ between the two networks of the same system since they are the products of the total system throughput with the average mutual information and the aggregate indeterminacy, respectively (Ulanowicz, 2009; Ulanowicz et al., 2009).

Results also showed that in both networks there were few highly connected countries which have been dominating the market, particularly the ones with more than 100 trade connections and mainly from an in-degree (import) perspective (e.g., China, France, Germany, the Netherlands, United Kingdom, United States among many others). This distribution is illustrated on Fig. 1i and j for the year 2022 as an example while similar patterns were observed for all the years studied. The detection of unevenly distributed trade flows is important because it implies that countries with few trade links (located at the periphery of the network) may have limited accessibility to secondary raw materials while being dependent on relatively fewer yet highly connected hubs (located at the core of the network), making their transition to circular economies more challenging. This periphery-core distinction may also suggest that the former contributes more to network efficiency and the latter more to network resilience.

3.1. *Future research directions*

The current analysis examined the structural dynamics of the global waste trade. Future studies may focus on causal relation analysis on the factors that may have led to such changes to provide deeper insights into the drivers and consequences of the observed patterns. This may also help explain further any differences in the results when studying the patterns of a single resource flow (here aggregate waste) through a system (i.e., global market) from two different perspectives (i.e., material and monetary flows). Further research is also needed to understand the actual impact of indirect flows, of *FCI*, and of homogenization (or lack of it) on the global trade of waste across diverse socio-economic contexts, as well as the reasons for convergence or divergence from an input-driven and an output-driven perspective (for example, convergence of the *FCI* values over the years from an input- and output-driven perspective may suggest improved reporting processes). Another methodological aspect which deserves a closer examination in the analysis of socio-metabolic systems as networks is the interpretation of the (logarithmic) average number of roles either as *"effective trophic levels"* in an economy (when studied from an ecosystem perspective) or as distinct socio-economic processes (when studied from a socio-metabolic perspective). This is important because the *a priori* perspective taken on the assumed underlying system structure before conducting the analysis matters since the system can be very linear (e.g., socio-metabolic system) or very interconnected (e.g., trade network), an aspect which is indicative of an anticipated performance in terms of robustness (Fath et al., 2019; Layton et al., 2015). Another aspect worthwhile of consideration is that the material network may be a more suitable choice for following an eco-mimicry perspective when the intention is to design sustainable systems since monetary flows are subject to arbitrary weighing factors shaped by complex economic behaviour. On a broader level, it would also be interesting to explore if other types of sustainable systems balance differently than natural ecosystems, since such possibility has not been excluded (Ulanowicz, 2020).

3.2. *Policy recommendations*

Policy measures that could be considered vary. On the one hand, and in line with the proposal of previous research (Iskrzyński et al., 2021), to improve further the material and monetary cycling of secondary raw materials worldwide, future policies may focus on activities which boost *"local"* (in network terms) resource circulation based on reciprocity, a strategy which may not require individual economic actors having detailed knowledge of the global system, in contrast with an orchestrated top-down global optimization process that is complex, fragile, and potentially intractable. On the other hand, future policies may also need to pay more attention to the adoption of indicators from network-based methods because they can be valuable complements in the development of early warning mechanisms for assessing the fragility and sustainability of socio-economic systems such as trade networks. Towards this end, it will be crucial to implement transparent monitoring processes over diverse resource flows (e.g., material, energy, monetary, and information) across various levels of spatio-temporal granularity (e.g., world, country, region, city, district, neighbourhood) to allow for the construction of harmonized multi-level databases which resemble input-output tables. A recent study showed that these network-based methods have the additional benefit of capturing organizational and operational characteristics of ecosystems designed on the principles of industrial symbiosis without the need of proprietary or sensitive data (Chatterjee et al., 2024). Having access to such databases, decision-makers will be able to obtain a more comprehensive understanding of the underlying complexity of socio-economic systems and their directional tendencies for change, an aspect which has already been used for tracking the development of natural ecosystems (Ito et al., 2023; Scotti et al., 2022; Smit et al., 2021). Particularly relevant for policy making would be the comparison of alternative circular strategies for shifting the global waste trade towards the *"window of vitality"* while identifying potential gains and losses during such a transition across different dimensions (i.e., social, environmental, and economic) and scales (i.e., global, national, regional, local). This implies additional reporting requirements on boundary input and output flows where environ network analysis may find fertile ground as a holistic approach for accounting for the effects of coupled processes and feedback loops (Fath, 2012).

4. Conclusions

In summary, the global trade of waste evolved both in terms of size and of complexity between 2000 and 2022, exhibiting considerable annual cycling of material and monetary flows, network resilience, and homogeneity but also having limited robustness (i.e., balance between network efficiency and network resilience). During this period many countries had relatively few trade connections and remained at the periphery of the material and economic networks whereas a relatively smaller number of countries were located at their core as highly connected hubs of trade activity.

Future research may focus on causal relation analysis, on studying the effects of homogenization (or lack of it) on the overall sustainability of the global trade network, and on interpreting the analogies made with natural ecosystems when adopting an eco-mimicry perspective. Future policies may focus on boosting *"local"* (in network terms) reciprocity, on the adoption of network-based indicators for assessing systemic properties, and on enabling the conditions for developing the necessary infrastructure to collect and analyse time series data on diverse types of resources flows across space and time throughout their life cycle. Such efforts will facilitate the development of early warning mechanisms on trade shocks.

From a thermodynamic perspective it is evident that even if a system can self-organize (or is designed) to an effective (i.e., robust) trade-off between network efficiency and network redundancy, it will seize to exist if its input flow stops. Then, perhaps one of the biggest challenges in the transition to regenerative circular economies will be to minimize their susceptibility to socio-metabolic collapse (Singh et al., 2022) by attaining context-specific bio-inspired designs (de Souza et al., 2019; Fath et al., 2019; Johnson and Webster, 2021; Jørgensen et al., 2015; Layton, 2014; Ulanowicz et al., 2009) which will allow them to adapt effectively their balance between efficiency and resilience under dynamic conditions for inclusive prosperity while simultaneously maintaining and improving their accessibility to reliable (i.e., renewable) inputs.

CRediT authorship contribution statement

Filippos K. Zisopoulos: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Brian D. Fath:** Writing – review & editing, Methodology. **Xin Tong:** Writing – review & editing. **Martin de Jong:** Writing – review & editing, 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.

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Data availability

The interested reader can download the Excel file from this hyperlink: https://doi.org/10.5281/zenodo.14237081.

References

Chatham House, The Royal Institute of International Affairs, 2020. Waste, Scraps, and Residues [WWW Document]. URL. www.circulareconomy.earth. https://circulareconomy.earth/trade?year=2020&category=6&units=value&autozoom=1. accessed 1.16.24.

Chatterjee, A., Minks, O., Triebe, M.J., Hapuwatte, B.M., Kietzer, D., kittali-Weidner, S., Morris, K.C., Mathur, N., 2024. Investigating the use of network analysis metrics to benchmark Industrial Symbiosis development. J. Clean. Prod. 143078. https://doi.org/10.1016/j.jclepro.2024.143078.

Circle Economy Foundation, Deloitte, 2024. In: Circularity Gap Report.

Compagnoni, M., Grazzi, M., Pieri, F., Tomasi, C., 2024. Extended producer responsibility and trade flows in waste: the case of batteries. Environ. Resour. Econ. https://doi.org/10.1007/s10640-024-00907-5.

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.

Fath, B.D., 2018. Systems ecology: ecological network analysis. In: Encyclopedia of Ecology, second ed.) 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., Fiscus, D.A., Goerner, S.J., Berea, A., Ulanowicz, R.E., 2019. 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. Model. 123 (2–3), 193–205.

Fath, B.D., Scharler, U.M., 2018. Systems ecology: ecological network analysis. Encyclopedia of Ecology, second ed. 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.

Global Footprint Network, 2024. Earth overshoot day 2024. https://www.footprintnetwork.org/our-work/earth-overshoot-day/ accessed 8.13.24.

Hagens, N.J., 2020. Economics for the future – beyond the superorganism. Ecol. Econ. 169, 106520. https://doi.org/10.1016/j.ecolecon.2019.106520.

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.

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.

Ito, M., Halouani, G., Cresson, P., Giraldo, C., Girardin, R., 2023. Detection of fishing pressure using ecological network indicators derived from ecosystem models. Ecol Indic 147. https://doi.org/10.1016/j.ecolind.2023.110011.

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

Jørgensen, S.E., Fath, B.D., Nielsen, S.N., Pulselli, F.M., Fiscus, D.A., Bastianoni, S., 2015. Flourishing within Limits to Growth - Following Nature's Way. Routledge, New York City.

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. V004T05A047. ASME. https://doi.org/10.1115/DETC2015-47560.

Li, B., Mu, Y., 2024. Impact of China's National Sword policy on waste import margins: a difference-in-differences approach. Sustainability 16. https://doi.org/10.3390/su16020776.

Mahyari, K.F., Sun, Q., Klemes, J.J., Aghbashlo, M., Tabatabaei, M., Khoshnevisan, B., Birkved, M., 2022. To what extent do waste management strategies need adaptation to post-COVID-19? Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2022.155829.

Mcnerney, J., Kryazhimskiy, A., 2009. Network Properties of Economic Input-Output Networks. Laxenburg, Austria.

Meng, S., 2019. The effect of border controls on waste imports: evidence from China's Green Fence campaign. China Econ. Rev. 54, 457–472. https://doi.org/10.1016/j.chieco.2019.02.009.

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. Sciences Advances, eadh2458. https://doi.org/10.1126/sciadv.adh2458.

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.

Scotti, M., Bondavalli, C., Rossetti, G., Bodini, A., 2022. Flow network indices signal a directional change in ecosystems: evidence from a small mountain lake (Lake Santo, northern Italy). Ecol Indic 139. https://doi.org/10.1016/j.ecolind.2022.108896.

Shevchenko, T., Shams Esfandabadi, Z., Ranjbari, M., Saidani, M., Mesa, J., Shevchenko, S., Yannou, B., Cluzel, F., 2024. Metrics in the circular economy: an inclusive research landscape of the thematic trends and future research agenda. Ecol Indic. https://doi.org/10.1016/j.ecolind.2024.112182.

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.

Smit, K.P., Bernard, A.T.F., Lombard, A.T., Sink, K.J., 2021. Assessing marine ecosystem condition: a review to support indicator choice and framework development. Ecol Indic. https://doi.org/10.1016/j.ecolind.2020.107148.

Tran, T., Goto, H., Matsuda, T., 2021. The impact of China's tightening environmental regulations on international waste trade and logistics. Sustainability 13, 1–14. https://doi.org/10.3390/su13020987.

Ulanowicz, R.E., 2020. Quantifying sustainable balance in ecosystem configurations. Current Research in Environmental Sustainability 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., 2006. Process ecology: a transactional worldview. Int. J. Ecodyn. 1, 114–125. https://doi.org/10.2495/ECO-V1-N2-114-125.

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., 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, 2024. Global Resources Outlook 2024: Bend the Trend – Pathways to a liveable planet as resource use spikes. Int. Res. Panel. Nairobi.

Yilmazkuday, H., 2019. The great trade collapse: an evaluation of competing stories. Macroeconomic Dynamics, Forthcoming Available at SSRN. https://doi.org/10.2139/ssrn.2170589.

Zhou, C., Yang, G., Ma, S., Liu, Y., Zhao, Z., 2021. The impact of the COVID-19 pandemic on waste-to-energy and waste-to-material industry in China. Renew. Sustain. Energy Rev. 139. https://doi.org/10.1016/j.rser.2020.110693.

Zisopoulos, F.K., Fath, B.D., Toboso-Chavero, S., Huang, H., Schraven, D., Steuer, B., Stefanakis, A., Clark, O.G., Scrieciu, S., Singh, S., Noll, D., de Jong, M., 2025. Inequities blocking the path to circular economies: a bio-inspired network-based approach for assessing the sustainability of the global trade of waste metals. Resour. Conserv. Recycl. 212. https://doi.org/10.1016/j.resconrec.2024.107958.

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.