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Resilience and malleability: New directions for socio-metabolic research in times of multiple crises

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ABSTRACT

The world faces multiple crises and disruptions, such as climate impacts, pandemics, geopolitical tension and competition, conflicts, and wars. Socio-metabolic research (SMR), the study of stocks and flows of materials and energy associated with socioeconomic activities, is not well equipped to address these challenges. SMR methods are predominantly descriptive, static or linear. They treat disruptions as exogenous and are ill-equipped to capture abrupt non-linear changes evident today and likely to intensify in the future. They lack the granularity needed to analyze how stocks and flows of resources relate to actors, institutions, and power relations characterized by vast inequalities. SMR relies primarily on quantitative data, which is often inadequate to understand qualitative system properties and mechanisms. These shortcomings hinder understanding resilience, the ability of social metabolism to recover from shocks, and malleability, the extent to which social metabolism can be transformed to promote sustainable wellbeing for all. SMR can respond through linkages with big data models treating economies as complex networked systems that allow analyzing system resilience, non-linearities, feedback mechanisms, and tipping points. Enhanced granularity in terms of higher resolution quantitative data and rigorous understanding of qualitative system properties can help connect actors' decision-making with their biophysical implications. This is a prerequisite for generating transformative knowledge through SMR. Linking complexity science, political ecology, and SMR is imperative for addressing pressing contemporary issues.

1. Introduction

The world faces multiple crises and rising levels of tension and conflict. We see the impacts of disruptive events (below referred to as 'disruptions') such as the Covid-19 pandemic, the Russian invasion of Ukraine, and increasingly frequent extreme climatic events (Sun et al., 2024). These events can affect resource supply (Barakat et al., 2023; Agrawal et al., 2024). Global supply chains have already been affected by past crises and disruptions are expected to rise in the future (Chowdhury et al., 2021), particularly under catastrophic climate-heating scenarios (Kemp et al., 2022).

Disruptions within production networks typically have cross-scalar effects, e.g., on regional and national economies (Laber et al., 2023). Changes in resource availability and access can have implications for various sectors such as steel and other bulk metal products, electronics and batteries, construction, agriculture, energy or food supply. But disruptions may also signal untenable socio-ecological conditions and could – depending on the response – catalyze critical junctures for broader transformations (Capoccia, 2016). They should thus not be seen solely as disturbances to the supposedly normal functioning of supply chains. Given the widespread harms of current trading systems, particularly in terms of social wellbeing and ecological outcomes (Dorninger et al., 2021), disruptions could also offer opportunities to alter trade relations, power dynamics, and related outcomes.

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Disruptions also affect option spaces for tackling challenges such as climate heating and biodiversity loss (IPBES, 2019; IPCC, 2022), and efforts towards sustainable wellbeing for all on a more just and equitable planet (Fanning et al., 2022; Pachauri et al., 2022). Addressing disruptions thus requires understanding of resilience, the ability to recover from shocks, and malleability, the purposive transformation of metabolism towards equitable and sustainable outcomes (see further elaboration of these terms below). Current socio-metabolic research (SMR) is not well equipped to tackle these demands (Section 2). We therefore outline new directions for SMR to address the resilience of social metabolism through novel approaches to disruptions in complex networked systems like global resource supply and demand. We explore how SMR could analyze malleability by linking social metabolism with actors, institutions, and power dynamics affecting decision-making and access to services in specific provisioning systems (Vogel et al., 2021), thereby reconciling quantitative and qualitative approaches in SMR.

We define 'resilience' as the ability of a system to persist and function under shocks or to regain or reconfigure its functions after disruptions (Holling, 2001). In a socio-ecological context, resilience depends on the ability of systems, actors and institutions not only to respond and adapt, but also to transform in the face of sustainability challenges (Folke et al., 2021). Technically, we also apply the term to shocked networked systems where reestablishing sufficient links and nodes restores functionality. Although resilience is often viewed as a positive attribute, we aim to use the term in a value-neutral sense where possible. For example, while resilience in agricultural production in response to climate-heating may be seen positively, the resilience of fossil fuel industries under similar pressures may be viewed more critically.

We define 'malleability' as the ability of systems, actors, and institutions to meet people's needs and wellbeing in an equitable way (Brand-Correa and Steinberger, 2017), while actively reshaping resource use towards sustainable patterns within planetary boundaries (Rockström et al., 2009). We propose this innovative concept to build bridges between SMR and Political Ecology, drawing on concepts used in fields such as material science or psychology (see detailed discussion in Pachauri et al., 2025). We organize our work around the multi-faceted concept of provisioning systems as complex systems through which human needs are met, and where societal stocks and flows of materials are entangled with wellbeing outcomes (Vogel et al., 2021). We use 'transition' to denote any system shift involving fundamental structural change, irrespective of its cause, and 'transformation' for changes actively shaped by actors or institutions in pursuit of normative goals such as sustainability.

2. Challenges for socio-metabolic research in a world of crises

Societies use resources such as materials or energy to produce, reproduce and operate not only their biophysical structures or 'material stocks' (Haberl et al., 2019); i.e., bodies of humans and livestock as well as artefacts such as buildings, infrastructures or durable commodities, but also to reproduce socio-culturally (Fischer-Kowalski and Weisz, 1999). Nearly all socioeconomic activities are closely tied to resource use, as production and consumption rely on flows of materials and energy required to operate, maintain or expand material stocks (Pauliuk and Müller, 2014; Weisz et al., 2015). Environmental problems emerge during extraction, processing, use and disposal of these resources (UNEP, 2019). Surging resource use is a pervasive driver of climate heating and biodiversity loss (IPBES, 2019; IPCC, 2022). SMR (Fig. 1) offers crucial linkages between natural and social/economic approaches in sustainability sciences (Haberl et al., 2019).

Antecedents of SMR emerged around 150 years ago, see the comprehensive review of Martinez-Alier (1987), with current approaches developing over the past 50+ years (reviewed by Fischer-Kowalski, 1998). Quantifying the material and energy flows of national economies enabled establishing 'territorial' (or 'production-based') accounts (Krausmann et al., 2017a). Complementary 'footprint' (or

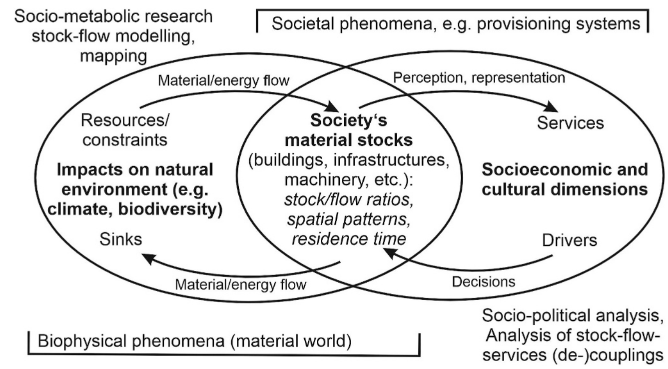

Fig. 1. Conceptual diagram of socio-metabolic research (SMR). Source: own graph.

'consumption-based') accounts use Environmentally-Extended Multi-Regional Input-Output (EE-MRIO) models to assess resources 'embodied' in consumption (Lenzen et al., 2022). These models allocate primary extraction globally to each country's final demand for products and services, tracing resource flows through complex global supply chains at the sectoral level to establish consumption-based material flow and emission accounts. Material flow accounts are regularly updated (Krausmann et al., 2017a; Giljum et al., 2022) and provide indicators used in policy contexts (e.g. SDG 8.4 and 12.2; Schandl et al., 2024). Over the past two decades, the accumulation of socioeconomic material stocks – now requiring more than half of all material extraction worldwide (Krausmann et al., 2017b) – has emerged as an important research area (Fu et al., 2022).

SMR has significantly advanced the granularity of data and models (Supplementary Information), allowing to trace resource flows from extraction through supply chains to material stock accumulation, recycling, and outflows of waste and emissions at the national level over decades and even centuries. Important socio-metabolic flows (e.g., biomass extraction, mining) and material stocks in built structures have been mapped globally, or for large regions with considerable resolution (additional text and references in the supplementary information).

Still much of SMR is descriptive and largely disconnected from advances in complex adaptive systems research. Descriptive models are widely used, mainly to fill data gaps (Krausmann et al., 2017a; Plank et al., 2022). Dynamic material and energy flow analysis models (Müller et al., 2014; Wiedenhofer et al., 2024) use stock-flow accounting algorithms akin to demographic cohort-component models that do not incorporate complex networks or non-linear dynamics. EE-MRIO models trace international resource flows and allocate inputs to final products, yet input-output analysis remains inherently static (Wiedmann et al., 2015; Lenzen et al., 2022). Diagnostic models using SMR principles have explored future biomass supply options but lack system-dynamic elements (Erb et al., 2016). Some agent-based models simulate non-linear material flow dynamics, e.g. for recycled construction minerals (Knoeri et al., 2014), critical raw materials (Knoeri et al., 2013), local agri-food networks (Fernandez-Mena et al., 2020), and industrial symbiosis processes (Han et al., 2022), but such work remains rare and has not addressed economy-wide material stocks and flows (Krausmann et al., 2017a). Efforts to conceptualize social metabolism as complex networks are still nascent (Hyde et al., 2024). Linkages with actors (e.g., firms) or provisioning systems remain underexplored, and nonlinear changes from singular events, e.g. at tipping points, remain unexplored (Binder et al., 2025).

By contrast, the Socio-Ecological Systems (SES) research community has examined the resilience of complex socio-ecological systems for decades, primarily through local or regional case studies and models. SES research emphasizes actors, governance, and institutions in natural resource management (Folke et al., 2021; Reyers et al., 2022). However, due to differing research foci, scales and methodologies, SES and SMR

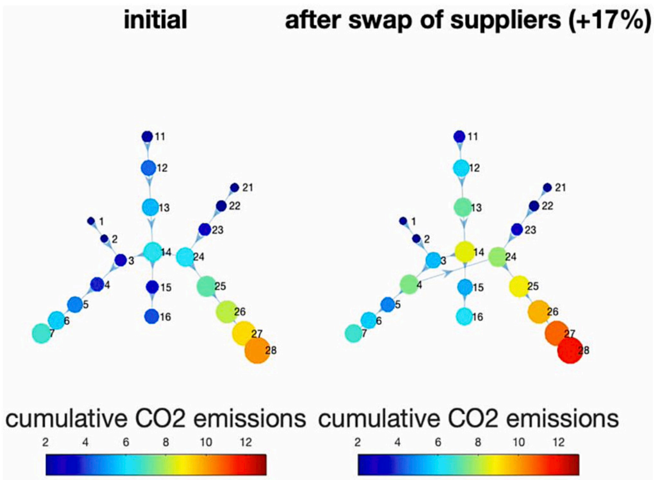

Fig. 2. Toy model showing possible unexpected effects of a restructuring of a supply chain network. The left panel shows three connected chains. Nodes represent firms, colors indicate the cumulative carbon emissions along the chain. In the right panel, firm 24 decides to switch from supplier 14 to supplier 4, which appears as a locally reasonable option for reducing emissions. In the entire network, however, this relinking results in 17% higher total CO_2 emissions than in the initial network. Source: own calculations & graph.

remain largely disconnected, hence analysis and modelling of nonlinear phenomena and network effects in societies' resource supply systems remain largely un-appreciated. Studies of socio-metabolic resilience are lacking (Binder et al., 2025). Links between resilience research, industrial ecology, and complexity science remain limited (Meerow and Newell, 2015). Some literature addresses the resilience of industrial ecosystems (Zhu and Ruth, 2013), industrial symbiosis networks (Li and Shi, 2015) or specific material flows and supply chains (Böcher et al., 2024). Life cycle assessment has examined the resilience of product systems (Pizzol, 2015). Some studies have applied SMR concepts to assess the resilience of cities (Bristow and Kennedy, 2013; Magoni, 2017) or the demand for mineral resources (Bleischwitz, 2020). Recent studies have explored the resilience of energy supply (Aldieri et al., 2022) and supply chains for rare earth and other metals (Mancheri et al., 2019; van den Brink et al., 2022). Yet these promising efforts remain scattered and not well integrated into SMR.

In geography, sociology and economics, studies of global supply chain resilience address intensifying disruptions (Lund et al., 2020), the Covid-19 pandemic and Russia's invasion of Ukraine (Barakat et al., 2023; Agrawal et al., 2024). This research focuses on impacts on supply chain restructuring and related geographical and organizational shifts (Yeung, 2023) but does not address the impacts of disruptions for social metabolism. Political ecology addresses questions of power and inequality in supply chains (Archer, 2022) but has not been linked with SMR. These missing linkages between various disciplines and approaches result in gaping holes in urgently needed scholarship in the face of current challenges.

3. Three research directions for tackling current challenges

Current SMR struggles to address complex networks and non-linear system dynamics and link with actor-based approaches. Resilience and malleability of social metabolism depend not only on materials and technology, but foremost on actors' constellations, interests, and decision-making power. An underlying challenge is the lack of integration between system-based SMR and primarily agency- and actor-based socioecological research (Plank et al., 2021; Österblom et al., 2022). This gap is unsurprising, as system-science and actor-centered perspectives remain largely disconnected across much of the social sciences and humanities (Hausknost et al., 2016; Thurner, 2024). In this section, we discuss three directions for SMR to tackle contemporary challenges.

3.1. Integrating SMR and the modelling of economic complexity

Resilience is a property of complex, dynamic systems. Therefore, studying socio-metabolic resilience requires integration of SMR with dynamic, non-linear network models. A promising approach involves coupling existing network models that leverage big-data techniques to represent non-linear system dynamics with data from SMR (Klimek et al., 2019; Diem et al., 2022; Laber et al., 2023). This integration could yield both quantitative and qualitative insights into the vulnerability and resilience of social metabolism to disruptions, thereby enabling analysis of tipping points (Binder et al., 2025), and mapping option spaces for socioecological transformations (Section 3.2).

Complexity scientists have applied such models to study bailout programs during financial crises (Klimek et al., 2015), economic resilience in times of crises (Klimek et al., 2019), firm-level economic risks in nationwide supply networks (Diem et al., 2022), and the propagation of shocks from the Russian invasion of Ukraine on food networks (Laber et al., 2023). Integrating SMR with data-driven agent-based dynamical multi-layer network models could enable the study of material flows along supply chains and effects of various disruptions on social metabolism. For example, SMR could be linked with data on global production networks of publicly listed firms (Chakraborty and Ikeda, 2020). Identifying key agents in socio-metabolic flows – including actors and institutions involved in regulation of mining, logistics, shipping, harbors, rail transport, and storage facilities – at the firm and institutional level could offer highly granular insights into the resilience of global production networks (Verschuur et al., 2022a, 2022b).

The reconstruction of national monetary economies of some countries at a granular firm level is now possible through the availability of novel datasets of individual buyer-seller relations at high granularity. These data allow designing and calculating novel metrics of economic resilience of national economies (Diem et al., 2022). Such studies have been pioneered for Hungary (Borsos and Stancsics, 2020), Ecuador, and Belgium, where value added tax (VAT) data are available to reconstruct national supply chains (Diem et al., 2022; Reisch et al., 2022). When combined with bilateral trade data from EE-MRIO models, this can allow for analysis of how systemic risks propagate globally (Chakraborty and Ikeda, 2020; Chakraborty et al., 2024). Similar approaches could contribute to quantifying resilience in SMR at firm level (Thurner and Poledna, 2013; Klimek et al., 2015, 2019). However, difficulties in generating data required to study processes at the firm level should not be underestimated. At the firm level, researchers are also confronted with issues of data confidentiality. While algorithms and methodology can always be shared, data itself often can't as that would violate data protection rights. Adhering to the principle of reproducibility requires innovative approaches well beyond methods like k-anonymity. This could include the sharing of anonymized datasets (which can be challenging since high-dimensional data can often be easily de-anonymized), or data that was specifically altered such that specific statistical information remains correct, but details are such that no firms could ever be identified. The latter approach can help to make sure that at least algorithms and methodology are reproducible and fully transparent.

In such work, systemic impacts are defined as the reduction or loss of a system's 'performance', such as reductions in production output, loss of jobs, or diminished functionalities and services resulting from links and nodes lost in production networks during disruptions. Resilience can be quantified as the time it takes for a system to recover lost nodes and reestablish connections between agents, to regain its functionalities, either fully, partially, or in a different form. For specific disruptions, systems may exhibit varying degrees of resilience – some may recover quickly, while others may be less resilient (taking longer or failing to regain previous functionalities). Whether resilience is desirable depends on the valuation of the system's functionalities.

Box 1
Nonlinearity and surprise in complex networked systems.

The toy model shown in Fig. 2 demonstrates the possibility that a switch of one firm to a supplier with lower CO_2 emissions per unit of product entails increased total CO_2 emissions of the entire network. Such unexpected effects can result from reconfigurations that alter the network's structure so that rises in emissions in one part of the production network overcompensate savings in another part. Anticipating such effects systematically is important for sustainability, and key for understanding malleability. However, the difficulties of such model linkages must not be underestimated, among others due to the high granularity of required input data.

National supply network models could be employed to study potential transition paths within multi-layer socio-metabolic networks following disruptions or at tipping points. The premise of such analyses is that transitions are shaped by the interaction topology of agents (i.e. representations of firms in the model) and their dynamic linking rules. For example, research could explore conditions under which modelled network systems undergo phase or percolation transitions (Hanel et al., 2005, 2007), typically from well-functioning diverse states to networks that lose most of their previous functionalities. Such work might well reveal unexpected – and undesired – effects of network reconfigurations in complex systems (see example in Box 1). Studies of complex, networked systems could also help understand other important nonlinear dynamics resulting from network reconfigurations unrelated to, or not amounting to, tipping points or percolation phenomena.

3.2. Improving granularity to integrate actors and institutions

Patterns of material stocks and flows and their relationship to wellbeing are dynamic and hence more or less malleable, i.e. moldable by human agency, strategies and institutions (Otto et al., 2020b). Analyzing the malleability and resilience of such system requires engaging with the interests, strategies, and power relations of states, firms and civil society, and the institutions shaping provisioning systems and their wellbeing outcomes for different locations and social groups (Rao and Min, 2018). In doing so, actors need to be appreciated as individuals and communities with lived experiences of differentiated access to resources, provisioning systems and decision-making power, which requires fine-grained quantitative and qualitative analysis.

Political ecology approaches in supply-chain research can serve as a starting point for such analysis (Archer, 2022). When combined with biophysical data and maps derived from remote sensing (Brenner et al., 2024) or socio-metabolic supply chain data (Plank et al., 2023), such mixed-methods approaches can reveal the interplay between actors and sociometabolic stocks and flows at larger (e.g., city) scales. Such research can create understanding of how social heterogeneities and inequities relate to the stock-flow-service (SFS) nexus (Haberl et al., 2021). The SFS nexus assumes that services require specific combinations of material stocks (e.g., built structures and machinery) and resource flows (Haberl et al., 2019; Carmona et al., 2022). For example, mobility services depend on transport infrastructures and spatial arrangements of dwellings, workplaces or schools as well as vehicles (bicycles, trains, cars, etc.), all of which need resources for construction, maintenance and operation. Such research can also reveal how wellbeing is related to provisioning systems (Lamb and Steinberger, 2017), and how these relationships might be transformed.

Patterns of built structures co-determine resource use (Haberl et al., 2023; Duro et al., 2024) and contribute to carbon lock-in (Seto et al., 2016). These patterns, in turn, are shaped by investments that are legally regulated, contested and subject to power relations, negotiations and conflicts (Schaffartzik et al., 2021). Both biophysical and actor configurations in these systems are of key importance for societies' ability to ensure wellbeing (Plank et al., 2021; Bayliss et al., 2021). While patterns and locations of built structures are important for resilience and malleability, the interrelationship between these structures, their resource use, and actor constellations that shape and are shaped by them, has not received much attention.

Concepts from SES research can help address this gap. The concepts of "adaptability" or the "capacity of actors in a system to influence resilience", and "transformability" defined as "[t]he capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system untenable" (Walker et al., 2004), complement the notion of resilience by emphasizing agency, institutions, and power relations. Importantly, these concepts recognize that resilience is not always desirable in the context of transformations towards sustainability (Clausen et al., 2017). Building on these insights, we propose the concept of malleability as a related critical factor in enabling such opportunities (Pachauri et al., 2025). Our use of 'malleability' relates to the concept of 'transformability' but, as defined earlier in Section 1, it has a clear normative connotation (Pachauri et al., 2025).

Material stocks and flows are both shaped by actors and, in turn, critically influence their option space (Plank et al., 2021), as well as their access to the social benefits of existing resource use. Identifying specific places and points in time where provisioning systems are most malleable, e.g. before large-scale investments into production capacities or infrastructures constrict the socio-metabolic corridor, is of key importance (Schaffartzik et al., 2021). Decisions regarding infrastructure, production and use take place within socio-political structures and geopolitical contexts, and are embedded in dominant social practices (Shove et al., 2012), i.e., routinized activities embedded in everyday life that depend on material conditions (e.g., infrastructures, settlement or production patterns), competencies (developed through education and training) and cultural meaning (Haberl et al., 2021).

A promising lens for examining the interplay between actors, practices, and metabolism is the study of provisioning systems for essential human needs. Since a substantial part of societies' resource use and GHG emissions is linked with shelter, food and mobility (Vita et al., 2019), these provisioning systems appear as logical starting points for starting such inquiries. For example, food provisioning can range from small-scale subsistence farming to large-scale, heavily industrialized agriculture, transport, processing and retail – each associated with vastly different social metabolisms. Linking SMR with actor-based approaches is needed to understand possibilities and constraints for resilience and malleability of provisioning systems. Recent progress in SMR (Section 2) has laid the groundwork to embark on this endeavor. Societies' collective ability to adapt to and manage non-linear changes, e.g., social tipping dynamics (Otto et al., 2020a), crises and transformation is a key research frontier of SES resilience science (Folke et al., 2021), and now SMR may follow suit.

3.3. Integrating qualitative and quantitative data and approaches

More detailed quantitative SMR can help understanding resilience but does not capture the diversity of actors and institutions, and what guides their decision-making. Improving data granularity using tax data can yield highly interesting insights on resilience (Section 3.1), but the resulting picture of the economy would still be incomplete with regards to actors who do not pay taxes or transactions that aren't taxed, which is specifically (but not only) relevant in countries of the Global South. Moreover, approaches based on tax statistics include a specific type of social interaction between actors, e.g. those that are related to monetary flows, but not those that aren't, such as unpaid care work or subsistence farming that is more generally excluded from the 'formal' economy.

The contribution of a corporation to total value added and hence to GDP may be a suitable proxy for the importance of that corporation's activities from a government perspective. But this will often not allow a comprehensive evaluation of its contributions to provisioning of key services, and hence of resilience and malleability. This could partially be addressed through further raising granularity, covering, for example, the contribution of the corporation to nutrition, mobility, shelter and, by extension, to aspects of human wellbeing. It is to be expected, however, that even this path would lead us to more questions – many of them related to so-called 'informal' production systems including non-market or small-scale, localized/community-based forms of production and consumption which may be more important for the wellbeing of different social groups (Dengler and Plank, 2024).

What role does resilience and malleability of subsistence agriculture play when it comes to providing people with food? How does paratransit operate to address mobility needs of marginalized populations, and what are the related resource requirements? How do shared spaces in housing and shelter influence related wellbeing outcomes? Addressing such questions, crucial as they are to our understanding of the resilience and malleability of social metabolism, requires greater qualitative understanding of provisioning systems that cannot be addressed through quantitative data alone (Choueiri et al., 2025). This understanding is also crucially linked to identifying the relevant actors and institutions, and what relates them to one another within an economy or a provisioning system. While some of the obstacles to integrating social sciences and qualitative perspectives with resilience research have been previously discussed (Olsson et al., 2015), SMR could greatly be enhanced by enabling integration of these perspectives.

4. Conclusions

SMR has yielded an array of useful insights over the past decades and is increasingly used in sustainability-related statistics, monitoring, and policy. It has created a wealth of data and tools upon which the scholarly community can now build to tackle current challenges, e.g. by tracing resource flows from extraction to final consumption and eventually recycling to emissions and waste, and by assessing the biophysical level of circularity of national economies (see supplementary information). However, it is currently not methodologically and conceptually well equipped to cope with today's volatile world. We here outlined two research directions to better connect existing communities and approaches, which would help SMR to substantially improve its ability to address current predicaments: (1) Novel, complexity-science based socio-metabolic models could help study the resilience of social metabolism to disruptions during abrupt systemic changes (e.g., at tipping points or following disruptions). Such assessments could be created by coupling SMR with current models used to study economies as complex multi-layered networks using big-data approaches. (2) Studying malleability of social metabolism needs a different research strand that links SMR with studies of provisioning systems delivering key services for social wellbeing, such as shelter, food and mobility. Recent progress in socio-metabolic data granularity allows for establishing explicit linkages with qualitative and quantitative studies of actors, institutions and power relations. This enables researchers to understand qualitative system properties, generate transformative knowledge, and analyze the malleability of social metabolism towards sustainability quantitatively and qualitatively, thereby combining the strengths of both approaches. Doing so requires forging closer ties between SMR and political ecology. Linking the currently largely separated communities of SMR and SES science – which would be underpinned by both research strands – can advance both fields and support transdisciplinary efforts to foster socio-metabolic resilience and malleability.

Author contribution

The authors jointly conceptualized and wrote the paper.

CRediT authorship contribution statement

Helmut Haberl: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Conceptualization. **Stefan Giljum:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Fridolin Krausmann:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Anke Schaffartzik:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Cornelia Staritz:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Conceptualization. **Stefan Thurner:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Martin Bruckner:** Writing – review & editing, Writing – original draft, Investigation. **Jan Streeck:** Writing – review & editing, Writing – original draft, Investigation. **Dominik Wiedenhofer:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Shonali Pachauri:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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Data availability

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

References

Agrawal, S., Agrawal, R., Kumar, A., et al., 2024. Can industry 5.0 technologies overcome supply chain disruptions?—a perspective study on pandemics, war, and climate change issues. Oper. Manag. Res. 17, 453–468. https://doi.org/10.1007/s12063-023-00410-y.

Aldieri, L., Gatto, A., Vinci, C.P., 2022. Is there any room for renewable energy innovation in developing and transition economies? Data envelopment analysis of energy behaviour and resilience data. Resour. Conserv. Recycl. 186, 106587. https://doi.org/10.1016/j.resconrec.2022.106587.

Archer, M., 2022. How to govern a sustainable supply chain: standards, standardizers, and the political ecology of (in)advertence. Environ. Plan. E 5, 881–900. https://doi.org/10.1177/25148486211014505.

Barakat, S., Cochrane, L., Vasekha, I., 2023. The humanitarian-development-peace nexus for global food security: responding to the climate crisis, conflict, and supply chain disruptions. Int. J. Disaster Risk Reduct. 98, 104106. https://doi.org/10.1016/j.ijdrr.2023.104106.

Bayliss, K., Mattioli, G., Steinberger, J., 2021. Inequality, poverty and the privatization of essential services: a 'systems of provision' study of water, energy and local buses in the UK. Compet. Chang. 25, 478–500. https://doi.org/10.1177/1024529420964933.

Binder, C.R., Athanassiadis, A., Bristow, D., et al., 2025. Tipping points towards sustainability: the role of industrial ecology. J. Ind. Ecol. https://doi.org/10.1111/jiec.70000 in press.

Bleischwitz, R., 2020. Mineral resources in the age of climate adaptation and resilience. J. Ind. Ecol. 24, 291–299. https://doi.org/10.1111/jiec.12951.

Böcher, C., Sprecher, B., Fishman, T., 2024. Integrating material flow analysis and supply chain resilience analysis to study silicon carbide. J. Ind. Ecol. 28, 1830–1841. https://doi.org/10.1111/jiec.13541.

Borsos, Stancsics, M., 2020. Unfolding the Hidden Structure of the Hungarian Multi-Layer Firm Network. Technical Report. Magyar Nemzeti Bank, Budapest.

Brand-Correa, L.I., Steinberger, J.K., 2017. A framework for decoupling human need satisfaction from energy use. Ecol. Econ. 141, 43–52. https://doi.org/10.1016/j.ecolecon.2017.05.019.

Brenner, A., Haas, W., Krüger, T., Matej, S., Haberl, H., Schug, F., Wiedenhofer, D., Behnisch, M., Jaeger, J.A.G., Pichler, M., 2024. What drives densification and sprawl in cities? A spatially explicit assessment for Vienna between 1984 and 2018. Land Use Policy 138, 107037. https://doi.org/10.1016/j.landusepol.2023.107037.

Bristow, D.N., Kennedy, C.A., 2013. Urban metabolism and the energy stored in cities. J. Ind. Ecol. 17, 656–667. https://doi.org/10.1111/jiec.12038.

Capoccia, G., 2016. When do institutions "bite"? Historical institutionalism and the politics of institutional change. Comp. Polit. Stud. 49, 1095–1127. https://doi.org/10.1177/0010414015626449.

Carmona, L.G., Whiting, K., Cullen, J., 2022. A stock-flow-service nexus vision of the low carbon economy. Energy Rep. 8, 565–575. https://doi.org/10.1016/j.egyr.2022.10.086.

Chakraborty, A., Ikeda, Y., 2020. Testing "efficient supply chain propositions" using topological characterization of the global supply chain network. PLoS One 15, e0239669. https://doi.org/10.1371/journal.pone.0239669.

Chakraborty, A., Reisch, T., Diem, C., et al., 2024. Inequality in economic shock exposures across the global firm-level supply network. Nat. Commun. 15, 3348. https://doi.org/10.1038/s41467-024-46126-w.

Choueiri, Y., Perrotti, D., Acevedo-De-los-Ríos, A., 2025. Characterizing informality in urban resource management: towards an integrated framework of urban metabolism and informal flows. Land Use Policy 151, 107472. https://doi.org/10.1016/j.landusepol.2025.107472.

Chowdhury, P., Paul, S.K., Kaisar, S., Moktadir, MdA, 2021. COVID-19 pandemic related supply chain studies: a systematic review. Transp. Res. E Logist. Transp. Rev. 148, 102271. https://doi.org/10.1016/j.tre.2021.102271.

Clausen, J., Göll, E., Tappeser, V., 2017. Sticky transformation – how path dependencies in socio-technical regimes are impeding the transformation to a green economy. J. Innov. Manag. 5, 111–138. https://doi.org/10.24840/2183-0606_005.002_0008.

Dengler, C., Plank, C., 2024. Foregrounding invisible foundations: (eco-)feminist perspectives on provisioning systems. Sustain. Sci. Pract. Policy 20, 2312667. https://doi.org/10.1080/15487733.2024.2312667.

Diem, C., Borsos, A., Reisch, T., et al., 2022. Quantifying firm-level economic systemic risk from nation-wide supply networks. Sci. Rep. 12, 7719.

Dorninger, C., Hornborg, A., Abson, D.J., et al., 2021. Global patterns of ecologically unequal exchange: implications for sustainability in the 21st century. Ecol. Econ. 179, 106824. https://doi.org/10.1016/j.ecolecon.2020.106824.

Duro, J.A., Perez-Laborda, A., Löw, M., et al., 2024. Spatial patterns of built structures co-determine nations' level of resource demand. J. Ind. Ecol. 28, 289–302. https://doi.org/10.1111/jiec.13470.

Erb, K.-H., Lauk, C., Kastner, T., et al., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat. Commun. 7, 11382. https://doi.org/10.1038/ncomms11382.

Fanning, A.L., O'Neill, D.W., Hickel, J., Roux, N., 2022. The social shortfall and ecological overshoot of nations. Nat. Sustainability 5, 26–36. https://doi.org/10.1038/s41893-021-00799-z.

Fernandez-Mena, H., Gaudou, B., Pellerin, S., et al., 2020. Flows in agro-food networks (FAN): an agent-based model to simulate local agricultural material flows. Agric. Syst. 180, 102718. https://doi.org/10.1016/j.agsy.2019.102718.

Fischer-Kowalski, M., 1998. Society's metabolism: the intellectual history of materials flow analysis, part I, 1860–1970. J. Ind. Ecol. 2, 107–136. https://doi.org/10.1162/jiec.1998.2.4.107.

Fischer-Kowalski, M., Weisz, H., 1999. Society as hybrid between material and symbolic realms. Adv. Hum. Ecol. 8, 215–251.

Folke, C., Haider, L.J., Lade, S.J., et al., 2021. Resilience and social-ecological systems: a handful of frontiers. Glob. Environ. Chang. 71, 102400. https://doi.org/10.1016/j.gloenvcha.2021.102400.

Fu, C., Zhang, Y., Deng, T., Daigo, I., 2022. The evolution of material stock research: from exploring to rising to hot studies. J. Ind. Ecol. 26, 462–476. https://doi.org/10.1111/jiec.13195.

Giljum, S., Lutter, S., Streeck, J., et al., 2022. Guidance Document on Measuring Demand-Based Material Flows (Material Footprints). OECD, Paris.

Haberl, H., Wiedenhofer, D., Pauliuk, S., et al., 2019. Contributions of sociometabolic research to sustainability science. Nat. Sustainability 2, 173–184. https://doi.org/10.1038/s41893-019-0225-2.

Haberl, H., Schmid, M., Haas, W., et al., 2021. Stocks, flows, services and practices: nexus approaches to sustainable social metabolism. Ecol. Econ. 182, 106949. https://doi.org/10.1016/j.ecolecon.2021.106949.

Haberl, H., Löw, M., Perez-Laborda, A., et al., 2023. Built structures influence patterns of energy demand and CO2 emissions across countries. Nat. Commun. 14, 3898. https://doi.org/10.1038/s41467-023-39728-3.

Han, F., Sun, M., Jia, X., et al., 2022. Agent-based model for simulation of the sustainability revolution in eco-industrial parks. Environ. Sci. Pollut. Res. 29, 23117–23128. https://doi.org/10.1007/s11356-021-17503-5.

Hanel, R., Kauffman, S.A., Thurner, S., 2005. Phase transition in random catalytic networks. Phys. Rev. E 72, 036117. https://doi.org/10.1103/PhysRevE.72.036117.

Hanel, R., Kauffman, S.A., Thurner, S., 2007. Towards a physics of evolution: critical diversity dynamics at the edges of collapse and bursts of diversification. Phys. Rev. E 76, 030101.

Hausknost, D., Gaube, V., Haas, W., et al., 2016. "Society can't move so much as a chair!" - systems, structures and actors in social ecology. In: Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V. (Eds.), Social Ecology. Springer, Cham, pp. 125–147.

Holling, C.S., 2001. Understanding the complexity of economic, ecological, and social systems. Ecosystems 4, 390–405. https://doi.org/10.1007/s10021-001-0101-5.

Hyde, G., Fath, B.D., Zoller, H., 2024. Measuring system resilience through a comparison of information- and flow-based network analyses. Sci. Rep. 14, 16451. https://doi.org/10.1038/s41598-024-66654-1.

IPBES, 2019. Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany.

IPCC, 2022. Climate Change 2022. Mitigation of Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Kemp, L., Xu, C., Depledge, J., et al., 2022. Climate endgame: exploring catastrophic climate change scenarios. Proc. Natl. Acad. Sci. 119, e2108146119. https://doi.org/10.1073/pnas.2108146119.

Klimek, P., Poledna, S., Doyne Farmer, J., Thurner, S., 2015. To bail-out or to bail-in? Answers from an agent-based model. J. Econ. Dyn. Control. 50, 144–154. https://doi.org/10.1016/j.jedc.2014.08.020.

Klimek, P., Poledna, S., Thurner, S., 2019. Quantifying economic resilience from input–output susceptibility to improve predictions of economic growth and recovery. Nat. Commun. 10, 1677. https://doi.org/10.1038/s41467-019-09357-w.

Knoeri, C., Wäger, P.A., Stamp, A., et al., 2013. Towards a dynamic assessment of raw materials criticality: linking agent-based demand — with material flow supply modelling approaches. Sci. Total Environ. 461–462, 808–812. https://doi.org/10.1016/j.scitotenv.2013.02.001.

Knoeri, C., Nikolic, I., Althaus, H.-J., Binder, C.R., 2014. Enhancing recycling of construction materials; an agent based model with empirically based decision parameters. J. Artif. Soc. Soc. Simul. 17, 10.

Krausmann, F., Schandl, H., Eisenmenger, N., et al., 2017a. Material flow accounting: measuring global material use for sustainable development. Annu. Rev. Environ. Resour. 42, 647–675.

Krausmann, F., Wiedenhofer, D., Lauk, C., et al., 2017b. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc. Natl. Acad. Sci. USA 114, 1880–1885. https://doi.org/10.1073/pnas.1613773114.

Laber, M., Klimek, P., Bruckner, M., et al., 2023. Shock propagation from the Russia–Ukraine conflict on international multilayer food production network determines global food availability. Nat. Food 4, 508–517. https://doi.org/10.1038/s43016-023-00771-4.

Lamb, W.F., Steinberger, J.K., 2017. Human well-being and climate change mitigation. Wiley Interdiscip. Rev. Clim. Chang. 8, e485. https://doi.org/10.1002/wcc.485.

Lenzen, M., Geschke, A., West, J., et al., 2022. Implementing the material footprint to measure progress towards sustainable development goals 8 and 12. Nat. Sustainability 5, 157–166. https://doi.org/10.1038/s41893-021-00811-6.

Li, Y., Shi, L., 2015. The resilience of interdependent industrial symbiosis networks: a case of Yixing economic and technological development zone. J. Ind. Ecol. 19, 264–273. https://doi.org/10.1111/jiec.12267.

Lund, S., Manyika, J., Woetzel, J., et al., 2020. Risk, Resilience, and Rebalancing in Global Value Chains. McKinsey Global Institute. https://www.mckinsey.com.

Magoni, M., 2017. Resilience thinking and urban metabolism in spatial planning: which possible integrations. City Territ. Archit. 4, 19. https://doi.org/10.1186/s40410-017-0074-0.

Mancheri, N.A., Sprecher, B., Bailey, G., et al., 2019. Effect of Chinese policies on rare earth supply chain resilience. Resour. Conserv. Recycl. 142, 101–112. https://doi.org/10.1016/j.resconrec.2018.11.017.

Martinez-Alier, J., 1987. Ecological Economics. Energy, Environment and Society, Blackwell, Oxford.

Meerow, S., Newell, J.P., 2015. Resilience and complexity: a bibliometric review and prospects for industrial ecology. J. Ind. Ecol. 19, 236–251. https://doi.org/10.1111/jiec.12252.

Müller, E., Hilty, L.M., Widmer, R., et al., 2014. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environ. Sci. Technol. 48, 2102–2113. https://doi.org/10.1021/es403506a.

Olsson, L., Jerneck, A., Thoren, H., et al., 2015. Why resilience is unappealing to social science: theoretical and empirical investigations of the scientific use of resilience. Sci. Adv. 1, e1400217. https://doi.org/10.1126/sciadv.1400217.

Österblom, H., Folke, C., Rocha, J., et al., 2022. Scientific mobilization of keystone actors for biosphere stewardship. Sci. Rep. 12, 3802. https://doi.org/10.1038/s41598-022-07023-8.

Otto, I.M., Donges, J.F., Cremades, R., et al., 2020a. Social tipping dynamics for stabilizing earth's climate by 2050. Proc. Natl. Acad. Sci., 201900577 https://doi.org/10.1073/pnas.1900577117.

Otto, I.M., Wiedermann, M., Cremades, R., et al., 2020b. Human agency in the Anthropocene. Ecol. Econ. 167, 106463. https://doi.org/10.1016/j.ecolecon.2019.106463.

Pachauri, S., Pelz, S., Bertram, C., et al., 2022. Fairness considerations in global mitigation investments. Science 387, 1057–1059. https://doi.org/10.1126/science.adf0067.

Pachauri, S., Schaffartzik, A., Staritz, C., Krausmann, F., Giljum, S., Zimm, C., Brutschin, E., Maile, F., Min, J., Ukita Shepard, J., Ialongo, L.N., Pungas, L., Pelz, S., Haberl, H., 2025. Conceptualizing and Operationalizing the Malleability of Society's Metabolism and Resource Provisioning (In review). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5906908.

Pauliuk, S., Müller, D.B., 2014. The role of in-use stocks in the social metabolism and in climate change mitigation. Glob. Environ. Chang. 24, 132–142. https://doi.org/10.1016/j.gloenvcha.2013.11.006.

Pizzol, M., 2015. Life cycle assessment and the resilience of product systems. J. Ind. Ecol. 19, 296–306. https://doi.org/10.1111/jiec.12254.

Plank, C., Liehr, S., Hummel, D., et al., 2021. Doing more with less: provisioning systems and the transformation of the stock-flow-service nexus. Ecol. Econ. 187, 107093. https://doi.org/10.1016/j.ecolecon.2021.107093.

Plank, B., Streeck, J., Virág, D., et al., 2022. From resource extraction to manufacturing and construction: flows of stock-building materials in 177 countries from 1900 to 2016. Resour. Conserv. Recycl. 179, 106122. https://doi.org/10.1016/j.resconrec.2021.106122.

Plank, C., Görg, C., Kalt, G., Kaufmann, L., Dullinger, S., Krausmann, F., 2023. Biomass from somewhere? Governing the spatial mismatch of Viennese biomass consumption and its impact on biodiversity. Land Use Policy 131, 106693. https://doi.org/10.1016/j.landusepol.2023.106693.

Rao, N.D., Min, J., 2018. Decent living standards: material prerequisites for human wellbeing. Soc. Indic. Res. 138, 225–244. https://doi.org/10.1007/s11205-017-1650-0.

Reisch, T., Heiler, G., Diem, C., et al., 2022. Monitoring supply networks from mobile phone data for estimating the systemic risk of an economy. Sci. Rep. 12, 13347. https://doi.org/10.1038/s41598-022-13104-5.

Reyers, B., Moore, M.-L., Haider, L.J., Schlüter, M., 2022. The contributions of resilience to reshaping sustainable development. Nat. Sustainability 5, 657–664. https://doi.org/10.1038/s41893-022-00889-6.

Rockström, J., Steffen, W., Noone, K., et al., 2009. A safe operating space for humanity. Nature 461, 472–475.

Schaffartzik, A., Pichler, M., Pineault, E., et al., 2021. The transformation of provisioning systems from an integrated perspective of social metabolism and political economy: a conceptual framework. Sustain. Sci. 16, 1405–1421. https://doi.org/10.1007/s11625-021-00952-9.

Schandl, H., Marcos-Martinez, R., West, J., et al., 2024. Global material flows and resource productivity: the 2024 update. J. Ind. Ecol. https://doi.org/10.1111/jiec.13593.

Seto, K.C., Davis, S.J., Mitchell, R.B., et al., 2016. Carbon lock-in: types, causes, and policy implications. Annu. Rev. Environ. Resour. 41, 425–452. https://doi.org/10.1146/annurev-environ-110615-085934.

Shove, E., Pantzar, M., Watson, M., 2012. The Dynamics of Social Practice: Everyday Life and how it Changes. SAGE, Los Angeles, CA.

Sun, Y., Zhu, S., Wang, D., et al., 2024. Global supply chains amplify economic costs of future extreme heat risk. Nature 627, 797–804. https://doi.org/10.1038/s41586-024-07147-z.

Thurner, S., 2024. New forms of collaboration between the social and natural sciences could become necessary for understanding rapid collective transitions in social systems. Perspect. Psychol. Sci. 19, 503–510. https://doi.org/10.1177/17456916231201135.

Thurner, S., Poledna, S., 2013. DebtRank-transparency: controlling systemic risk in financial networks. Sci. Rep. 3, 1888. https://doi.org/10.1038/srep01888.

UNEP, 2019. Global Resources Outlook 2019: Natural Resources for the Future we Want. United Nations Environment Programme, International Resource Panel, Nairobi, Kenya.

van den Brink, S., Kleijn, R., Sprecher, B., et al., 2022. Resilience in the antimony supply chain. Resour. Conserv. Recycl. 186, 106586. https://doi.org/10.1016/j.resconrec.2022.106586.

Verschuur, J., Koks, E.E., Hall, J.W., 2022a. Ports' criticality in international trade and global supply-chains. Nat. Commun. 13, 4351. https://doi.org/10.1038/s41467-022-32070-0.

Verschuur, J., Pant, R., Koks, E., Hall, J., 2022b. A systemic risk framework to improve the resilience of port and supply-chain networks to natural hazards. Marit. Econ. Logist. 24, 489–506. https://doi.org/10.1057/s41278-021-00204-8.

Vita, G., Hertwich, E.G., Stadler, K., Wood, R., 2019. Connecting global emissions to fundamental human needs and their satisfaction. Environ. Res. Lett. 14, 014002. https://doi.org/10.1088/1748-9326/aae6e0.

Vogel, J., Steinberger, J.K., O'Neill, D.W., et al., 2021. Socio-economic conditions for satisfying human needs at low energy use: an international analysis of social provisioning. Glob. Environ. Chang. 69, 102287. https://doi.org/10.1016/j.gloenvcha.2021.102287.

Walker, B., Holling, C.S., Carpenter, S.R., Kinzig, A.P., 2004. Resilience, adaptability and transformability in social-ecological systems. Ecol. Soc. 9, art5. https://doi.org/10.5751/ES-00650-090205.

Weisz, H., Suh, S., Graedel, T.E., 2015. Industrial ecology: the role of manufactured capital in sustainability. Proc. Natl. Acad. Sci. 112, 6260–6264. https://doi.org/10.1073/pnas.1506532112.

Wiedenhofer, D., Streeck, J., Wieland, H., et al., 2024. From extraction to end-uses and waste management: modeling economy-wide material cycles and stock dynamics around the world. J. Ind. Ecol. 28, 1464–1480. https://doi.org/10.1111/jiec.13575.

Wiedmann, T.O., Schandl, H., Lenzen, M., et al., 2015. The material footprint of nations. Proc. Natl. Acad. Sci. 112, 6271–6276. https://doi.org/10.1073/pnas.1220362110.

Yeung, H.W., 2023. Troubling economic geography: new directions in the post-pandemic world. Trans. Inst. Br. Geogr. 48, 672–680. https://doi.org/10.1111/tran.12633.

Zhu, J., Ruth, M., 2013. Exploring the resilience of industrial ecosystems. J. Environ. Manag. 122, 65–75. https://doi.org/10.1016/j.jenvman.2013.02.052.