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Surveys

Linking systems to agencies in urban metabolism studies: A conceptual framework and computational analysis of research literature

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ABSTRACT

This study outlines a conceptual framework linking a conceptualization of agency in urban metabolism studies with a systems-based perspective. To this aim, we engage with contributions to socio-metabolic studies, notably from social ecology, that are not directly concerned with the urban dimension but explicitly question how systems and actors shape each other and how social practices can influence the distribution of resource flows and stocks and their interdependencies. Based on those contributions, we identify three critical axes of investigation that help track implicit uses of the concept of "agency" in urban metabolism studies and constitute the pillars of our proposed framework: (1) characterizing structures comprising urban social-ecological systems – understood as patterns of connections among elements and subsystems – as actors, (2) identifying the chains of events that such actors influence by exerting their agentic capacities, and (3) associating those same actors with definite agentic dimensions, i.e., specific modalities of agency. By drawing on methods from computational linguistics, text mining, and semantic network analysis, we extract concepts cognate to "urban metabolism" from a relevant body of research literature. Through our framework, we show how such concepts define forms of agency that can be ascribed to structural components of urban social-ecological systems.

1. Introduction

The concept of "urban metabolism" (UM) has become a prominent research focus for urban sustainability studies (e.g., Céspedes Restrepo and Morales-Pinzón, 2018; Dijst et al., 2018; Guilbrunet and Sánchez Jiménez, 2023), including in the pages of this journal (e.g., John et al., 2019; Bahers et al., 2020; Cremades et al., 2021). Such an uptake in interest can be linked to the UM concept's potential for informing practices and policies in urban design, planning, and management (see, e.g., Bristow and Kennedy, 2013; Bristow and Mohareb, 2020; Kissinger and Stossel, 2021). This potential has been widely explored by studies rooted in urban political ecology (e.g., Gandy, 2004; Swyngedouw, 2006; Zimmer, 2010). Such studies have deployed the notion of "agency" to uncover the power dynamics underpinning the resource exchanges through which cities interact with nature (Gandy, 2022; Zimmer, 2010). Nevertheless, compared to other fields of study focusing on the UM, urban political ecology has historically put less emphasis on systems-based thinking as a bridge between the biophysical and the social sciences in addressing socio-ecological issues (Gandy, 2022, p. 26). In contrast, industrial ecologists (Kennedy, 2016) have explicitly conceptualized the UM from a systems-based perspective, i.e., as a process characterizing the growth, development, and sustenance of urban social-ecological systems. However, despite notable exceptions (e.g., Andrews, 2000), the link between systems and agencies seemingly constitutes a blind spot for industrial ecology. Accordingly, industrial ecology-based accounts of the UM have generally devoted limited attention to the notion of "agency" and, more specifically, to the various forms of agency that urban political ecology has identified as laying at the very core of the UM concept (Perrotti, 2022).

In addition to industrial ecology, contributions to developing systems-based approaches to the UM (see, e.g., Wu, 2014; Cui, 2018; Haberl et al., 2019) have come from urban (e.g., Grove et al., 2017) and social ecology (e.g., Haberl et al., 2016). Unlike industrial ecology, however, those other fields have explicitly addressed the issue of clarifying how systems and actors shape each other in social-ecological processes (Perrotti, 2022). For instance, Hausknost et al. (2016) have highlighted possible gaps in how the relations between systems, structures, and actors are conceived within the metatheoretical framework

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underlying social ecology. This framework is based on "general systems theory as elaborated by Maturana and Varela (1975) and applied by Luhmann (1984) to social systems" (Hausknost et al., 2016, p. 218). It posits that human beings, as potentially willful actors, are "hybrid entities" existing at the interface between two kinds of systems: the symbolic system of culture and communication, on the one hand, and the system of nature, which comprises their bodies and brains as material elements, on the other hand. Those hybrid entities are embedded in both systems, on which they rely for their existence and which they can shape through their agency (e.g., farmers discussing soil conditions together can change their understanding of those same conditions and identify ways of modifying them as material realities). In this sense, the collective formation resulting from the activity of human actors – i.e., society – ensures the "structural coupling" of the symbolic and material realms. However, according to Hausknost et al. (2016), this structural coupling needs further theorizing: How are different forms of agency shaped by the structures of the systems in which they operate? In turn, how can they shape those same structures?

To address such questions, this study outlines a conceptual framework for identifying agencies embodied in structural components of urban social-ecological systems from a metabolic perspective. In the remainder of this paper, Section 2 lays the foundations for our conceptual framework by identifying three critical axes of investigation that can help track implicit uses of the concept of "agency" in UM studies. Those axes are: (1) characterizing structures comprising urban social-ecological systems as actors, (2) identifying the chains of events that such actors influence by exerting their agentic capacities, and (3) associating those same actors with definite agentic dimensions, i.e., specific modalities of agency. By working along these three critical axes, we identify and classify various structural forms of agency in urban social-ecological systems through concepts cognate to the UM notion – i.e., terms belonging to a semantic field associated with the word "UM" itself – and extracted from a relevant body of research literature. Drawing on text mining and computational linguistics methods presented in Section 3, we identify this semantic field and map it via four semantic networks. Finally, Section 4 discusses how such networks express UM-cognate concepts that ascribe agencies to structural components of urban social-ecological systems, while Section 5 highlights the main conclusions entailed by our study.

2. Theoretical background

Social ecology's socio-metabolic studies have explicitly addressed the relations between systems, structures, and actors, notably the "stock-flow-practice nexus" (SFP nexus) framework proposed by Haberl et al. (2021) to describe the interrelations between human activities, material/energy flows, and material stock patterns. To this aim, the SFP nexus framework relies on a particular concept of "practice" (informed by social practice theory) as "a routinized type of behavior which consists of several elements, interconnected to one other: forms of bodily activities, forms of mental activities, 'things' and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge" (Reckwitz, 2002, p. 249; see also Schatzki, 1996, 2002; Shove et al., 2012; Warde, 2014; Watson et al., 2020). Within the SFP nexus approach, the socio-economic and biophysical dynamics constitutive of urban and social metabolisms can thus be shaped by routinized activities. Such activities result from "self-organizing processes unfolding in time and space", are embedded in social structures to which they owe their specific meanings, and depend on the availability of physical resources and artifacts ("such as equipment, tools, materials, and infrastructures") in addition to skills and competences (Haberl et al., 2021). Consequently, the SFP nexus approach can contribute to bridging the divide between systems, structures, and actors by positing that the latter influence the sustainability of social-ecological systems by adhering to collective systems of practices – i.e., systems of socially embedded and materially grounded routinized activities. Nevertheless, the SFP nexus approach needs to be further expanded to articulate an extended view of agency that could highlight the UM concept's potential as a tool for promoting urban sustainability by considering a broader range of agentic capacities and activities. The conceptual framework outlined by our study aims to achieve such a goal. However, what explicit conceptualization of agency can be drawn from Haberl et al. (2021)? And to what ongoing efforts to deploy an agentic perspective in systems-based urban or socio-metabolic research can this same conceptualization be linked?

2.1. *What is agency? A social practice theory-based perspective from environmental politics*

The SFP nexus approach, as expressed in Haberl et al. (2021), can highlight the structural aspects of agency in social-ecological systems, i.e., how the exercise of agency embodies itself in social structures grounded in material (biophysical) substrates. Such a view of agency can be linked to previous theoretical efforts to characterize agentic dynamics in social ecology, such as Hausknost's (2014) analysis of the structural causes of the "agentic deadlock" that describes how liberal-democratic political systems react to pressures for transformative change in environmental politics. To this aim, he introduces the concept of "agentic operators". Such operators are the three general and abstract modes of (human) agency – i.e., "decision", "solution" and "choice" – which serve to account for how specific actors can change material realities through the channels and constraints provided by social structures, e.g., institutions and social practices. In other words, those structures allow actors to influence the state of the world by enabling specific patterns of actions and preventing others, i.e., by connecting the abstract modes identified by the three agentic operators with concrete forms of agency. The agentic operator "*decision*" characterizes how political structures such as parliaments or courts of law allow for selected patterns of actions to be played out, i.e., by eliminating alternative options through sovereign force. The operator "*solution*" accounts for how social structures like public administrations, science, and technology produce specific patterns of actions as necessary outcomes of rational problem-solving processes. Finally, the operator "*choice*" describes how social structures such as markets for goods or services allow actors to make arbitrary decisions between incommensurable patterns of actions without permanently discarding the alternatives that are not selected. Furthermore, Hausknost et al. (2018) expand on this agentic operator framework by focusing on the strategies that particular social structures, such as municipalities or communities, can implement to change the patterns of actions embodied in existing social practices. Based on Reckwitz's (2002) definition, social practices are here characterized as the dual product of the interactions between social structures and individual behaviors. On the one hand, "a practice is the performance of a routine (practice-as-performance)". On the other hand, it is also the pattern of actions through which this same performance is routinely enacted ("practice-as-entity") (Hausknost et al., 2018, p. 373). Drawing on Spurling et al. (2013), three strategies are identified through which social structures can modify social practices as performances and entities: (1) "re-crafting practices" by changing some of their constitutive elements without questioning the practices themselves or the frequency of their performance; (2) "substituting practices" by identifying and encouraging alternative performances and patterns of actions that are more sustainable than existing ones while meeting the same (or comparable) needs and wants; (3) "changing how practices interlock" by intervening in the broader system of practices that produce needs fulfilled through unsustainable performances and patterns of actions to make such needs, performances, and patterns of actions obsolete (Hausknost et al., 2018, pp. 373-374). Therefore, even without mentioning the term "agency" itself, Hausknost et al. (2018) foreground how social practice theory illuminates the links between social structures and various forms of agency by identifying ways in which the former can influence the latter through the emergence of different social practices.

2.2. How can actors shape structures? Different levels of human agencies as a consequence of socio-metabolic agent class divisions

Other relevant contributions to illuminating the links between structures and agencies in social-ecological systems have come from research connecting socio-metabolic analysis with social class theory. For instance, Otto et al. (2020) have relied on various conceptualizations from the social sciences (e.g., Dobres and Robb, 2000; Ostrom, 2005; Dellas et al., 2011) to account for "the tension between agency and structure" – i.e., between self-determination and social embeddedness – in assessing how humanity influences the Earth system's governance. Their analysis is thus grounded in an understanding of humanity as a "global subject" (Schellnhuber, 1999) – i.e., "a real but abstract force that represents the collective [and self-conscious] action of humanity" at global scales, e.g., through the adoption of protocols for climate protection (Otto et al., 2020, p. 2) – that is key to Earth system research. Drawing from studies such as Lister (2003) and Coulthard (2012), they have distinguished between different "agentic dimensions" associated with humanity's agency: (1) "everyday agency" (i.e., the modality of humanity's agency that is involved in daily decision-making), (2) "strategic agency" (i.e., associated with long-term planning), (3) "personal agency" (i.e., characterizing individual choices), and (4) "political and citizenship agency" (i.e., associated with collective political action). To account for all those agentic dimensions, social structures are understood as sets of collective prescriptions and constraints that influence how actors (individuals, organizations, or networks) participate in decision-making processes. In this view, only some such actors – identified as "agents" – have the power to change those same prescriptions and constraints (Otto et al., 2020). More specifically, social structures constitute the various institutional (informal/formal behavioral rules), organizational (governance structures, organizations, and agent networks), and "technosphere" (infrastructures and technology) layers of the social systems through which human agency manifests itself, notably by shaping them. Each such layer is associated with "dominant types of human agency", characterized through the abovementioned agentic dimensions, e.g., "collective and strategic agency" and "collective and citizenship agency" in the institutional layer's case. Since not all human agents can exert those forms of agency to the same degree, understanding the connections between human agents and social structures requires accounting for how the former are stratified in different classes. For this reason, socio-metabolic analysis (Fischer-Kowalski, 1997) can be used to distinguish between various hierarchically structured social classes of agents through their respective socio-metabolic profiles (Martinez-Alier, 2009), notably their respective average energy consumption and CO_2 emission levels. Based on data from Oxfam (2015) and Otto et al. (2019), Otto et al. (2020) thus identify different socio-metabolic agent classes, ranging from the "socio-metabolic underclass" to the "super-rich". This characterization of human agency based on socio-metabolic classes has been operationalized to analyze household-level energy use patterns in the UK (Schuster et al., 2023) and the linkage between social profiles and high emission levels in Germany (Schuster and Otto, 2023). Finally, Otto et al. (2020) highlight two additional aspects of the connection between social structures and agencies from a socio-metabolic perspective: (1) Not only are human agencies enabled and constrained by structural patterns of actions, but they can also shape those same structural patterns; (2) The modalities through which human agency is exerted are not homogeneous since they are determined by socio-metabolic class divisions.

2.3. From environmental politics and socio-metabolic analysis to urban metabolism studies. Three core questions for characterizing structural forms of agency embedded in the urban metabolism

The characterization of agency that we can draw from the insights provided by Haberl et al. (2021), Hausknost (2014), Hausknost et al. (2018), and Otto et al. (2020) is thus four-pronged: (1) Agency is both enabled and constrained by the social structures through which it plays out. Those structures are, in turn, grounded in natural (biophysical) ones; (2) Social practices as multifaceted and routinized patterns of actions constitute the medium through which agency is connected to social structures; (3) At the same time, actors can use such practices to influence the social structures to which they are connected, and potentially change them; (4) However, not all actors can exert the same influence on the social structures in which they are embedded. The capacity to shape such structures notably depends on the possibility of accessing material resources unequally distributed among actors and exerting agency in one's relation with such resources. Such a four-pronged characterization of agency is thus consistent with Schatzki's (2002, 2014). From this other perspective, agency means the capacity to introduce change in the world by intervening within a causal chain of events, but it is not a feature of individual entities. Thus, Schatzki's (2002, 2014) understanding of agency is highly relational. It rests on the assumption that the kind of change characterized by this concept results from and is embedded in "bundles" (Schatzki, 2014, p. 15) comprising two complex ensembles of elements: on the one hand, "open spatial-temporal nexuses" of actions and utterances linked by socially accepted or enforced rules, understandings, values, emotions, etc., i.e., "social practices" (Schatzki, 2014, p. 15); on the other hand, "collections of people, artefacts, organisms and things" that are linked by physical and causal relationships, i.e., "material arrangements" (Schatzki, 2014, p. 15). From this standpoint, agency is a feature of how practices are induced, channeled, and supported by relevant material arrangements and how the former interact with and give meaning to the latter. Therefore, Schatzki's (2002, 2014) view of agency adds another element to the four-pronged characterization we established above: the tight interconnection between practices and material arrangements.

Moreover, we can use such a view to ascribe agency to UM structures by turning to the general systems theory developed by von Bertalanffy (1968), i.e., the common background shared by industrial ecology, social ecology, and urban ecology-based accounts of the UM, notably through the influence of E. P. Odum (1953), H. T. Odum (1983), and Maturana and Varela (1975). The reason is that general systems theory provides us with definitions of the concepts of "system" and "structure" that are coherent with Schatzki's (2002, 2014) conceptualization of agency. As characterized by von Bertalanffy (1968), for instance, a system is "a set of elements standing in interrelations. Interrelation means that elements, p, stand in relations, R, so that the behavior of an element p in R is different from its behavior in another relation, R'" (von Bertalanffy, 1968, p. 56). From this standpoint, a structure can be defined as a particular ordering of some (or all) of the elements that compose the system through their interrelations, i.e., as a specific "pattern of connections" (H. T. Odum, 1983, p. 19) among those same elements. Accordingly, the structures comprising an urban social-ecological system can be regarded as patterns of connections among the social or natural units contained in this same system. From a UM-based perspective, such patterns of connections amount to patterns of metabolic exchanges among units of an urban social-ecological system. Urban metabolic structures can thus be seen as emerging from how matter, energy, etc. flow or cycle through this same system.

It follows that our general systems theory-based definition of "system" and "structure" and Schatzki's (2002, 2014) definition of "agency" allows us to pinpoint how metabolic structures within urban social-ecological systems – viewed as patterns of metabolic exchanges among the units comprising those same systems – can be construed as actors. On the one hand, we can regard such urban metabolic structures as specific kinds of material arrangements. On the other hand, we need to connect those same structures, as material arrangements, to particular systems of practices. The reason is that, per Schatzki's (2002, 2014) definition of "agency", material arrangements and social practices are both required to identify a given entity as an agent or actor. In the remainder of this study, we thus establish a conceptual framework that fulfills both conditions. To this aim, we extract concepts cognate to the UM notion from a relevant body of research literature and assess how interpreting the meaning of such concepts enables us to construe various UM structures as actors. This interpretation is guided by three core questions that can be asked to unearth implicit uses of the agency concept in studies on the UM:

1. "Whose agency?" – i.e., "What entities, including structures, can be identified as the actors possessing an agentic capacity (i.e., the capacity to exert a certain influence) over UM stocks and flows?" – which explicitly states that metabolic structures, as patterns of connections among the elements comprising a social or urban system, can be regarded as actors.
2. "What is acted upon?" – i.e., "What chains of events are targeted by the actors' influence?" – which defines how those same structures can be said to exert agency as per Schatzki (2002, 2014).
3. "How, where, and when do those actors exert their agentic capacity?" – i.e., "What are the concrete and spatiotemporally situated events, processes, mechanisms, etc. through which the actors in question exert their influence?" – which suggests a characterization of agentic dimensions in line with those identified by Hausknost (2014) and Otto et al. (2020) but specific to the UM (see the table in Supplementary material 1 for an overview of all relevant concepts).

3. Methods and results

An interdisciplinary body of 24 sources was constituted by collecting (1) literature reviews or conceptual papers explicitly mentioning "UM" (e.g., Golubiewski, 2012; Kennedy et al., 2011; Zhang et al., 2015); (2) additional texts related to either one of the systems-based approaches to the UM discussed in Section 1 or a mixture thereof (e.g., Bai and Schandl, 2010; Fischer-Kowalski and Weisz, 2016; Pickett et al., 2022) (see Supplementary material 2 for a table describing the source documents used to assemble the corpus). Each source was assigned to industrial ecology, social ecology, urban ecology, or a combination thereof by considering key features: title, first author, publication venue, author or indexed keywords, and content. 1481 journal articles were then selected by browsing each source's bibliography and only retaining references that met specific selection criteria – i.e., research articles, editorials, or literature reviews written in English and relevant to the content of the sources referencing them and not only to the methods herein employed (e.g., Blondel et al., 2008, cited in Tang et al., 2021, was excluded) – regardless of whether they explicitly mentioned "UM" in their titles, abstracts, associated keywords, or article bodies. Those references had all been published between 1899 and 2023, with 82 % of them (1218 out of 1481) issued during the 2003–2023 period. Furthermore, by considering the same features used to classify the source documents, we assigned each reference to one of four disciplinary categories: industrial ecology (40 %), urban ecology (33 %), social ecology (18 %), and "interdisciplinary articles", i.e., articles that could be ascribed to more than one approach, (9 %) (Fig. 1).

We extracted from Scopus and Google Scholar the abstracts (or else the first two paragraphs), titles, and, when available, author or indexed keywords of the 1481 references thus selected (see Supplementary material 3 for the whole database thus created, including relevant metadata). Those elements were assembled into documents preprocessed using the R packages UDPipe (Wijffels, 2021) and Quanteda (Benoit et al., 2018) to abide by standard pre-processing practices (Chai, 2023) (see Supplementary material 4 for the code used to preprocess the documents, analyze the data, and plot the semantic networks and Supplementary material 8 for further methodological details). In this way, all articles were reduced to sets of tokens, which were cleaned by removing tokens shorter than four characters and non-meaningful tokens (see Supplementary material 5 for a list of all the corrections made). Based on the tokens previously selected, we used Quanteda to generate possible multi-word expressions in the form of N-grams – i.e., phrases of n consecutive tokens occurring in the same document, identified through a sliding window filter (Manning and Schütze, 1999). Each document in our corpus was thus represented as a "bag of 1-to-5-grams", i.e., a collection of monograms (individual tokens), bigrams (two-word expressions), trigrams (three-word expressions), tetragrams (four-word expressions), and pentagrams (five-word expressions). (see Supplementary material 8 for further methodological details and Supplementary material 6 for all the corrections made upon review at this other stage).

By performing the computational linguistics and text mining-based analysis described in Supplementary material 8 and Fig. 2 (see also Supplementary materials 7, 9, 10, 11, and 12 for data and further observations relative to our analysis), we identified 202 terms (either keywords or key expressions) significantly associated with "UM" from a statistical standpoint. We ranked them according to their respective Simpson coefficient values[1] relative to "UM" and split them into four groups: (1) terms weakly co-occurring with "UM" (40 items with Simpson coefficient values between 1.61 and 20.72, 19.8 % of the total); (2) the lower tail of the group comprising terms mildly co-occurring with "UM" (51 items with Simpson coefficient values between 28.05 and 50, 25.2 % of the total); (3) the upper end of this same group (74 items with Simpson coefficient values between 51.85 and 77.78, 36.6 % of the total); (4) terms strongly co-occurring with "UM" (37 items with Simpson coefficient values between 80 and 100, 18.3 % of the total) (see Supplementary material 13 for a table describing the final selection of significant terms). Based on those groups of terms, we mapped four layers of the UM term's semantic field – i.e., "a set of terms with a close relation in meaning, all of which can be subsumed under the same general label" (Akmajian et al., 2001, p. 240) – by representing each such layer as a semantic network – i.e., a graph whose nodes represent terms and whose edges reflect the relevance with which those same terms directly or indirectly co-occur in predefined textual units (Segev, 2022) – plotted through the R package Igraph (Csarvi and Nepusz, 2006) (see Supplementary material 8).

By selecting up to five most influential nodes for each network as a whole and, within each network, for each cluster, we identified sets of "structuring terms", i.e., terms likely to play a central role in defining the semantic relations represented by the structures of those same networks or clusters. All such terms are listed in Table 1 and depicted in Fig. 3. More specifically, Fig. 3a depicts Network 1, which represents terms weakly co-occurring with "UM" and consists of four clusters. Fig. 3b portrays Network 2, which charts the lower tail of the terms mildly co-occurring with "UM" and comprises four clusters. Fig. 3c showcases Network 3, which is associated with the upper end of the terms mildly co-occurring with "UM" and consists of three clusters. Finally, Fig. 3d highlights Network 4, which maps semantic relations between terms strongly co-occurring with "UM" and comprises five clusters. All networks' nodes were assigned to a specific discipline (industrial ecology, urban ecology, or social ecology) (see Supplementary materials 14, 15 and 16 for further information about the nodes and edges contained in the four networks). In this section's figures, industrial ecology-affiliated, urban ecology-affiliated, and social ecology-affiliated nodes are thus colored in red, green, and blue. Furthermore, for each network and cluster, we identified up to ten documents providing relevant context for interpreting how the corresponding structuring terms mutually define their respective meanings (see Supplementary material 8 for further

[1] The "Simpson coefficient" ($c_{i,j}$) measures the strength of the association between terms i and j from a set-theoretical standpoint: $c_{i,j} = \frac{\#(D_i \cap D_j)}{min(\#D_i, \#D_j)} \bullet (100)$, where $\#(D_i \cap D_j)$ represents the size of the intersection between the set of all the documents containing the term i, D_i, and the set of all the documents containing the term j, D_j, while $min(\#D_i, \#D_j)$ represents the size of the smaller of the two sets (Van Eck and Waltman, 2009).

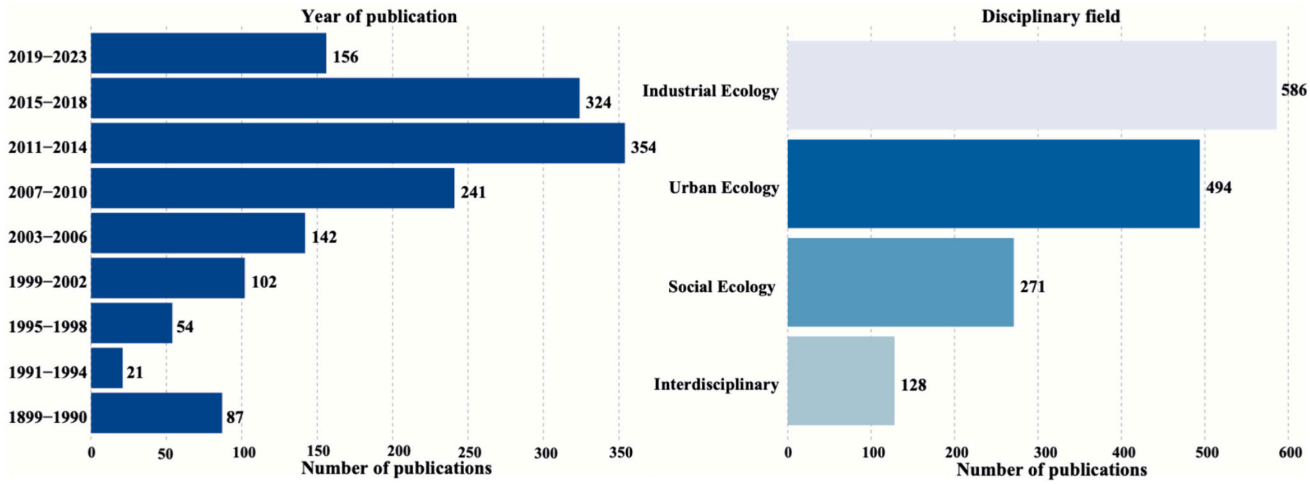


Fig. 1. Number of publications selected for the corpus by period (left chart) and disciplinary affiliation (right chart). Notes: (1) Publications from 1899 to 1990 have been aggregated due to insufficient numbers (less than one publication per year, on average); (2) The 2019–2023 column only contains part of the relevant articles published in 2023.

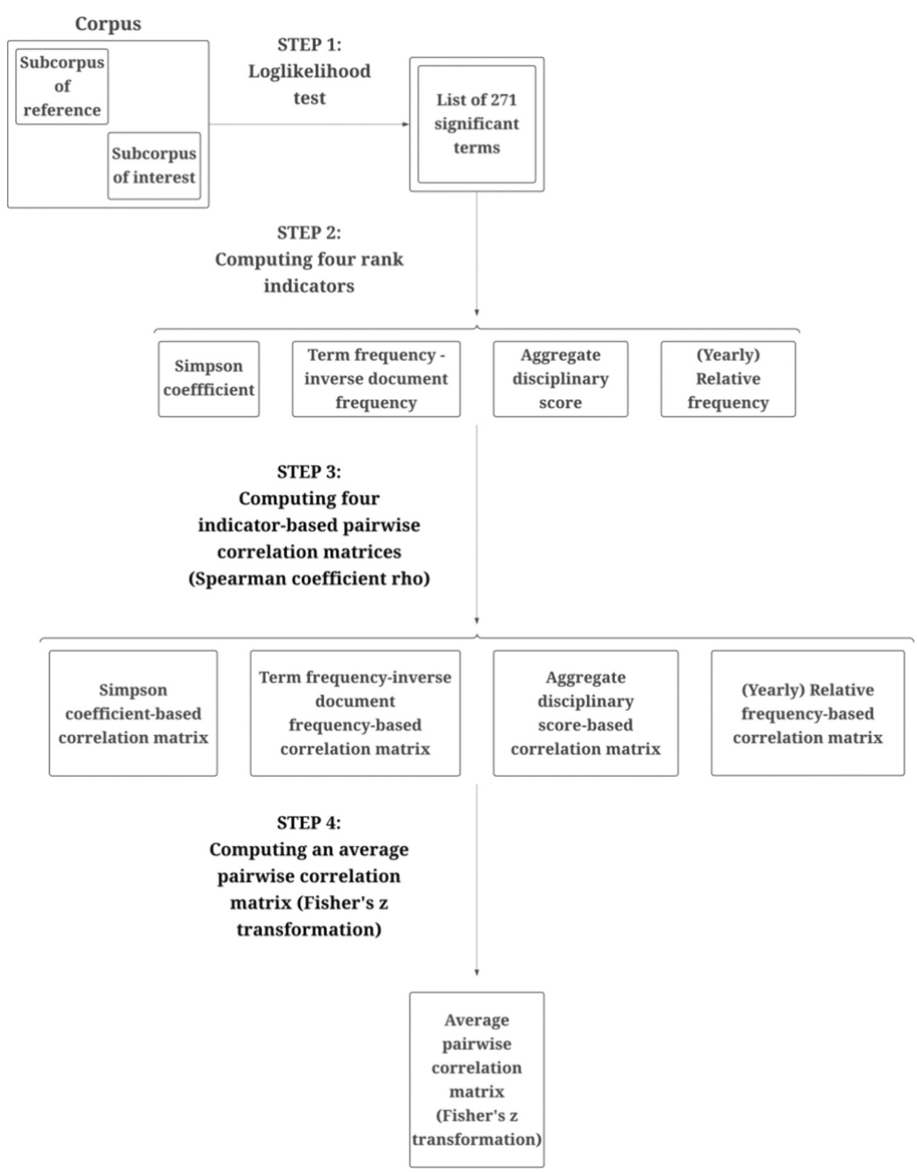


Fig. 2. Computational linguistics and text mining-based methodology used to analyze the corpus.

Table 1
Structuring terms for each cluster (Network-structuring terms are highlighted in bold and numbered according to their ranking order relative to the whole network).

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Network 1 (Terms only weakly co-occurring with "urban metabolism")	**1. human (2)** **2. earth (3)** **3. science (4)** **4. biophysical (5)** 5. long term	1. baltimore 2. land 3. surface 4. disturbance 5. gradient	1. effect 2. factor	**1. biodiversity (1)** 2. extraction 3. environmental policy 4. nation 5. world	
Network 2 (Lower tail of the terms mildly co-occurring with "urban metabolism")	1. case study 2. ecological network 3. hebei 4. ecological network analysis 5. network analysis	**1. urban system (2)** **2. sustainable (4)** **3. urban sustainability (5)** 4. sustainability 5. sustainable urban development	**1. waste (1)** **2. material flow (3)** 3. industrial 4. material 5. consumption	1. indicator 2. energy flow	
Network 3 (Upper end of the terms mildly co-occurring with "urban metabolism")	**1. city (1)** **2. flow (2)** **3. flow city (5)** 4. concept urban 5. urban energy	**1. urban resource (3)** 2. resource 3. consumption waste 4. sustainable urban 5. consumption resource	**1. metabolic (4)** 2. metabolic process 3. urban level 4. metabolic system 5. case study beijing		
Network 4 (Terms strongly co-occurring with "urban metabolism")	**1. metabolism (1)** **2. urban (2)** **3. metabolism research (4)** **4. metabolism assessment (5)** 5. method urban	1. **metabolic flow (3)** 2. material urban 3. lisbon 4. category material 5. waste output	1. urban metabolic system 2. development beijing 3. analysis urban metabolic 4. model development case study beijing	1. urban scale 2. analysis system 3. flow region 4. regional urban 5. control relationship	1. metabolism model 2. urban living 3. potential application 4. application city

methodological details).

4. Discussion

This section provides an interpretation of the four networks based on the three core questions outlined in Section 2 ("Whose agency?", "What is acted upon?", and "How, where, and when?") by identifying concepts cognate to the UM notion. For each network, we analyze the dominant clusters. Moreover, for each dominant cluster, we assess what kinds of answers the corresponding most influential cluster-level structuring terms provide to those three questions. To this aim, we rely on the context supplied by documents from the whole corpus or from the sub-corpus of interest that are particularly relevant to understanding the meaning of such most influential cluster-level structuring terms (i.e., documents especially significant for the cluster in question in which a given structuring term occurs, see Supplementary materials 17 and 18). As discussed in Section 1, the outcome is a conceptual framework comprised of UM-cognate concepts that emerge from the literature analyzed in this study and are associated with a taxonomy of different forms of structural agency.

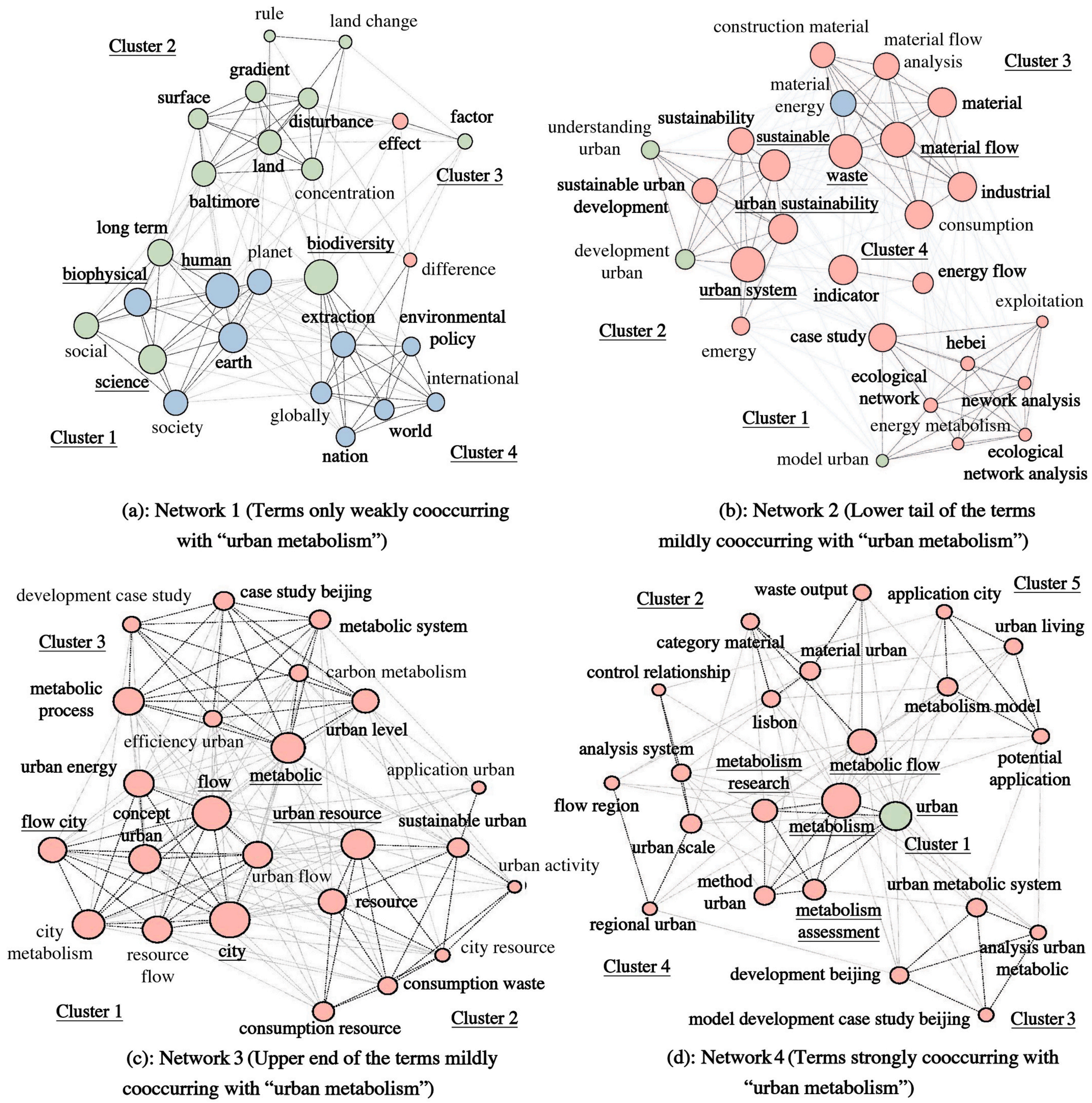
4.1. Network 1: Human agency over the integrated Earth system in the Anthropocene

4.1.1. "What is acted upon?"

The top-ranked structuring term in Network 1, "biodiversity", belongs to Cluster 4. In such a context, the documents from the whole corpus most informative about this word's meaning are – in decreasing order based on their relevance score relative to this same term (see Supplementary material 18, as well as Supplementary material 8 for further methodological details) – Griggs et al. (2013) and Schandl et al. (2018). On the one hand, Griggs et al. (2013) link "biodiversity" to "environmental policy" and "nation" in discussing the preservation of "Earth's life-support system" as a goal for sustainable development. Through the concept of "planetary boundaries" – i.e., parameter values describing the limits beyond which perturbations to core planetary processes threaten Earth's global ecological stability (Rockström et al., 2009) – they characterize the rate of biodiversity loss as a fundamental "Earth-system process" subject to anthropogenic influence. On the other hand, Schandl et al. (2018) highlight the relations between "biodiversity" and the remaining structuring terms in Cluster 4 in their analysis of a dataset tracking global material flows from 1970 to 2010 as a support for environmental policymaking. They account for biodiversity loss in nations from the Global South through the concept of "material extraction", i.e., by ascribing this loss to a worldwide acceleration in the extraction, trade, and use of materials like metal ores or fossil fuels. Accordingly, both articles contribute to defining the concept of "biodiversity" as a feature of ecosystems ranging from local areas to the whole Earth. They allow us to frame biodiversity loss as the outcome of long chains of events influenced by human-led planetary social-ecological processes like international trade. Through this concept, Cluster 4 arguably identifies the type of change introduced by the actors characterized through Network 1.

4.1.2. "Whose agency?"

The other dominant cluster in Network 1 is Cluster 1, which contains the remaining four network-level structuring terms. Within this cluster, the most influential term is "human", whose contextual meaning is illuminated by documents like Rockström et al. (2009) and Steffen et al. (2015a). Both articles rely on the concept of "planetary boundaries" to connect "human" with "earth" and "biophysical", on the one hand, and with "earth" and "science", on the other hand. Rockström et al. (2009) present a framework for studying and possibly mitigating the impact of human activities on the integrated Earth system. This framework covers various biophysical complex subsystems and processes, e.g., the biosphere and biodiversity loss. Steffen et al. (2015b) expand on it by focusing on contributions from the biophysical sciences relevant to the different boundaries. They propose a local-to-global approach to the threshold associated with each boundary by considering cross-scale interactions and identifying two core Earth-system processes whose alteration can shift the whole system's equilibrium, i.e., climate change and biodiversity integrity. By doing so, Rockström et al. (2009) and Steffen et al. (2015a) explicitly tie global human-led processes such as those described by Cluster 4 to changes generally associated with the Anthropocene concept (Crutzen and Stoermer, 2000; Crutzen, 2002). This connection suggests a conceptualization of humanity as an ecological force (Bai et al., 2016) that contributes to shaping the integrated Earth system. We can thus infer that, through Cluster 1, Network



(a): Network 1 (Terms only weakly cooccurring with "urban metabolism")

(b): Network 2 (Lower tail of the terms mildly cooccurring with "urban metabolism")

(c): Network 3 (Upper end of the terms mildly cooccurring with "urban metabolism")

(d): Network 4 (Terms strongly cooccurring with "urban metabolism")

Fig. 3. (a): Network 1, comprising nodes representing terms weakly associated with "urban metabolism". (b): Network 2, comprising nodes from the lower tail of the group representing terms mildly associated with "urban metabolism". (c): Network 3, comprising nodes from the upper end of the group representing terms mildly associated with "urban metabolism". (d): Network 4, comprising nodes representing terms strongly associated with "urban metabolism". Nodes representing structuring terms are labeled in bold. The labels of nodes representing the network's structuring terms are also underscored. In-cluster relations are represented by dashed black edges, whereas between-cluster relations are represented by dotted grey edges. At most eight nodes per cluster are depicted for increased readability. The size of each node is proportional to its influence within its network (i.e., to its eigenvector centrality). Nodes representing terms affiliated with industrial ecology, urban ecology, or social ecology are colored, respectively, in red, in green, or in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1 captures the "anthropocenic" dimension of human agency. In other words, Network 1 expresses an understanding of humanity as a global actor that constitutes a structural component of the integrated Earth system. From this perspective, humanity amounts to a pattern of connections among various individuals that collectively operate as an ecological force within the Earth system – albeit not homogeneously (Malm and Hornborg, 2014; Steffen et al., 2015b).

4.1.3. "How, where, and when?"

Network 1's Cluster 2 provides a finer understanding of how humanity exerts agency as a structural component of the integrated Earth system, notably through the term "disturbance". The most relevant document associated with Cluster 2 in which this term occurs is Grimm et al. (2017). The authors of this article deploy the concept of "ecological disturbance" as an event "[disrupting] ecosystem, community or population structure and [changing] resource, substrate availability, or the physical environment" (White and Pickett, 1985, p. 7). More specifically, they apply this concept to systems ranging from cities to the whole Earth, thus potentially bridging the gap between human agency at the urban scale and human agency at the planetary level. To this aim, they explore how shifts in disturbance regimes due to demographic and socio-economic changes can both drive global systemic alterations and affect the interactions among heterogeneous components that typify cities as integrated "urban social-ecological-technological systems" (Grimm et al., 2017). Therefore, relative to such a context, the structuring term "disturbance" and the concept it expresses – i.e., the notion of "cross-scale ecological disturbance" – characterize humanity's (anthropocenic) agency as the capacity to intervene in global chains of events through interactions unfolding along a cross-scale spatiotemporal continuum – ranging from cities to the Earth system. Relevant documents from the sub-corpus of interest like Ramaswami et al., 2012b exemplify such cross-scale dynamics. In this article, the authors outline a "social-ecological-infrastructural systems framework" that illuminates how urban social-ecological systems are embedded in cross-scale metabolic networks of resource flows, i.e., through structural connections among heterogeneous urban socio-economic metabolic actors, such as households, infrastructure designers and operators, or policy actors. Those connections are notably channeled through transboundary infrastructures – like water or electricity supplies – that serve as vectors for such a form of structural agency.

4.1.4. Overall interpretation

Through the cognate concepts expressed by Clusters 4, 1, and 2 (i.e., "biodiversity", "humanity as a global ecological force", and "cross-scale ecological disturbance"), Network 1 allows ascribing a form of structural agency to humanity as a component of the integrated Earth system. This agency is structural since it is embedded in patterns of connections among individuals and more localized forms of organization (e.g., households). Furthermore, conceived as a structural component of the integrated Earth system through the notion expressed by Network 1's Cluster 4, humanity exerts its agency by intervening in chains of events that cut across different spatiotemporal scales. The modality through which this agency is exerted – characterized by the concept of "ecological disturbance" – constitutes an agentic dimension that lies between two poles: the scale of global chains of events (e.g., global biodiversity loss) and the scale of local ones (e.g., interactions across city boundaries channeled through infrastructural systems). Accordingly, our interpretation of Network 1's meaning is consistent with recent literature highlighting the relevance of the UM concept for addressing issues faced by cities in the Anthropocene (e.g., Dijst et al., 2018; Thomson and Newman, 2018; Palme and Salvati, 2021).

Furthermore, our analysis showcases how relevant scientific literature from the field of UM studies can offer insights into the material arrangements in which human agency in the Anthropocene is embedded (e.g., groups of heterogeneous human actors connected through infrastructural systems), as exemplified by Ramaswami et al. (2012b). It also highlights that this same literature does not provide hints about how such arrangements are bundled up with systems and regimes of practices. However, our interpretation of Network 1's meaning foregrounds a connection between the literature analyzed in this paper and a body of research focusing on the nexus between social practices, human agency, and environmental policies. Such a connection is provided by the heterogeneity of the units comprising humanity as a global structural actor. This heterogeneity stems from the nature of the material arrangements in question but also from the social stratification brought about by particular kinds of practices (e.g., tax regulations advantageous to the 1 % of socio-metabolic super-rich), as highlighted by Otto et al.'s (2020) classification of human agents into socio-metabolic classes. Consequently, Network 1's meaning for future research about the metabolic dynamics underlying human agency in the Anthropocene lies in the following question: How are the social practices described by Otto et al. (2020) linked to the material arrangements highlighted, e.g., by Ramaswami et al. (2012b)?

4.2. Network 2: The abstract agency of social-ecological factors and its links to the concrete agency of stakeholders

4.2.1. "What is acted upon?"

The cluster containing the largest number of structuring terms in Network 2 is Cluster 2. It comprises "urban system", "sustainable", and "urban sustainability". In this context, the meaning of "urban system" is illuminated by documents such as Ioppolo et al. (2019) and Agudelo-Vera et al. (2012). The first document connects "urban system" with "sustainable", "sustainability", and "sustainable urban development". The authors propose a systems-based framework for categorizing and quantifying data about the metabolisms of urban systems. This framework promotes urban sustainable development by mediating between urban planning and participatory processes involving different stakeholders. It integrates material flow analysis (MFA) as an analytical tool with an urban planning decision-making system like Strategic Environmental Assessment (SEA) to manage resource consumption. The other document links "urban system" to the remaining structuring terms in Cluster 2. More specifically, Agudelo-Vera et al. (2012) discuss a UM-based method for harvesting urban resources by looping linear metabolic pathways. This method assumes that cities and their immediate peri-urban surroundings can become self-sufficient through a three-pronged strategy for reducing resource consumption: "minimizing demand, minimizing outputs, and multisourcing" (Agudelo-Vera et al., 2012). Both articles thus provide a conceptual definition of the sustainability of urban systems. This conceptualization of urban sustainability foregrounds how urban systems are influenced by a form of agency exerted through the chains of events that make up the structures of metabolic processes, e.g., the "catabolic", so to speak, processes associated with resource consumption.

4.2.2. "How, where, and when?"

The other dominant cluster in Network 2 is Cluster 3, which contains the network's top-ranked structuring term, i.e., "waste". Focusing on the sub-corpus of interest, one can identify documents that provide relevant context for how this cluster conceptualizes waste as a driver of urban metabolic processes, notably Huang and Hsu (2003) and Barles (2009). On the one hand, Huang and Hsu (2003) foreground the relations between "waste", "material flow", "material", and "consumption" by assessing the impact of urban construction on Taipei's sustainability. To this aim, they rely on a framework consisting of MFA and emergy evaluation-based quantitative indicators, including intensity of resource consumption and metabolic efficiency. They conclude that "the recycling and reuse of construction waste can not only create circular patterns of urban metabolism but is also vital to the sustainable development of Taipei" (Huang and Hsu, 2003, p. 61). On the other hand, Barles (2009) connects "waste" with the remaining four structuring terms in Cluster 3. The author uses MFA to assess how waste exports from Paris impact regional material flows by introducing two local MFA-based quantitative indicators, i.e., local and exported processed outputs (LEPO) and corrected domestic material consumption (DMC_{corr}). Both articles thus insist on the relevance of processes associated with waste consumption (waste use, recycling, reuse, and export) for fostering the sustainability of urban systems, notably by reducing or closing material flows (see also Lehmann, 2011). Based on such considerations, we can suggest that Cluster 3 expresses the UM-cognate concept of "metabolic waste consumption". This concept helps clarify how the agency characterized by Network 2 acts over urban social-ecological systems, i.e., through chains of events that make up the urban catabolic processes mentioned above in this same section.

4.2.3. "Whose agency?"

Ioppolo et al. (2019) and Barles (2009) reveal the dual nature of the agency described by Network 2, which determines the distribution of resources within urban social-ecological systems. On the one hand, there is the abstract agency of the socio-economic, ecological, or technical factors characterized by quantitative sustainability indicators such as those discussed by Huang and Hsu (2003). This specific form of agency is akin to the one ascribed to humanity as a global subject (see Section 2.2). In other words, those factors abstractly represent the real agency embodied in the resource consumption patterns enacted by human and non-human components of the urban social-ecological systems under consideration. Therefore, they abstractly represent the agency exerted by the urban metabolic structures emerging from how such human and non-human elements consume available resources, notably waste. Furthermore, this representation relies on statistical techniques and theoretical frameworks such as those underpinning MFA and emergy evaluation. On the other hand, there is the concrete agency of the various stakeholders – including planners, designers, and policymakers – who contribute to selecting those same indicators and using them to promote urban sustainability. This other form of agency is concrete since individual actors directly exert it without the mediation of any form of theoretical or statistical representation. Moreover, this form of agency is also political. It stems from social relations between different stakeholders aiming to enact specific policies or practices within a given urban social-ecological system. Such social relations thus constitute a parallel urban metabolic structure coupled with the one emerging from consumption behaviors and activities since the stakeholders comprising the former aim to shape those same behaviors and activities.

4.2.4. Overall interpretation

Through the cognate concepts expressed by Clusters 2 and 3 (i.e., "sustainability of urban systems" and "metabolic waste consumption"), Network 2 ascribes a form of agency to two kinds of urban metabolic structures: (1) the structure emerging from the patterns of resource consumption and waste generation abstractly represented by factors quantified through urban sustainability indicators, which determine the sustainability of a given urban social-ecological system; (2) the structure emerging from social relations among stakeholders aiming to shape those same consumption patterns through specific policies and practices and, by doing so, wield their own influence on the sustainability of the urban social-ecological system in question. Therefore, exerting those two forms of agency means intervening in chains of events constitutive of catabolic processes associated with urban waste consumption. Consequently, our interpretation of Network 2's meaning connects the question of the UM concept's relevance as a theoretical and practical tool for achieving urban sustainability with the methodological problem of overcoming the "black box" approach inherent in the flow accounting framework that underpins the UM concept itself (see, e.g., Zhang, 2013; Athanassiadis et al., 2015; Huang et al., 2018).

Furthermore, our interpretation of this network leads to the conclusion that UM studies can provide additional insights into how the material arrangements that make up urban waste consumption patterns are "bundled up" with networks of social relations whose goal is shaping those same patterns through practices and policies. This connection between material arrangements and practice-oriented social relations raises one further question for future research on urban metabolic dynamics, exemplified by Barles (2009). In this article, the author showcases how the "corrected domestic material consumption" indicator reveals differences in construction material flows between Paris' dense suburbs and the rest of the Île-de-France region. To identify the drivers behind such regional differences, Barles (2009) explicitly connects the detailed analysis of the factor described by corrected domestic material consumption with two broader planning and management issues: (1) the quantity and quality of housing construction in both regions; (2) the nature and intensity of the demand driving construction material flows. Consequently, the link between the two forms of agency that we identified through Network 2 pinpoints the possible interplay between two among the modes of agency discussed in Hausknost (2014). On the one hand, the mode of agency that corresponds to the agentic operator "choice", which could be used to analyze how the abstract agency of factors quantified by indicators such as corrected domestic material consumption is brought about through economic and market dynamics. On the other hand, the mode of agency that corresponds to the agentic operator "decision", which could be used to analyze how the concrete agency of stakeholders concerned with planning and management issues like those mentioned by Barles (2009) is played out through political and legal institutions.

4.3. Network 3: The agencies of sustainable resource consumption vs resource flow management

4.3.1. "What is acted upon?"

Network 3's Cluster 2 contains the network-level structuring term "urban resource". The context-specific meaning of this term is revealed by documents such as Xu et al. (2021) and Currie et al. (2017), which link "urban resource" to "resource". The first article connects those two terms by characterizing the UM concept as a "systems-oriented" approach to the sustainability of cities, understood as complex (eco) systems. By combining MFA with the classification and regression tree model (CART), Xu et al. (2021) correlate a city's socio-economic, demographic, and climatic features with a class of resource consumption patterns specific to a given type of UM. Based on this classification, they identify how the social-ecological features of urban systems influence such resource consumption patterns. In contrast, Currie et al. (2017) deploy a UM-based approach to analyze the main social-ecological processes through which resources like water, energy, and food are consumed in the city of Cape Town by focusing on infrastructure systems and urban migration patterns. Through its association with those documents, Cluster 2 arguably defines a concept of "urban resource consumption" that characterizes the chains of events targeted by the form of agency expressed in Network 3. Those chains of events constitute resource consumption patterns sensitive to specific socio-economic, demographic, infrastructural, etc. features of particular urban social-ecological systems.

4.3.2. "How, where, and when?"

Network 3's top structuring term, "city", is contained in Cluster 1. The contextual meaning of this term is illuminated by documents from the sub-corpus of interest, such as Ramaswami et al. (2012a) and Pincetl et al. (2016). On the one hand, Ramaswami et al. (2012a) connect "city", "flow", "urban energy", and "concept urban" by deploying the notion of "urban carbon footprinting". They argue that this notion sheds light on urban sustainability by combining MFA with greenhouse gas emission accounting-based methods for calculating the environmental footprints of different aggregates of material and energy flows (e.g., the flows driven by infrastructures vs those driven by household consumption). This dual perspective aims to underscore "the diversity of cities and the diverse nature of resources serving cities" (Ramaswami et al., 2012a, p. 785). On the other hand, Pincetl et al. (2016) link "city" to "flow", "urban energy", and "flow city" by suggesting a UM-based methodology for correlating the intensity of energy use in urban systems with various socio-economic and technical features of those same systems (e.g., customer wealth or building size). They claim that this methodology provides an assessment of energy use that is reflective of urban morphology and helpful for setting energy conservation and efficiency policies. Both documents thus suggest that, by conceptualizing cities as heterogeneous systems, Cluster 1 highlights the specific features of urban social-ecological systems that determine the modality through which the form of agency characterized by Network 3 is played out: e.g., urban morphology, wealth, or demography.

4.3.3. "Whose agency?"

Cluster 3 comprises "metabolic" as another structuring term in Network 3. The contextual meaning of this term is determined through documents from the sub-corpus of interest like Zhang et al. (2009) and Zhang et al. (2022). On the one hand, Zhang et al. (2009) link "metabolic" to "metabolic process", "metabolic system", and "case study beijing". The authors developed an emergy-based system of quantitative indicators for characterizing factors – i.e., "flux, structure, intensity, efficiency, and density" (Zhang et al., 2009, p. 1692) – likely to convey information about Beijing's metabolic status. In other words, this system of indicators quantitatively assesses how Beijing – as an urban metabolic system – extracts, processes, consumes, recycles, and discards material, energy, and monetary resources. On the other hand, Zhang et al. (2022) connect "metabolic" with "metabolic system" in their characterization of Hefei's multiple-source organic solid waste metabolism through MFA and ecological network analysis (ENA). In this case, the authors identify five metabolic nodes – the environment, the agricultural sector, the manufacturing sector, recycling industries, and household consumption (Zhang et al., 2022, p. 990) – and note that the dominant ecological relationships among such nodes are ones of control and exploitation (Zhang et al., 2022, pp. 993–995). Although their authors conclude that the urban social-ecological systems analyzed are far from reaching sustainability, both documents identify structures emerging from within such systems that can contribute to regulate excess resource consumption, e.g., the emergence of mutualistic/symbiotic relationships among socio-economic sectors as metabolic nodes (Zhang et al., 2022, p. 993) or a trend towards the relative decoupling between GDP and metabolic flows (Zhang et al., 2009, p. 1695). Consequently, Cluster 3 pinpoints two structural forms of agency relevant to metabolic resource flows and sustainable development in urban social-ecological systems. The first is the structural agency of the ecological networks through which resource flows are distributed and consumed within a system. The second is the agency exerted by emerging structures whose ecological function is to manage those same flows and ensure the system's overall sustainability. Both forms of agency thus fall under the concept of "metabolic system and process" implicitly contained in documents such as Zhang et al. (2009) and Zhang et al. (2022).

4.3.4. Overall interpretation

The cognate concepts expressed by the clusters in Network 3 (i.e., "urban resource consumption", "cities as heterogeneous systems", and "metabolic system and process") reveal how assessing and promoting the sustainability of urban social-ecological systems depends on grasping the connection between two distinct forms of structural agency exerted by: (1) the metabolic networks through which resources flow in social-ecological systems and are consumed by different metabolic nodes; (2) the structures emerging from within those same systems and whose ecological function is managing resource consumption. Both agencies affect chains of events constitutive of resource consumption patterns that are, in turn, determined by specific features of urban social-ecological systems. The modality through which such agencies play out is structured by the dichotomy between resource consumption and resource consumption management. Furthermore, relevant documents like Zhang et al. (2009), Ramaswami et al. (2012a), Currie et al. (2017), and Zhang et al. (2022) highlight how developing UM-based analytical tools can provide valuable information for improving urban sustainability strategies. Such improved strategies might, in turn, inform the development of additional analytical tools by producing new data and raising new scientific questions. Therefore, we can interpret the information provided by Network 3 as signaling the existence of an epistemological and practical feedback loop between the twin processes of resource consumption and resource consumption management.

This interpretation of Network 3 pinpoints issues similar to those discussed in our overall interpretation of Network 2 (Section 4.2), notably the interplay between forms of agency that can be analyzed through different agentic operators (Hausknost, 2014). For instance, Zhang et al. (2009) and Zhang et al. (2022) explicitly frame their methods as scientific tools for promoting a sustainable management of urban resource flows by optimizing the metabolic status of urban social-ecological systems. Accordingly, relevant documents associated with Network 3 suggest that the agency exerted by metabolic structures devoted to resource consumption management can be understood from two perspectives. On the one hand, since they can be modeled as ecological relationships within an ENA-based framework, the relations from which such structures emerge can be parsed through the agentic operator "solution", i.e., the agentic operator of science and technology. From this standpoint, resource consumption management within urban social-ecological systems can be understood as a natural process to be influenced with the tools of science and technology. On the other hand, those same relations are also socio-economic, meaning they can be framed through the agentic operator "choice", i.e., the operator that characterizes economic exchanges carried out through social institutions, like the market. Therefore, our interpretation of Network 3 reveals the dual nature of the form of agency embedded in resource consumption management. Furthermore, this duality raises the question of characterizing and exploring the connection between material arrangements and social practices in the case of metabolic structures such as those discussed in this section. Since those structures are represented as emerging from ecological relationships, to which extent can such relationships be regarded as material arrangements or, in contrast, as social practices? Moreover, if those relationships are viewed as social practices, what institutional strategies could be implemented to change them, e.g., based on the framework developed by Hausknost et al. (2018)?

4.4. Network 4: The cybernetic agency of urban subsystems as metabolic actors

4.4.1. "What is acted upon?"

Network 4's most influential term, "metabolism", belongs to Cluster 1, along with three other network-structuring terms. Two documents from the sub-corpus of interest likely to illuminate this term's meaning are Dakhia and Berezowska-Azzag (2010) and Musango et al. (2020). On the one hand, Dakhia and Berezowska-Azzag (2010) use the concept of "institutional ecological footprint" (IEF) to connect "metabolism", "urban", and "metabolism assessment". Through this concept, they develop a model of cities as "complex open dynamic systems" (de Rosnay, 1975, pp. 134-136) and showcase how political and legal institutions, instruments, standards, and programs can act as control mechanisms that regulate metabolic resource (energy, matter, water, etc.) flows within such systems. On the other hand, Musango et al. (2020) link "metabolism" to the remaining four structuring terms in Cluster 1. The authors draw attention to the need for effectively tracking and quantifying metabolic resource flows to empower urban planners with relevant knowledge. To this aim, they propose integrating social, political, and legal relations within UM-based assessments of sustainable urban development indicators through the concept of "informal city metabolism". Accordingly, in association with such documents, Cluster 1 characterizes the concept of "urban metabolism" as describing an urban metabolic system sustained by resource flows that constitute precisely the chains of events targeted by the forms of agency expressed in Network 4.

4.4.2. "How, where, and when?"

Cluster 2 comprises the second most influential structuring term in Network 4, i.e., "metabolic flow". One document particularly relevant for analyzing this term in such a context is Zhang et al. (2006). This article connects "metabolic flow" with "waste output" based on a view of cities as complex urban ecosystems comprising three main subsystems: society, economy, and nature (Zhang et al., 2006, p. 78). More specifically, the authors frame urban resource flows as materially analogous to metabolic pathways and the production of urban waste as materially analogous to the production of metabolites. Within this framework, they deploy specific indicators to describe and quantify the determinants of those same metabolic pathways. Such determinants are the interactions between the developmental paths followed by the three subsystems (notably the interactions between socio-economic developmental pressures and the environment's carrying capacity) under the constraints imposed by the complex urban ecosystem's overall metabolic capacity. Accordingly, the indicators deployed by the authors rely on three indices reflecting how ecologically developed a complex urban ecosystem is – i. e., the developmental degree, the harmonious degree, and the recycling degree. Therefore, Zhang et al.'s (2006) definition of "metabolic flow" arguably describes the modality through which the agency identified by Network 4 shapes urban resource flows. This modality is analogous to a process of ecological development during which resources are distributed within the (eco)system as a function of specific interactions among its component subsystems.

4.4.3. "Whose agency?"

In sum, Network 4's Clusters 1 and 2 identify the resource flows that pass through an urban metabolic system as targets for a form of agency embedded in ecological relations and interactions among the components of this same system. This characterization is consistent with how Cluster 3 defines the actors exerting such a form of structural agency. More specifically, Cluster 3's most influential term is "urban metabolic system", whose meaning is elucidated by two documents from the subcorpus of interest. The first is Zhang et al. (2013), which connects the structuring terms "urban metabolic system" and "model development case study beijing". The second is Yang et al. (2014), which links "urban metabolic system" to "development beijing". Both documents use ENA-based methods to uncover the metabolic actors that comprise the overall structure of an urban metabolic system, i.e., the component subsystems that can be identified through those same methods. Such subsystems are structures per the definition outlined in Section 2.4 since they correspond to different production or consumption sectors (e.g., mining or domestic consumption), i.e., patterns of physical and socio-economic connections among individuals and narrower forms of organization (e. g., households or firms). Their mutual relations shape the overall structure of the social-ecological system in which they are integrated. Accordingly, we can infer that the concept of "urban metabolic system" defined by Network 4's Cluster 3 characterizes such subsystems as metabolic actors whose target is precisely the structure of the urban social-ecological system they comprise. Their agentic influence is expressed by ecological relationships driving metabolic flows like the ones described by Network 4's Cluster 2. Furthermore, Zhang et al. (2013) and Yang et al. (2014) frame the ecological relations expressing the agentic capacities of those subsystems as mutual input-output exchanges. From this perspective, such relations can be quantified and categorized as exploitation, control, competition, synergy, or mutualistic relations based on how the various inputs and outputs are eventually distributed within the overall system itself. Those exchanges thus constitute the global structure of an urban social-ecological system as an "ecological hierarchy" (see Yarrow and Salthe, 2008). The reason is that the different component subsystems can be ranked according to their respective contribution weights to the aggregate throughflow of the metabolic network running through the system itself (Yang et al., 2014, p. 24). In this sense, the sustainability of an urban social-ecological system relies on the dynamic balance between different types of exchanges between its component subsystems, i.e., between the structural forms of agency that the latter exert on each other and, indirectly, the whole system.

4.4.4. Overall interpretation

Through the cognate concepts defined by Clusters 1, 2, and 3 (i.e., "urban metabolism", "metabolic flow", and "urban metabolic system"), Network 4 conveys a view of urban social-ecological systems as "cybernetic systems". Cybernetic systems are "a special class of cause-and-effect (input-output) systems in which input is determined, at least in part, by output" (Patten and Odum, 1981, p. 886) through feedback loops and control mechanisms. Accordingly, this network characterizes what we might call "the cybernetic agency" that an urban social-ecological system's component subsystems exert on one another and, indirectly, on the whole system. This agency is exerted by altering the chains of events through which input-output exchanges among the system's components are enacted within a broader hierarchical structure. Such exchanges, shaped by ecological dynamics, determine how sustainable an urban social-ecological system is. Furthermore, the modality through which the cybernetic form of agency described by Network 4 is played out – characterized by the concept of "metabolic flow" – constitutes an agentic dimension defined by the relations between two levels: (1) the whole and (2) its constitutive parts. However, as evidenced by Dakhia and Berezowska-Azzag (2010) and Musango et al. (2020), the exchanges through which this cybernetic agency unfolds are also determined by political, institutional, and legal factors. Consequently, Network 4 points to a cybernetic form of agency that results from and is embedded in a network of ecological interactions among the components of an urban social-ecological system, which is consistent with Schatzki's (2002, 2014) definition of "material arrangement". The material arrangements constituted by such ecological networks are bundled up with webs of institutions, laws, instruments, legal standards, programs, and mechanisms enabling stakeholder participation (see, e.g., Dakhia and Berezowska-Azzag, 2010). Each of those webs can be regarded as a meshwork of social practices, per Schatzki's (2014) characterization, which contributes to shaping the material arrangement – i.e., in this particular case, the ecological network – with which it is associated. Thus, both components are needed for the cybernetic agency described by Network 4 to play out.

In sum, when interpreted through the conceptual framework outlined in Section 2, the semantic networks yielded from our analysis characterize four structural forms of agency embedded in the UM, which can be ranked according to the distances of their respective cognate concepts from the UM concept. Such distances are expressed by the magnitudes of the pairwise Simpson coefficient values of the various cognate terms relative to the word "UM" itself. From this perspective, the four forms of agency constitutive of the UM concept can be visualized through the agentic pyramid depicted in Fig. 4.

4.5. Limitations and outlooks for future research

In terms of limitations of our study, first, our results necessarily reflect the quantitative bias of our source documents towards industrial ecology. Second, the effectiveness of the text mining and computational linguistics methods we deployed heavily depends on the text preprocessing techniques we chose (see, e.g., Hickman et al., 2022). Third, the relations among terms revealed by our semantic networks rely upon correctly estimating quantitative correlations by selecting the most suitable metrics (e.g., Pearson or Spearman coefficients), upon which there is no consensus (see van den Heuvel and Zhan, 2022).

Notwithstanding such limitations, the characterization of agency in the UM provided by our conceptual framework entails that urban sustainability depends on the interplay between agencies specific to actors, structures, and processes influencing urban social-ecological systems at different levels: humanity as a whole with its structural agency upon the integrated Earth system; stakeholders influencing UM processes; the agency of abstract factors influencing the distribution of local UM resources which can be contrasted with that of the socio-economic sectors shaping the UM as component subsystems through their ecological interactions; the agency embedded in resource consumption and resource management practices; and finally the cybernetic agency of the ecological networks structuring the UM. All these forms of agency can be understood in connection with "agentic operators" (Hausknost, 2014) and, as such, used to explain the connections between material arrangements and social practices. In this sense, our work can contribute to ongoing experimental applications of the SFP nexus approach in social ecology by expanding the link with Schatzki's practice theory and providing a deeper understanding of the influence of different social

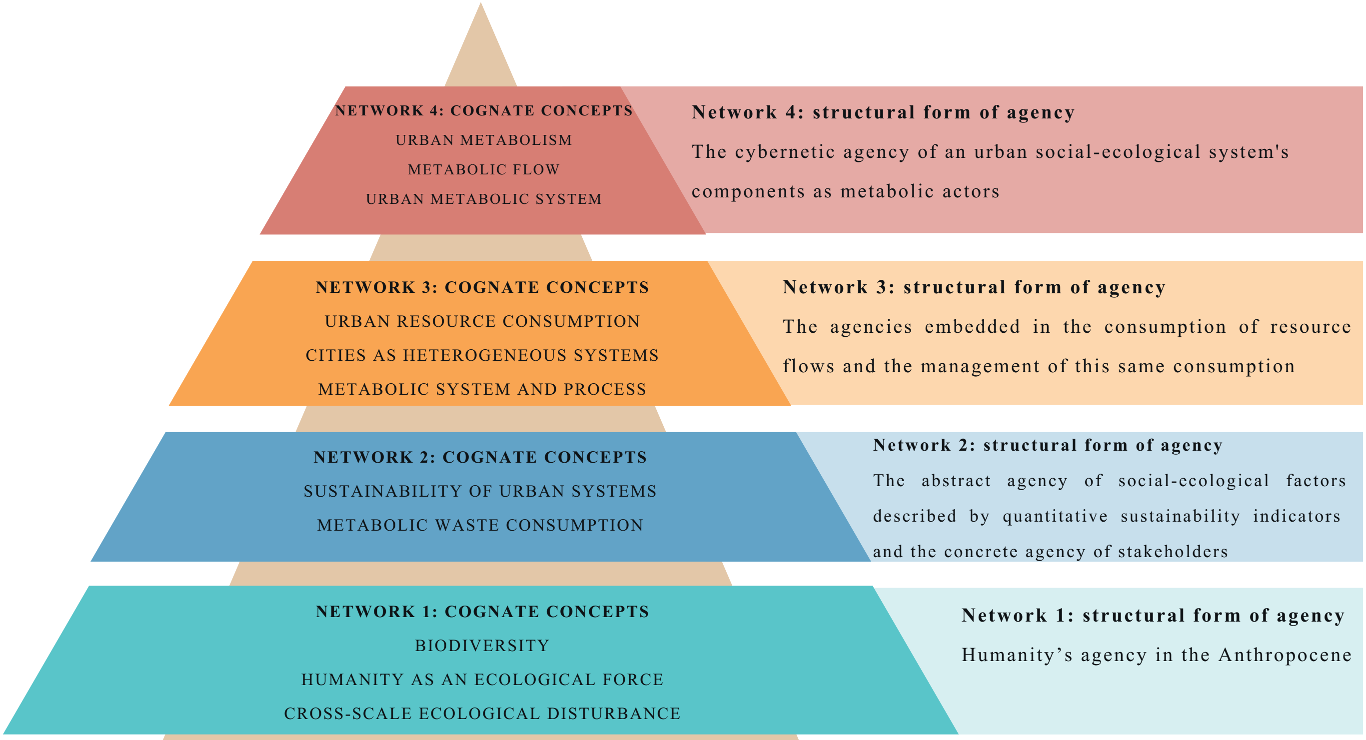


Fig. 4. Pyramid of the structural forms of agency we identified. The breadth of each layer visualizes the distance of the corresponding form of agency from the core of the semantic field associated with "urban metabolism", as measured through the Simpson coefficient.

practices and practice patterns on resource stocks and flows through our characterization of different modes of agency underpinning the UM.

5. Conclusions

Drawing on the theoretical background in social ecology, industrial ecology, and social practice theory discussed above, this study presents a literature-based conceptual framework that can contribute to moving beyond the structure-agency dichotomy in systems-based approaches to UM research. On the one hand, the various forms of agency we identified highlight how agency is both enabled and constrained by the social structures through which it plays out. On the other hand, those same (structural) forms of agency showcase how social practices are levers to influence and potentially change social structures. However, the level of agentic influence on social structures always depends on the actors involved.

Such conclusions align with ongoing efforts in social ecology research by connecting the different agencies underpinning the UM to social structures (which are, in turn, embedded in biophysical structures) via social practices as multifaceted and routinized patterns of actions. Moreover, in line with Hausknost et al.'s (2016) recommendations, our results pinpoint how urban social-ecological systems and actors can be regarded as "structurally coupled" by adopting a systems ecology perspective on the UM (E. P. Odum, 1977; H. T. Odum, 1983), i. e., by characterizing the agency of component subsystems that shape and are shaped by the corresponding urban system's overall hierarchical structure via mutual functional ecological relations. Last but not least, our analysis reveals how methodological problems concerning the sustainability of urban social-ecological systems are also political-economic issues since analyzing and predicting UM processes means considering parameters and indicators that depend on policies influencing how resources are distributed across space and time.

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CRediT authorship contribution statement

Nicola Bertoldi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Daniela Perrotti:** Writing - review & editing, Validation, Methodology, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The data supporting this study's findings and the code used to analyze those data are included in the present submission as supplementary materials. They are also available in Zenodo, respectively, at https://doi.org/10.5281/zenodo.8385964 and https://doi.org/10.5281/zenodo.12747263, following an embargo from the date of publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2024.108397.

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