Chapter 2

Urban metabolism: old challenges, new frontiers, and the research agenda ahead.

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In Urban Ecology: Emerging Patterns and Social-Ecological Systems. Verma, P., Singh, P., Raghubanshi A.S., & Rishikesh, S. (eds.) Elsevier, Cambridge, MA, p.17-32. https://doi.org/10.1016/B978-0-12-820730-7.00002-1
Preprint July 2020

Abstract: The "Urban Metabolism" concept has in recent years gained popularity in urban sustainability research and still thrives in disciplinary fields as varied as urban ecology, industrial ecology, political ecology, and political-industrial ecology. The popularity of the concept stems from increased recognition of the need for a whole system approach to better understand the challenges resulting from cities' ever-growing demand for natural resources and their environmental impacts. Beyond the concept, the urban metabolism field provides analytical tools and methods to assess the resource-intensity of cities and associated waste and pollutant rejection.

Despite recent efforts to unlock key technical aspects of the most popular assessment methods through, for example, a growing number of science-policy collaborative initiatives, urban metabolism research has not yet consistently delivered on its promises. This article concentrates on three main challenges identified from analysis of recent literature and retrospective evaluations of previous research: the persistence of conceptual and methodological silos across urban and industrial ecology, the still limited understanding of the interdependence between biophysical and socioeconomic aspects of the metabolism of urban systems, and, finally, the missing link between urban metabolism analysis and the implementation of real-world design solutions. The discussion of these three challenges offers the opportunity to identify

new research frontiers for the field and to outline a tentative research agenda for urban metabolism as a framework for better integration of urban disciplines and for strategic investigation and action on the ecology *of* the city.

Key Words: Biogeochemical cycles; Ecosystem services; Material flow analysis; Nature-based solutions; Urban design.

1. Urban Metabolism: from concept to methods

1.1. One concept, a variety of methods

Urban metabolism (UM) is an interdisciplinary research field, spanning across disciplines as different as industrial ecology, urban ecology, political ecology, and political-industrial ecology (Wachsmuth, 2012; Castàn Broto et al., 2012; Newell et al., 2017). Each of these disciplines encompasses different schools, which focus on a wide range of methods and diversified scales of analysis. In quantitative terms, industrial ecology is the most influential research path in UM studies (Newell and Cousins, 2014). Industrial ecology approaches to resource accounting have extended beyond the original focus on the metabolism of industrial systems and industrial symbiosis to include the broader scale of cities (Bai, 2007; Kennedy et al., 2012). In industrial ecology, UM is defined as "the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2007). In UM research, cities are studied as open systems whose metabolism is the result of the interactions with other (close or remote) anthropogenic systems and the natural environment. Beyond the concept, industrial ecology UM research provides analytical tools and methods to assess the resource intensity of urban systems and, when applied in policy and practice, to enable resource use optimization.

Material Flow Analysis (MFA) is the most used method for resource accounting in industrial ecology (Cui, 2018; Kennedy et al., 2011). Rather than a single model, it consists of a family of mass-balance models that can vary from national to local scales and includes aggregate materials and energy accounts as well as assessments of a single material or substance. The Eurostat's Economy-wide material flow accounting (EW-MFA) is the most widely spread method within the MFA family and represents the basis of standard statistical reporting in the EU (Eurostat 2001). The EW-MFA was introduced in the late 60s (Ayres and Kneese, 1969) and further developed in the 90s (Baccini and Brunner, 1991; Bringezu et al. 1997). It was initially conceived as a standardized method for flow accounting at the scale of national economies. Hammer et al. (2003) adapted the EW-MFA at the city and regional level, opening the path to a still growing number of applications to urban systems (e.g., Hammer and Giljum, 2006; Barles, 2009; Voskamp et al., 2017; Bahers et al., 2019). In the EW-MFA, only material input and output flows entering or leaving the system are considered, excluding in-boundary processes and dynamics associated with resource use. Hence the model results in a "black box" representation of the socioeconomic system itself. The method has in the last decades gained maturity thanks to considerable efforts by the scientific community to work consistently towards methodological harmonization and standardization across existing datasets (Fischer-Kowalski et al., 2011). In the last few years research efforts have concentrated on integrating the EW-MFA with other methods for the assessment of urban resource flows (Daigger et al., 2016) and with ecosystem services frameworks (Perrotti and Stremke, 2018). Substance Flow Analysis (SFA) belongs to the same mass-balance family of accounts as the Eurostat EW-MFA. It concentrates on the analysis of substance fluxes and key nutrients (primarily carbon, nitrogen, and phosphorus) which are assessed either separately or coupled with other fluxes. SFA applications at the city level range from analysis of individual elements responsible for human-induced water, air or soil contamination in urban ecosystems (or contamination risks) (Barles, 2010), to investigation into the mutual dependency of multiple elements in water-agro-food systems (Verger et al., 2018; Esculier et al., 2019), and to coupled material and energy fluxes in a "urban nexus" perspective (Chen and Lu, 2015).

Beyond MFA and SFA, other popular methods for resource accounting within industrial ecology include Emergy-based analysis and Energy Flow Accounting (EFA). Emergy-based analysis is characterised by the use of the "emergy" concept as a basis for resource accounting (Odum, 1996). Emergy is defined as the total amount of solar energy that is used directly and indirectly to deliver a product or a service. As exemplified in the study of Beijing from 1990 to 2004 (Zhang et al., 2009), in emergy-based analysis, the studied UM system includes the socioeconomic system and the natural subsystems (the natural capital included within the city's administrative boundaries). Solar equivalent joule (SEJ) is used as a common unit to account for all flows, including renewable sources (wind, rain, rivers, earth cycles), indigenous non-renewable resources (e.g., coal, iron ore, sand, gravel), and all other resources imported from other systems (fuels, goods, services). The emergy issued from renewable and non-renewable indigenous sources is considered regardless of the amount of final energy used in the socioeconomic subsystem. Despite the limits resulting from the use of a single unit for different energy flows and qualities (Hau and Bakshi, 2004), the emergy method provides a clear picture of the contribution of natural energy to the system's economy. Since the beginning of the 2000s, EFA has been established as an alternative method to the EW-MFA in industrial ecology research (Haberl, 2001a; Krausmann and Haberl 2002). EFA is grounded on a socio-economic perspective of the energy metabolism of human organizations and emphasizes the central role of energy flows in metabolic analysis, integrating technical energy (power and heating) with biomass flows (wood, food, feed, and bio-materials). EFA adapts the set of indicators used in MFA to account for all streams of energy (including energy from renewable sources) and energy-rich materials that cross the system boundary based on their gross calorific value, regardless of the purpose for which they are used (Haberl, 2001a). All energy inputs that build up the biophysical structures of the societies are considered alongside the biomass combusted to generate heat and/or electricity. EFA also tracks the main energy conversion processes throughout the system (primary-final-useful energy) for both technical energy (used in artefacts) and nutritional energy (for humans and livestock). The EFA's focus on biomass is essentially due to the historical perspective adopted in these studies. This allows for comparison between different types of societal organizations, such as hunter-gatherer and agricultural societies, in which technical energy from fossil sources was not as dominant as in industrial societies. System boundaries are rarely restricted to a single administrative urban unit and EFA is mostly performed at the regional, national, or supranational scale (Krausmann, 2013). Moreover, through the introduction of additional indicators such as Human Appropriation of Net Primary Production (HANPP), EFA also offers valuable insights into the relations between land use and resource flows (Haberl et al., 2006), placing human social activities (e.g., economic production or the use of technologies) in a broader ecological context (Haberl, 2001b). EFA is regarded as a valuable tool to integrate socio-economic and natural flows in a comprehensive UM framework (Golubiewsky, 2012) and can provide an interdisciplinary knowledge base for industrial ecology, ecological economics, and human ecology to jointly advance UM research (Barles, 2010).

Recent years have seen the rise of political-industrial ecology, an interdisciplinary field concerned with the cross-fertilization of epistemologies and the hybridization of qualitative and quantitative methodologies used in industrial and political ecology (Newell et al., 2017). In political ecology, socioeconomic flows of the UM are analysed as the result of the interactions between power, institutional structures, politics, social and human capital (Swyngedouw and Heynen 2003; Castan Broto et al., 2012). Criticisms are addressed to "orthodox" industrial ecological methods for their limited engagement with the social and political challenges arising from unequal access to resources across societies or stakeholder groups (Dalla Fontana and Boas, 2019) and uneven relations of power in the governance of natural resources (Gandy, 2004).

On the urban ecology side of the UM research spectrum, synergies and trade-offs between environmental and social concerns were central to the studies carried out since the 1970s within the UNESCO–Man and the Biosphere Programme (UNESCO, UNEP 1971). Follow-up research by the United Nations University Institute for the Advanced Study of Sustainability (UNU-IAS, former United Nations University Institute of Advanced Studies) has allowed fostering an "urban ecosystems" approach to resource management and policy development in cities (Marcotullio and Boyle, 2003). Similar interdisciplinary questions were explored in experimental programmes such as the Long Term Ecological Research Program in the United States (LTER) that started in the 1980s and included 24 different projects (Hobbie et al., 2003). A long-lasting dialogue across disciplines was foreseen as a means to achieve shared theoretical bases to understand cities as dynamic, complex and adaptive systems linking ecology and society (Grimm et al., 2000; Pickett et al., 2011). More recently, interdisciplinary exploratory research initiatives were carried out within the US National Science Foundation's Urban Long-Term Research Areas (ULTRA-Ex) with pilot projects developed in over 20 US cities. The program specifically tailored the opening of the "black box" of city systems and the study of the dynamic interactions between people and natural ecosystems occurring in urban settings as well as their influence on cities' liveability and the health and functionality of non-urban systems. For example, in the "Ecosystem Study of Baltimore, Maryland, and the District of Columbia-Baltimore City ULTRA-Ex" project, bio-geophysical models of water, carbon, and nitrogen cycles from the watershed to the parcel scale were coupled with econometric and structural models simulating locational choices and patterns of land development; this aimed to inform sustainability policy scenarios for enhanced water quality and carbon sequestration (Grove et al., 2013). Other urban ecology experiments include the research, development, and demonstration projects within the Public Interest Energy Research Program (PIER) established by the California Energy Commission in 1998. A research roadmap issued at the end of the program proposed an expanded energy and resource use accounting framework including life cycle cost assessment, sociodemographic data, and policy drivers underlying energy use. Outcomes of these projects provide evidence of the benefit of combining socio-economic and environmental perspectives within UM research (Pincetl and Bunje, 2010; Pincetl et al., 2012).

When navigating through the aforementioned projects, one could argue that the strong interdisciplinary focus of contemporary ecological science links back to Eugene P. Odum's original idea of a "new ecology" (Odum, 1977). E.P. Odum intended ecology as a conceptual framework and a project which should benefit society through linking physical and biological processes, combining holism and reductionism, and bridging social and natural sciences. Ecology as a new "integrative science" provides fertile soil to experiment with the integration of biophysical and socioeconomic parameters within the same system framework, bridging communication gaps and combining with economics methods (Barret and Odum, 1998; Barret, 2001). In line with this ambition, this chapter will focus on the interoperability of industrial and urban ecology methods and on the rise of new integrated approaches in ecological science as a way forward to face current challenges and identify opportunities for advancing UM research.

1.2. A variety of practical applications and end-users

Practical applications of UM research have developed in fields as varied as the definition of sustainability and environmental pressure indicators (e.g., Wood, 2012), the development of Decision Support Systems (e.g., Chrysoulakis et al., 2013), GHG emission accounting tools (e.g., Mohareb and Kennedy, 2012), and urban planning and design (e.g., Brugmans and Strien, 2014; Metabolic et al., 2015). There is nowadays a broad consensus that UM assessments can have significant impacts on the work of professional designers and planners and help streamline urban planning strategies toward resource optimization (Perrotti and Galan, 2019). For urban planners and designers, an UM perspective is key in understanding the natural and anthropogenic processes that sustain socioeconomic activities and ecological cycles in humans' physical environments. These include both present and projected spatial and temporal dynamics through which cities gather, transform, and use biotic and abiotic resources to ensure their functioning and, when relevant, growth. Applications of UM studies in design extend from mono- or multi-process engineering systems and utility infrastructure (e.g., water, heat and electricity, waste cycling) to urban form at the neighborhood and city scale. If engineering applications represent a traditional focus of industrial ecology, spatial design strategies have gained increased attention across the industrial ecology research community over the last two decades (Ibañez and Katsikis, 2014; Galan and Perrotti, 2019). A better understanding of the interdependency between scopes and scales of these two design domains is a major challenge ahead and an essential condition for enhancing the applicability of UM models in policy and practice.

Following up from the abovementioned practical applications, end-users of UM studies range from urban sustainability analysts (cf. previous section) to environmental and civil engineers, policy-makers and urban planning and design professionals. The uptake of the UM concept and the applicability of UM studies may vary substantially according to the targeted end-users, their background, expertise, specialist and tacit knowledge, urban sustainability visions, as well as specific goals and priorities (Taleghani et al., 2020). Consequently, the design of UM assessment methods with the profile of the targeted end-users in mind, or in collaboration with them, is crucial for successful incorporation of the results of UM studies in policy and urban planning practice (Perrotti, 2019). Awareness of key characteristics and needs of end-user profiles and more structured collaborative approaches for co-designing resource accounting methods can increase the meaningfulness of UM research and its relevance for policy and practice. Moreover, the integration of end-users' input (on key characteristics of the studied urban system or specific policy orientations) since early stages of the research can favour successful UM knowledge exchange between science and practice. Knowledge co-production in UM research is essential not only to favour the uptake of the UM concept by professionals but also for the development of assessment methods that can better serve practitioners' daily work and catalyse the move from research to action (Newell et al., 2019). With the considerable success known by the field in recent years, topics such as the actionability of the UM concept and UM theory and the delivery of more practice-relevant UM methods are constantly moving up in both industrial and urban ecology research agendas (Cui, 2018; Perrotti, 2019).

2. Challenges and new frontiers for urban metabolism research

2.1 Understanding distinct conceptual underpinnings and common methods across ecological sciences

There exist both conceptual differences and methodological commonalities between industrial ecology and urban ecology approaches in UM research. Understanding them can help identify common grounds and opportunities for cross-fertilization and more integrated work.

On the conceptual level, a main difference between industrial ecology and urban ecology approaches consists of their use of the "organism" analogy (industrial ecology) and the "ecosystem" concept (urban ecology) to refer to the city and to study its metabolism. A recurring tendency to use these two terms nearly interchangeably could be observed in industrial ecology studies until at least a few years ago (Golubiewsky, 2012; Kennedy, 2012). Interdisciplinary work across the two communities (Newell and Cousins, 2014; Bai, 2016) has favoured substantial progress and increased clarity and consensus on the fact that rather than organisms, cities are ecosystems and not analogous to them (Pickett et al., 1997; Grimm et al., 2008). Tansley (1935) originally coined the term "ecosystem" to describe the constant interchange among organic and inorganic components in a biome, i.e. between the living organisms (individual plants and animals) and between these and all the inorganic elements that compose their environment. He did not attempt to translate these interchanges into energy and material flows, which was done later by Lindemann (1942), with the metabolism idea applied to ecosystems subsequently popularized by Odum (Fischer-Kowalski, 1998), nor he referred to human-dominated or urban ecosystems in particular. However, his contribution has the merit to have opened the discussion on which level is the most appropriate to study a city's degree of heterotrophy through consideration of the relationship with its environment and among its biotic and abiotic components (Golubiewsky, 2012). The urban ecosystem concept as defined in contemporary urban ecological science (Cadenasso and Pickett, 2013) is grounded in an understanding of cities as human-dominated systems (and, as such, different from "natural" and said "wild" ecosystems), characterised by interrelations and feedback loops among material cycles and energy flows (rather than linear input-output dynamics). Here regulating and governing mechanisms such as policy and planning play a crucial role in shaping social and ecological processes (Bai, 2016). Differentiating between the "organism" and "ecosystem" levels when referring to cities from an UM perspective is more than a question of semantics. Confining UM within the limits of the organismal analogy can limit the effective use of scientific principles and frameworks in analysing how cities function and their relationship with the surrounding environment, as well as hamper the consolidation of a common knowledge base for more interdisciplinary work (Golubiewsky, 2012). In general, moving beyond organismic and biological metaphors to properly organize comprehensive knowledge frameworks and city-specific system analytics reflects a growing concern in systems thinking (Yang and Yamagata, 2019). A call for different urban disciplines to coalesce around a "new science of cities" has been expressed in the last decade (Batty, 2013), stressing the need for streamlining theory and methods to better describe the intricate structure of the networks and flows that compose urban systems.

From a methodological standpoint, mass balance methods are used in both industrial and urban ecology to measure urban resource flows in order to understand drivers of human control upon them. Input-output studies of biogeochemistry fluxes (water, nutrients, carbon, and other substances) and flows of useful and waste energy in ecosystems have a strong research tradition in urban ecology (McHale et al., 2015). Complementarily, industrial ecology EW-MFAs of cities concentrate on the account of flows of materials and technical energy that make up the economy of urban systems. MFA studies that consist of a mass-balance model for a single element (e.g., metals) normally concentrate on the pools and fluxes required for economic consumption, manufacturing and recycling process, as well as on waste generation. In general, industrial ecology studies focus on applications in human-dominated processes and systems, although using the same mass balance methods as in ecosystem ecology. The call for combining engineering with traditional biogeochemical models has been already expressed more than a decade ago, pointing, for example, to the need for the refinement of mechanical urban water modelling with data on soil and water processing through vegetation (Kaye et al., 2006). Building on common mass-balance methods, cross-fertilization between the two families of models can lead to the development of more comprehensive UM knowledge frameworks. Multi-element mass-balance accounts can help identify the links between socioeconomic and biophysical UM dynamics as well as help understand the coupling and decoupling between human-dominated flows and biogeochemical cycles in cities (Bai et al., 2016).

2.2 Expressing interdependency between biogeochemical cycles and socioeconomic flows of the urban metabolism

In industrial ecology, the need to expand traditional engineering accounting models and to couple them with urban ecology methods has been expressed in previous research (Pincetl et al., 2012; Perrotti and Iuorio, 2019). For example, the use of the ecosystem service concept and the integration of provisioning and regulating services in the Eurostat's EW-MFA can help express the contribution of urban green infrastructure towards the optimization of UM flows (Perrotti and Stremke, 2018). More generally, the incorporation of urban biogeochemical models in material and energy flow studies can help assess the biotic-abiotic interactions occurring heterogeneously within the urban natural capital (currently only scarcely accounted in industrial ecology research) as a part of the UM (Perrotti and Iuorio, 2019).

In urban ecology, an "ecology *of* the city" approach (as complementary to an "ecology *in* the city") has emerged in the 1990s as a project aiming at broadening the focus from just the vegetated areas to the entire urban social-ecological system and to reflect the multidisciplinary scope of urban ecological sciences (Pickett et al., 1997a; Grimm et al., 2000). This approach strives for synthesizing human and social behaviours alongside purely ecological dynamics of specific species and organisms and for opening the "black box" of urban systems to look into their physical, biological, and social heterogeneities (Cadenasso et al., 2007, 2013).

Integrated socioeconomic and biogeochemical understanding of the UM in industrial and urban ecology becomes even more relevant when moving from analysis to policy implementation and action. Human-subsidized biogeochemical flows have been demonstrated to have a strong impact on biodiversity and the provision of ecosystem services in cities (DeStefano and DeGraaf, 2003). Hence their intensification as a consequence of strategies aiming at enhancing cities' self-sufficiency (e.g., intensification of urban agriculture initiatives) may result in ecological misfunctioning of both the urban system itself and the surrounding habitats (e.g., eutrophication of waterbodies) (Perrotti 2012; Bai, 2016). This suggests that differentiation of resources based not only on quantity (mass) but also on the quality of the embodied substances (nutrients) is central to the design of effective resource optimization strategies. For example, in the case of water management policy, harmonization of quality and quantity accountings, linking analysis of the magnitude of wastewater flows with geochemical composition of nutrient flows and sediments (water quality parameters and pollutant concentration) can point to opportunities for water harvesting at the plot level and, potentially, sewage separation projects. Urban MFA studies in which water flows are accounted as a part of the total material balance traditionally do not include storm water in the wastewater flow and only concentrate on sewage from piped/drinking water (e.g., the MFA of Sydney, Newman 1999). A recent MFA of Amsterdam is amongst the few exceptions (Voskamp et al., 2017). Storm water flows are accounted alongside piped drinking and non-drinking water since both flows are treated at the main local, publicly-held treatment plant (combined sewage) which implies higher operational, management, and maintenance costs for the local authority. When coupled with geochemical analysis of storm water flows across seasons, this type of analyses can help identify the risk for chemical pollutions of soils and water bodies from runoffs. Hence they can inform decision-making on whether sustainable drainage systems (SuDSs) may represent an ecologically and economically viable option in a given context. In general, it is paramount to interpret results of industrial ecology material balance studies (such as EW-MFA) based on consideration of reactants ratios in each flow analysed (Kaye et al., 2006). Beyond the calculation of material flow mass, the relative proportion of nutrient elements in each mass unit per material flow is crucial to understand the behaviour of that flow when it becomes waste products and its impact on downstream recipients both in-boundary and within other systems. For example, in the case of water management, consideration of quality aspects should involve studying the impacts of optimized and decentralized water retention/absorption solutions to reduce runoff and flood control (e.g., bioswales, rain gardens integrated in parking lots) on sediment transport, pollutant concentrations and water quality at the watershed scale (Pataki et al., 2011). The same applies to human-controlled airflow regulation (e.g., windbreaks through screening vegetation, street trees, or, in some cases, urban form), which may represent an opportunity for passive cooling at both the building and open-space level. Consideration of air quality aspects is paramount to avoid exposure of urban populations to atmospheric pollutants and hence should be coupled with consideration of particulate matter (PM) sequestration capacity by street trees or other urban vegetation (Tiwary et al. 2009, Nowak et al. 2012). Quality aspects are indeed only rarely included in ecosystem service assessment and monitoring at the urban scale, which in general rest on GIS and remote sensing techniques and concentrate on quantification of biomass volumes (Wirion et al. 2017). Policy focusing only on reducing the magnitude of energy and material inflows to improve cities' self-sufficiency based on industrial ecology research may carry implications on ecosystem nutrients and energy provisioning structures, which can generate undesired side-effects at the urban and regional ecology scale (Bai 2016). Cost-effectiveness at the urban system level (local authorities' budgets for urban infrastructure and utility management) needs to be coupled with ecological logics which in many cases extend beyond the administrative boundaries of the studied socioeconomic metabolism. Hence, coupling ecological and economics logics as argued in Odum's new integrative science requires cross-scale analysis to overcome methodological limitations of established models and rest on the willingness of public and private stakeholders to engage in alternative governance systems to change current resource management models.

Similar concerns can be raised on the other side of the UM research spectrum. Urban-ecology-extended mass balance studies have traditionally mainly focused on human-influenced ecological processes and the biogeochemical cycles of key nutrients such as carbon, nitrogen, and phosphorous (Churkina, 2008). They need to be further expanded to incorporate also the study of other purely anthropogenic material and energy flows (including products and wastes) (Bai, 2016). A sign of relevant progress in this direction comes from the increasing number of studies incorporating both MFA and SFA methods as a means to establish a broader knowledge base on potentials for optimization across ecology and economy (Cui, 2018). They provide an accounting of anthropogenic flows and cycles linked to manufacturing and consumption, such as fossil fuels, water, and construction materials and waste (e.g., excavated soil) while illustrating the biogeochemical breakdown of UM flows and level of contamination produced by the chemical substances incorporated in them. Further, working across urban scales (from the dwelling to the city and their surrounding habitats and landscapes) can help better understand the impact of human choice on ecosystems' functioning and vice-versa. Results of multi-scalar, integrative ecological research such as the above-mentioned LTER and ULTRA-Ex projects have shed new light on how the ecologies of an urban system and its biophysical structure react to human management, intervention, policy, and design (Cadenasso and Pickett, 2013).

2.3. Linking urban metabolism research with design: systematising the growing evidence-base on nature-based solutions

It has been widely acknowledged in the literature that the reference to the UM concept is of great interest for developing analytical tools that can broaden designers' understanding of the material and energy requirements of cities and support the optimization of resource demand through urban design strategies (Galan and Perrotti, 2019). In particular, the contribution of green and blue infrastructure design towards the cycling of material and biophysical flows and emission abatement has represented a strong focus in recent research (Hansen and Pauleit, 2014). Nature-based solutions (e.g., combined heat-and-power systems from bio-waste, sustainable drainage systems for decentralized storm water management, PM capture by urban trees) provide an extensive reservoir of techniques and strategies to mitigate urban resource demand and to reduce the magnitude of associated carbon and pollutant emissions through the supply of provisioning and regulating ecosystem services (Hansen and Pauleit, 2014). Their fast growth in cities as well as the increasing uptake of the ecosystem service concept in urban policy (Hansen et al., 2015) point to the need to structurally address the role of green and blue infrastructure (and natural systems in general) in minimizing the resource-intensity of cities. Despite its relevance for UM research, there remains little evidence of how UM methods can help advance the scholarly discourse on nature-based solutions and their potential to improve resources management in cities. The EW-MFA model does not provide sufficient scope for systemic analysis of the potential of nature-based solutions to mitigate urban resource demand (Perrotti and Iuorio, 2019). Consequently, nature-based solutions are rarely addressed in UM-informed policy and circular economy action plans and often incorporated only in a restricted number of sectoral measures (e.g., energy recovery from organic waste). This limits the opportunities for systemic decision-making and the formulation of comprehensive resource-management strategies. As argued elsewhere, a new frontier in UM research consists of facilitating the application of industrial ecology mass balance methods and urban ecology biogeochemical models in the planning and design of urban green infrastructure (Perrotti and Stremke, 2018). This involves studying how engineering solutions and spatial strategies for local sourcing and production (food, energy, water, bio-based materials) can be designed to make a clear and measurable contribution towards the optimization of urban resources flows and stocks and to be assessed as an integral part of the UM. A range of evidence-based approaches are well documented in the literature but still randomly integrated into practice, triggering the question as for why these approaches are not yet "mainstream". Beyond designers' growing enthusiasm for "the fluidity of metabolic processes" (Ibañez and Katsikis, 2014), the agency of design could be deployed more strategically in order to benefit current scientific efforts towards the development of advanced and higher-impact UM accounts. A few existing nature-based initiatives already provide good examples of integrated energy and water management systems, in which recreational and ecological benefits by green infrastructure come into play (Lehmann, 2019). However, there remain little investigation on the implementation of monitoring systems that can inform a more systematic knowledge base on the metabolic gains that nature-based solutions can provide in different contexts. Additionally, designers' efforts towards metabolic optimization should not overview potential trade-offs and environmental and social disservices that nature-based solutions can cause to urban populations. These include, for example, environmental disservices generated by resource demand and related carbon footprint of services provided by park and green space facilities. For example, a study of the Barcelona Montjuic Park showed that the CO2-equivalent emissions produced by the life cycle of the energy consumed by the park's services would require a forest surface of more than 12 times the park's area to be absorbed (Oliver-Solà et al., 2008). Similar concerns can be raised for the social disservices and negative externalities on property value and community life in neighbourhoods affected by the development of green "landmarks" projects (Lehmann, 2019). As argued for the New

York City High Line, a greenway created on a former elevated railroad in Manhattan, often quoted as a paradigmatic ecological urbanism example, nature-based solutions can be detrimental to social equity and trigger gentrification processes at the neighbourhood level, which can disrupt the delicate social-ecological balance in an urban system (Land and Rothenberg, 2016). In sum, closing the loop from UM analysis to nature-based solution design and implementation requires more research into processes and strategies to systematize methods and connect findings across scientific domains, as well as research-practice joint efforts to monitor design outcomes. Such requirements reflect a set of fundamental steps towards the negotiation of a common UM research agenda, one that gives high priority to the translation of UM studies into actionable knowledge for policy and practice.

3. Conclusions: a tentative research agenda

This article has focussed on three main challenges that UM research needs to face in order to serve as a conceptual and operational framework stimulating cross-fertilization among ecological sciences and to increase impact on policy and practice. The first challenge relates to the interdisciplinary nature of UM studies and the identification of silos across urban ecology and industrial ecology as the two main disciplines offering UM assessment methods. Although the two disciplines share the same mass balance methods to quantify material and substance inflows and outflows and to measure the performance of urban systems, on a conceptual level they differ substantially in the way the urban system is defined. Moving beyond biological metaphors and engaging with the study of urban ecosystems and the biotic-abiotic interactions occurring heterogeneously within them is essential to properly organize comprehensive UM frameworks. The second challenge discussed in the article consists of broadening the

UM interdisciplinary knowledge base to facilitate the understanding of the interdependency between biogeochemical cycles (e.g., ecosystem services) and socioeconomic flows of the UM. Linking engineering and biogeochemical modelling of the UM is crucial for bridging quality and quantity assessments of material resource flows and nutrient cycling in urban ecosystems. Industrial ecology resource-optimization strategies based on the regulation of human-controlled flows within the urban system boundary (e.g., local cycling of water, soil and excavated earth, airflow control through organic or inorganic structures for passive cooling) should be considered for their impacts on the health and functionality of other ecosystems at the level of watersheds, natural habitats and regional landscapes. This involves a more flexible approach to system boundary setting without neglecting methodological requirements for scientifically-valid UM analysis and to avoid double counting. Reciprocally, urban ecology mass balance studies should be expanded beyond the accounting of human-influenced nutrient cycles (e.g., carbon, nitrogen, phosphorous) and incorporate the study of other purely anthropogenic material and energy flows (including products and wastes). The call for integrated UM accounting methods becomes even more compelling when research aims to inform more transversal urban policy and facilitate action across policy domains. Finally, the third challenge addressed in the article relates to the need for systematising the increasing reservoir of design technics and methods for the implementation of nature-based solutions in cities. This involves making sense of the growing evidence-base that landscape design research is gathering on the benefits that urban ecosystems can provide, both in terms of resource-use optimization in urban ecosystems and the health and wellbeing of urban populations. Lessons learnt from the design and implementation of nature-based solutions, through for example continued and longitudinal monitoring of impacts on material and biogeochemical cycles, can shed new light on what kind of design solutions can lead to resource-use optimization and the quality and quantity of the metabolic gains provided. Systematization of efforts across analysts' and designers' communities can also benefit the search for innovative bottom-up modelling approaches that can bridge the divide between material flow and biogeochemical cycle accountings at multiple operational levels and scales of analysis.

Learning from the discussion of the three challenges identified, a tentative research agenda can be sketched to stimulate the adoption of UM as a mainstream, comprehensive framework for investigation and action on the ecology of the city. A first focal area would revolve around prioritizing cross-disciplinary efforts for the harmonisation of languages and the establishment of a common vocabulary of concepts, which, beyond the use of metaphors, can express theoretical and methodological contributions of each scientific field to the UM discussion. A second point would aim at raising understanding of the UM "physical nexus" linking resource flows and socioeconomic consumption patterns (e.g., water, energy, food, materials), on the one hand, and the ecological productivity capacity of natural habitats, on the other hand (based on water and air quality indicators and soil composition and properties). Finally, a third research frontier would consist of setting the ground for collaborative research efforts between science and design to work across analytical and operational frameworks and optimize (or potentially upscale) solutions. Establishing a more systematic dialogue among knowledge domains would also involve identifying levers to broaden current resource-management governance bases. The proposed interdisciplinary investigation into the UM "physical nexus" could be expanded as a means to explore opportunities for a "policy nexus", bridging UM stakeholders' competencies and policy domains. Last but not least, implementing such an ambitious

UM research agenda would require addressing questions of stewardship systematically and comprehensively, for each stakeholder group in science, policy, and practice to be given the opportunity and the responsibility to be part of the UM research to be.

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