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Author response to comments on the manuscript titled "A multi-level framework for metabolism in urban energy systems from an ecological perspective"

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We kindly thank Arbabi et al. for their interest in our study on the multi-level nature of Urban Metabolism (UM). In their comments, the authors raise a number of concerns that we aim to address in the following response.

In their comment 1A Arbabi et al. present a relevant addition to our review on the need to distinguish between literature on material flow analysis and literature on Ecological Network Analysis (ENA). We would like to clarify that we have, in generic terms, reviewed the literature on ENA in our section titled *Ecological origin of urban metabolism*. Fundamentally, ENA has its roots in the economic input-output analysis developed by Leontief to analyze the interdependence of industries in an economy (Fath and Patten, 1999). According to Fath and Patten (1999) ENA is the environmental application of an input-output analysis. Although it has several different lines of investigation, the general approach of ENA is to develop network models that include all ecological compartments and interactions as well as the overall relationships and significance of each, mainly based on the food webs theories and data (Fath et al., 2007). From an ecological perspective, the common type of compartments used are producers, decomposers and consumers, which are defined based on their functions in the network. In a more disaggregated view, the different compartments may also be defined as different species (Fath et al., 2007).

The debate about the applicability of ENA to urban metabolism studies involves a theoretical discussion on the different approaches of urban metabolism and their practical contribution to the sustainability of cities (Golubiewski, 2012; Rapoport, 2011). Opponents of the way urban metabolism has been applied in the urban context argue that making explicit the resources and waste pressures of cities by describing energy and material flows does not necessarily constitute an ecological assessment (Golubiewski, 2012). Following these discussions we argue that a description of material and energy flows within the city does not necessarily provide fundamental insight in the complex nature of urban metabolism. Still, ENA presents an interesting and relevant concept for studying urban processes via the analogy where a city can be treated as a 'superorganism' (Wolman, 1965). This concept presents an alternative to analyze systems, and to define structure and functions of urban systems beyond the black box approach. However, the pertinence to use ENA for comparing urban metabolism to metabolism of ecological systems is still unresolved. In ecological systems network analysis is used for testing food web theories (Fath et al., 2007). In ecology, information about food webs is obtained from observation, where relationships between components result from dynamics at the individual or population level. In urban studies, compartments and pathways are deliberately proposed, assuming that the definition of such compartments and pathways already embraces the complexity of internal dynamics of the urban system organization. In our view, ENA therefore mostly serves as a tool to identify and quantify interactions between system components that occur at a single level. The information gained may provide guidance on, for example, questions related to how environmental pressure may be reduced by decreasing inflows from nature and outflows from waste. What remains uncertain is how ecological network analysis in the urban context may be compared to multi-level metabolism in ecological systems.

We further discussed the hierarchical organization of ecosystems and how metabolism may shape the different levels of the system organization following the metabolic theory of ecology (Brown et al., 2004; Enquist et al., 2003; Peters, 1986). According to this theory, metabolic processes that occur at the level of a single organism can influence higher-level processes via mutual constraints and information exchange. Thus, metabolic processes are fundamental to the complexity attributed to ecological systems, as described in our framework along three levels: organism, population and ecosystem. In contrast, the ENA approach examines cities by using different sectors of economy as compartments. To apply the nested condition that our conceptual framework advocates for in ENA will require further analysis in order to identify the individual constituents of each sector, and to identify how their aggregated effect determines the relationships among sectors. Importantly, ENA attributed trophic qualities (such as producers, consumers, decomposers) to sectors in the city organization (Fan et al., 2017) or to socio-economic processes (Yang et al., 2014). However, this approach disregards transactional relationships that may occur across levels due to the presumed nested nature of the urban system. The question remains how the multilevel organization of an urban system should be defined. The ENA approach using economic sectors for describing compartments and pathways based on monetary flows and financial relationships assumes that these sectors are determinant for

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studying the metabolism of a city. However, in our view, urban metabolism should embrace all interactions between society, economy and natural processes. Therefore, we advocate for a more interdisciplinary approach to studying urban metabolism.

In response to the comment 1B of Arbabi et al., we would like to clarify that we aimed to integrate concepts that are used interchangeably in between ecology and the study of urban metabolism. The first point posed by Arbabi et al. questions the pertinence of the definition of spatial scales in urban systems compared to ecological systems. The need for a disaggregated view of cities advocated for in our conceptual framework requires framing the different processes occurring in urban systems in terms of their relevant spatial and temporal. The definition of such scales is crucial to set the boundaries of the different levels of the system as they provide an indication of the degree of nestedness of the relevant (sub) systems. We agree with Arbabi et al. that such definitions of scale do not necessarily need to relate to physical and territorial area as for urban and for ecological systems. The second point posed by Arbabi et al. relates to our statement regarding the contrast between cities and ecosystems in terms of importing resources. We agree with Arbabi et al. that resources are still finite at the country and planetary boundaries. However, in our review we are proposing the analysis of the system dynamics of a city at different levels. In this sense, we contrast natural ecosystems to the current reality that resources can reach cities and their inhabitants with relatively few restrictions. Although apparent, we do not aim to discuss the disproportional exchanges between cities and their surroundings. The third point posed by Arbabi et al. raises two particular aspects concerning the validity to extent the concept of power-law relationships from individuals to other properties of species in ecological systems, and the pertinence to advocate for it in urban energy systems. We recall the metabolic theory of ecology which provides the foundations of our conceptual framework (Brown et al., 2004). According to these authors, the metabolic theory predicts how metabolic rate controls ecological processes at all levels of organization. Therefore, we argue that the same principles of allometry can be used to understand fluxes of energy and materials in organisms and ecosystems. We agree with Arbabi et al., there is no justifiable theory to predict scaling in urban systems. Still we argue that information from ecological systems may provide information on scaling in urban systems, especially when considering resource supply constraints. Moreover, we would like to clarify that, even though linear relationships are often associated with non-complex system behavior, linear scaling relationships at aggregate scales may also be the result of interactions in complex systems. Yet, recognize the need for further analysis with regards a particular indicator that demonstrate the applicability of our conceptual framework in the urban context.

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