The place of space in urban metabolism research: towards a spatial turn?

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Highlights

- **We conduct a bibliometric analysis of spatialization in UM**
- **448 publications are analyzed**
- **We identify five main research themes**
- **20 research communities are involved in the spatial debate**
- **A spatial turn in UM research seems a possible horizon**

Key words: urban metabolism; space; urban planning; city-hinterland relations; interterritoriality

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The place of space in urban metabolism research: towards a spatial turn? A review and future agenda.

Abstract

The concept of urban metabolism has been profusely used by various disciplines over the last and current century to describe different urban phenomena. One theme that appears to gain importance in the interdisciplinary field of urban metabolism is the spatial dimension. In this article, we have carried out a bibliometric and qualitative analysis of the use of this multi-faceted notion in order to understand the place of space in urban metabolism research. Our results show that several communities within the urban metabolism field use and manipulate space for their research according to different approaches (territorial economic, socio-political, socio-ecological, governance and urban planning, and modeling). We discuss recent contributions of these communities and their approaches, their limitations, and a future agenda that might cross-fertilize them in order to embed space more consistently in urban metabolism research.

I. Introduction

The world is rapidly urbanizing, resulting in ever-increasing resource requirements and pollution flows. It is now estimated that cities are responsible for 80% of global energy consumption and more that 40 billion tons per year (since 2010) of materials are extracted-transformed-transported by urban technical networks (IRP 2018). As a consequence of this mobilization of matter and energy, cities are also responsible for 65% of global atmospheric emissions (IRP 2018). Urban Metabolism (UM) is an interdisciplinary concept that studies how cities interact with the environment and more specifically how they use resources and emit pollution flows as well as the associated societal, economic and environmental challenges around these flows. UM research thus attempts to better understand the functioning of cities by characterizing and understanding all socio-technical and socio-ecological processes by which flows of materials, energy and water are consumed, transformed and rejected in different forms by cities. Over the last century, the UM concept has been profusely used to describe, by various academic disciplines, the above-mentioned urban socio-technical phenomena. Josh P. Newell and Joshua J. Cousins (2015) have highlighted that within UM, different disciplinary fields exist which in turn have created islands of knowledge with quite distinct boundaries between them. Yet, one recurring aspect that can be found in each of these islands of knowledge is to acknowledge the importance of the spatial dimension of UM. Reciprocally, UM is for some authors seen as "a series of intersections between capital and nature encompassing infrastructure, technological networks, and other functional components of urban space" (Gandy 2018, p. 102).

Yet, while the importance of the spatial dimension is recognized and highlighted by researchers from different islands of knowledge, they use the term *space* very differently in order to describe different phenomena. The polysemy of this term not only illustrates the wide range of studies and application of UM studies but also the potential confusion or discrepancies of such a disciplinary-sensitive and politically-charged term. The confusion hinders not only the generation and/or consolidation of knowledge but also its application in policy-making and practice in the fields of urban planning, economic development, resource and waste management.

In this article, we will highlight how UM researchers have included this spatial approach in their work and what this inclusion can bring to the wider UM concept. Indeed, it appears that an increasing body of research refers to and works with this notion, so much so that we can ask ourselves what “the place of space” in UM research is and whether there is a "spatial turn" in UM studies. To answer this research question, a bibliometric analysis (coupled with a qualitative analysis) was carried out to encompass the largest possible sample of publications (448 in our dataset). While many reviews on UM have been published over the last few years, none directly addresses the issue of space as the main focal point (Wang et al. 2021; Tang et al., 2021; Céspedes Restrepo and Morales-Pinzón, 2018; Cui, 2018; Dijst et al., 2018; John et al., 2019; Zhang et al., 2015, Kennedy, 2016, Broto et al., 2012). In addition, we wished to go beyond traditional review papers on UM which mainly focus on accounting and modeling techniques (i.e. the industrial ecology perspective of UM) such as Zhang et al. (2015) or Beloin-Saint-Pierre et al. (2017) and omits a considerable part of scholarship, notably in social sciences. In our opinion, the spatial dimension of UM should not be treated as universal and uniform, since it can be highly politically-charged and refers to numerous contextual socioeconomic and territorial processes.

Although, ultimately, the role of this paper is not to provide a final definition or to uniform the use of space in UM studies throughout different disciplinary vantage points, here below the authors provide a preliminary definition that helps to set a broader context for the bibliometric analysis.

Our definition of space in UM is *a physical and conceptual construct which considers space as a 1) political space, in the sense that material relationships of domination, ecological inequalities and strategies of actors are played out, 2) as a territorial economic space in which raw materials, goods, waste, and value-chains are organised, 3) a socio-ecological space which reflects society-nature interactions through local and global biogeochemical cycles, 4) a space for planning UM infrastructures and socio-technical networks, and 5) a space of flows which concerns the circulation of materials, energy and waste between the city and its hinterland (including the spatial footprint of urban resource use and pollution emissions).*

This definition encompasses a plurality of approaches to space, which refer to general categories, but also to the different scientific fields found in our literature review. In this definition, the place of space in UM is also dynamic over time and multi-disciplinary (from understanding conflict to urban governance and flow assessment). It recognizes the importance of territorial and temporal scales, and advocates an interdisciplinary vision over a domain-specific adaptation.

To illustrate the breadth and depth of the use of space in UM studies, the goal of this paper is threefold:

- To introduce a bibliometric analysis on the topic of “spatializing UM” and better understand what researchers mean by this notion. In addition, we will investigate how UM researchers mobilize the notion of spatialization and space.
- To highlight how different disciplinary vantage points can broaden current understanding of space as well as its meaning and use in UM research. The differences, limits and complementarities among these different perspectives will also be described.

- To identify emerging notions which could consolidate research on space in UM studies as well as suggest new perspectives and research areas based on the combination of themes that have emerged through our bibliometric analysis.

The novelty of this paper is therefore to establish a state of the art of research on the spatialization of UM, by including a broad spectrum of disciplines (and not only the dominant fields of accounting and modeling) and by drawing from it a new integrative definition of space in UM. Section 2 presents the bibliometric and qualitative methods. Section 3 shows the results of the scientific landscape analysis and the qualitative analysis of the "spatial" themes and emerging notions. Finally, in section 4, new research avenues to establish interdisciplinary collaborations around novel cross-thematic research areas are proposed based on current limits of 5 identified compartmentalized approaches and our own definition of space in UM.

II. Methods

A bibliometric analysis was carried out to study the potential spatial turn in UM research as well as map the boundaries between the different scientific communities. The bibliometric analysis was performed using Scopus. Unlike Web of Science, it allows direct search of papers' bodies of text and not only from their titles or abstracts. In fact, using Web of Science, only 80 papers could be found which were all already present in Scopus. In addition, we chose to limit our study to works published between 1980 and 2020 in all English-language publications. Once the articles identified and selected, their references were analyzed. Finally, a qualitative analysis of recurrent themes was conducted.

II.1. The construction of a literature dataset on the spatial dimension in urban metabolism research

Firstly, a literature dataset from the following Scopus search string was built:

TITLE-ABS-KEY ("urban metabolism") AND ALL (spatial) OR ALL (space)

This query was conducted to identify all research works on UM that dealt with the spatial question. As such, our search is narrower than many UM reviews which can explain why some well-known UM articles do not appear in our database. A total of 448 publications based on this Scopus search were found, which formed our working dataset. We did not need to exclude any references; all were suitable, even those referenced in surprising fields such as pharmacology-toxicology or physics-astronomy.

Most of the publications resulting from this search were journal articles, but 26 chapters from books were also identified, including influential monographs in political, industrial and social ecology. However, a strong limitation of this type of dataset is that the books are not well represented both quantitatively and qualitatively as Scopus does not reference all books (nor journals).

The results of our literature review show that the topic of "spatializing the UM" has been met with growing interest among researchers and has significantly grown in recent years especially after 2010 (see Figure 1, number of documents found per publication year).

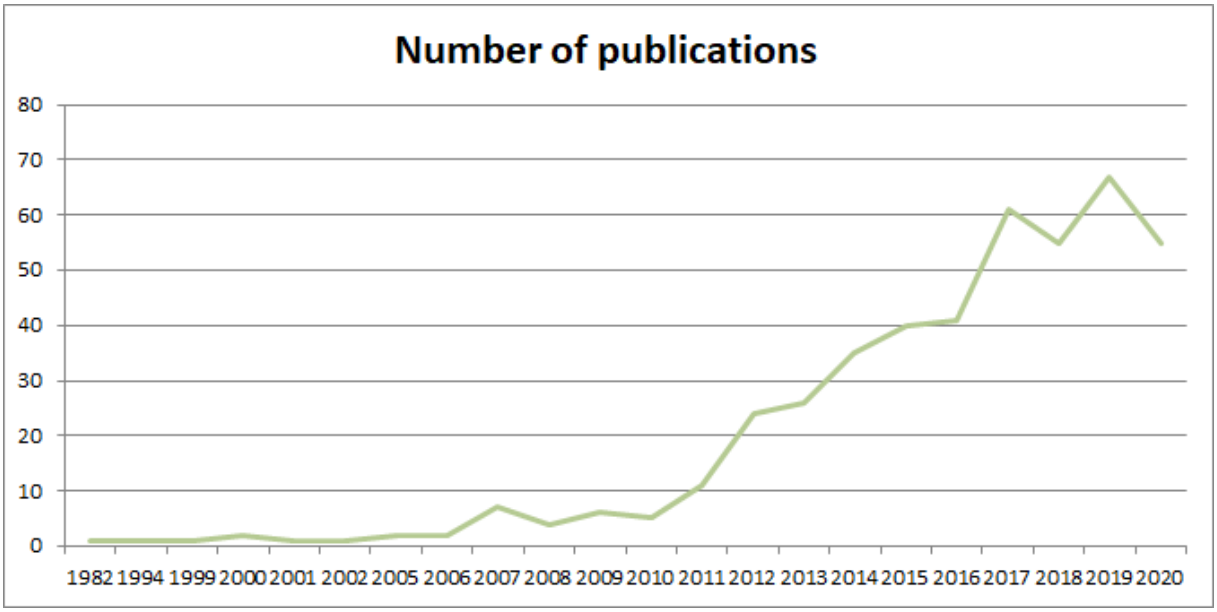

Figure 1: Academic publications on spatializing the urban metabolism, 1982–2020.

The number of publications dealing with space and UM has increased significantly over the studied period (1982-2020). The trend of the curve is therefore about +5.6 publications per year since 2010. However, while the increase of articles appears to be quite high, it is also strongly correlated with the shear increase of publications in journals in the same field[1] as well as with the increase in publications on UM in general (+7.6).

II.2. Defining the urban metabolism scientific landscape through a bibliometric analysis

To visualize and analyze the scientific landscape formed by the literature dataset, first, the open software VOSviewer from Leiden University was used. More specifically, co-authorships were mapped in Figure 2 and weighted by a number of documents and number of citations. Secondly, we were interested in the references cited in our database. Thus, the objective was to identify the major scientific schools of thoughts that develop research on the spatial dimension of UM. Our dataset (448 published articles) contains 26 631 cited references (corresponding to 28 078 authors).

II.3. A qualitative analysis of urban metabolism "spatial" themes and emerging notions

Results shown in Figures 2 and 3 focus on the quantity of scientific production, rather than quality, novelty and their influence within the scientific community. The bibliometric study of keywords did not yield interesting results, as it only highlighted banal and generic words (such as "sustainability" or

[1] Thus, after a quick calculation based on Scopus data of all publications, we obtain the same order of magnitude of increase for the 1st (+5.1) for the "Journal of Industrial Ecology", and much lower (+40 and +530) for "Resources, Conservation and Recycling" and "Journal of Cleaner Production".

145 "urban planning"). We therefore did not pursue this step, which did not provide any detailed analysis
146 of the important concepts and themes characterizing the spatial dimension of UM. To better
147 understand the different themes of this dataset, we conducted a qualitative analysis by extracting
148 the most relevant spatial notions of all titles, abstracts and keywords (Table 1), informed by our own
149 judgment. As such, Table 1 gather notions which, in our opinion, best illustrated the spatial
150 components of the UM articles identified in the dataset.

151

152 **III. Results: the research on "spatializing the urban metabolism"**

153 This section presents the results from the bibliometric analysis, including a scientific landscape
154 analysis of the dataset, a table summarizing the main concepts covered in the literature we analyzed,
155 and, finally, a description of the value and limits of current contributions on the topic of spatial UM.

156

157 **III.1. The scientific landscape analysis**

158 Figure 2 illustrates the results of our article co-authorship analysis. The map shows the 20 (small)
159 research communities making up the spatial UM scientific landscape, each identified by a different
160 color and author interlinkages (including influential authors in the UM community at large).

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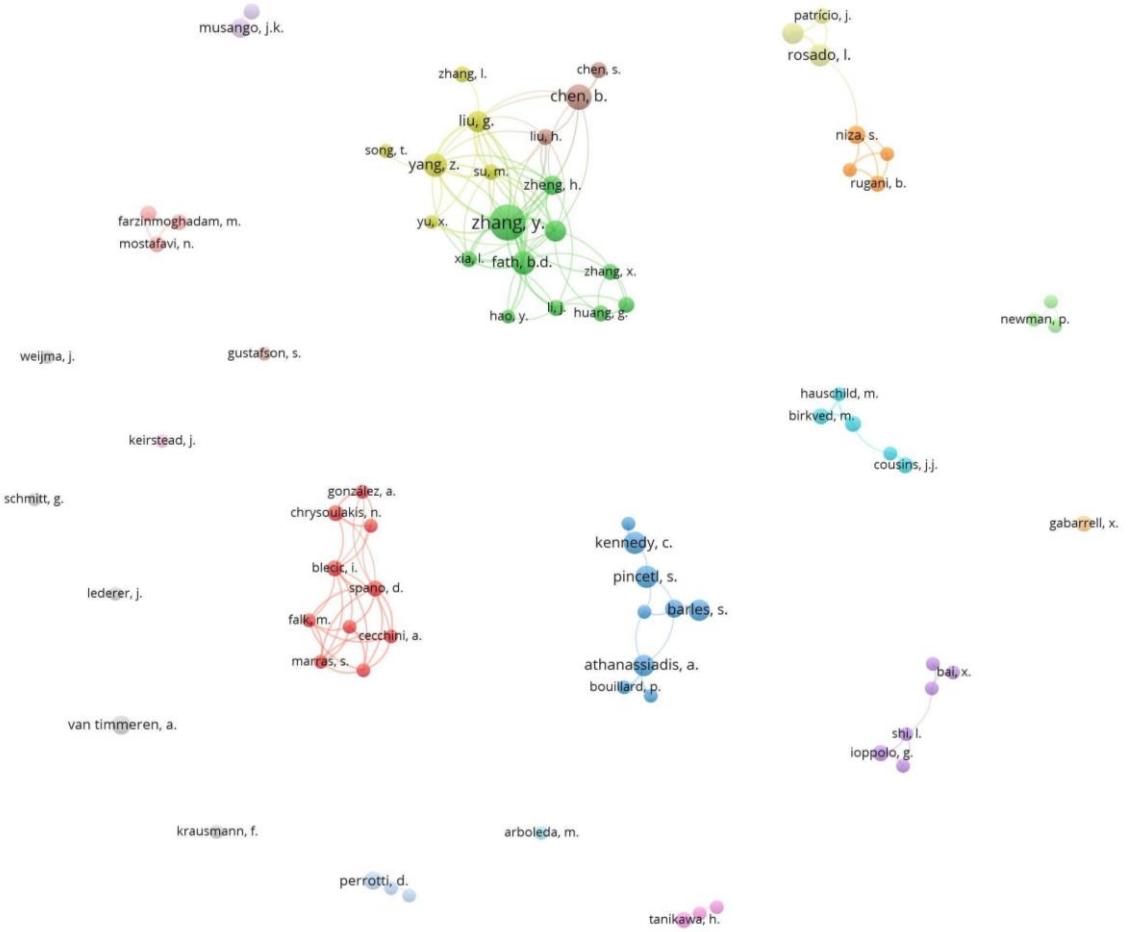

Figure 2 : Scientific landscape analysis - Co-authorship map based on bibliographic data (Source: Scopus; Realization: VOSviewer - Copyright © 2020 Centre for Science and Technology Studies, Leiden University) – visualization of scales according to the number of documents (min=3)

The largest community (green-yellow-brown) corresponds mainly to researchers at the Laboratory of Environmental Simulation and Pollution Control in Beijing Normal University. This group has produced the highest number of publications, including reviews but also empirical case studies in China (Guan et al., 2019; Zhang et al., 2016, 2014). For this community, space is a determinant of flow modeling, for example with the research objective of "construct(ing) a spatial model of an urban network's carbon metabolism" (Zhang 2016). Therefore, the spatial question is approached from the point of view of measuring the origin and destination of flows, and modeling the spatial heterogeneity of urban resource use and pollution flows.

The blue community includes some of the foundational figures of UM such Chris Kennedy and Sabine Barles as well as some of their collaborators (Barles, 2010; Pincetl et al., 2012; Kennedy et al., 2011, 2015). Their cluster of articles has a predominant urban planning and civil engineering perspective, with a focus on megacities. For them, space is characterized in particular by the links between the city and the hinterland, through the concept of “environmental footprints or imprints [which] is,

however, particularly important for characterizing the impacts of metabolism (urban in the context of this article) on the biosphere. The term 'footprint' (or imprint) is used to designate the spatial dimension of the impacts" (Barles, 2010: 450). The spatial dimension is also investigated through comparison of cities' metabolic profiles, the study of hinterland characteristics and spatial indicators (e.g. local versus international supply), as well as the identification of social and spatial drivers of energy metabolism.

The red cluster identifies the team of the FP7 EU project - BRIDGE (sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism, 2009–2011). Their approach for spatializing the UM combines "in situ measurements of physical flows, high spatial resolution numerical models to simulate these flows, indicators to link the bio-physical processes in urban environment with socioeconomic parameters'' (Chrysoulakis et al., 2013: 115). The spatial dimension is therefore the very foundation of the decision support system they build to assess alternative urban planning interventions.

The turquoise community gathers political-industrial ecologists (Cousins and Newell, 2015; Newell and Cousins, 2015). For this emerging field, which consists of coupling political ecology with environmental assessment approaches, space is a basis to develop methods of "spatial sensitivity and critical political economy" (Cousins and Newell, 2015: 721) and a means through which the boundaries of UM research are questioned. In contrast, the orange and yellow communities focus predominantly on prescriptive approaches (they are connected through Leonardo Rosado's work from Lisbon to Göteborg). The space in the UMAN model (Urban Metabolism Analyst Model) regards "the spatial location of material flows through economic activities within the urban area" (Rosado et al. 2014: 84).

Xuemei Bai, with well-established work on UM and urban energy systems (including their climate implications), is part of the purple community, alongside other researchers dealing with space for strategic environmental assessments (Ioppolo et al., 2019). The mauve community includes Cape Town-based researchers Musango, Currie and Hoekman (Currie et al., 2017), whose work concentrates on the spatial study of African urbanization processes through UM methods and the concept of "household energy metabolism" especially in the South African context. In the context of the Global South, the spatialization of the UM focuses rather on resource equity, accessibility and justice rather than resource optimization and forecasting.

The figure also shows smaller communities such as those gathered around: i) Mostafavi's work on an integrated UM analysis tool which "includes different scales of spatial interaction that dynamically influence how urban system parameters are affected" (Mostafavi et al., 2014), ii) Weijma and his team on spatial nutrient supply through agricultural demand (Wielemaker et al., 2020), iii) Newman and his work on the spatial fabric and the concept of regenerative cities (Thomson and Newman, 2018), iv) Tanikawa's spatial analysis of material stock accumulation (Tanikawa and Hashimoto, 2009), v) Arboleda's work on urban political ecology and spaces of planetary urbanization (Arboleda, 2016), vi) as well as a few other smaller communities.

All in all, our map features three larger communities, four medium and 13 small ones from a variety of disciplinary fields and domains, showing the dynamism of the spatial dimension research strand in the broader UM field. These communities are also relatively young. Nevertheless, some of these groups can sometimes hide larger and more established communities in the fields of social and

industrial ecology, which might not have a distinct focus on spatial UM (e.g. Kraussmann and van Timmeren). Similarly, we can observe that these communities are relatively fragmented with few links existing between them. Through this first step, we could identify the research networks working in the direction of a spatial turn in UM studies. The next step is to investigate the main research fields influencing these relatively young (and still compartmentalized) small communities.

III.2. The scientific landscape analysis of the dataset references

To further characterize the scientific landscape of the use of space in UM studies, we analyzed all works referenced in the 448 publications we retrieved (and presented in the previous section), representing a total 26 631 references (corresponding to 28 078 authors). Using VOSviewer, a bibliometric analysis of all these references was performed in the form of co-citation of cited authors (Figure 3). To ensure visibility, only papers having more than 30 citations were displayed (reducing the number of authors displayed to 236) (Fig. 3). Through this analysis, we could identify main fields and research strands authors refer to when developing research on the spatial dimension of the UM .

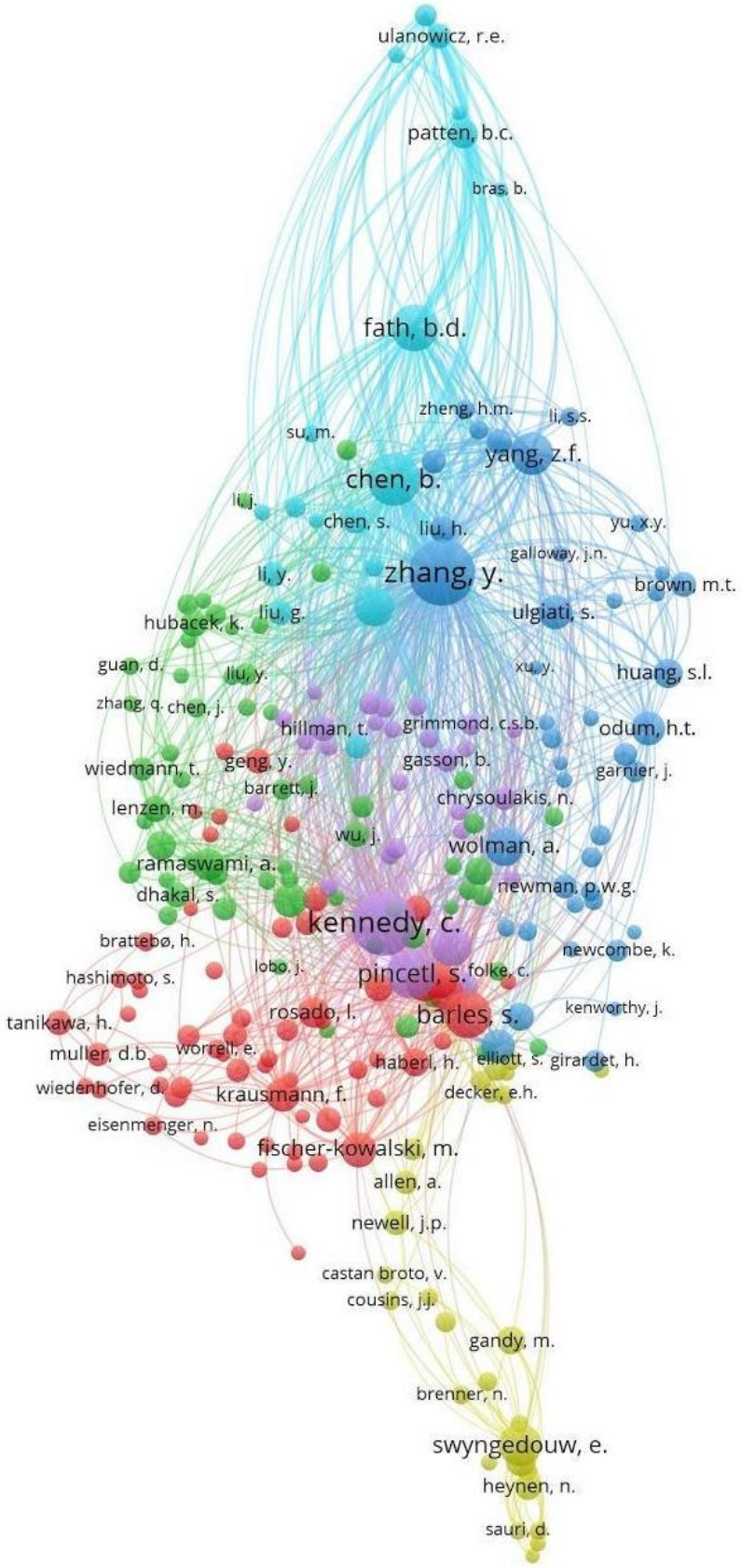
ulanowicz, r.e.
patten, b.c.
bras, b.
fath, b.d.
zheng, h.m.
li, s.s.
su, m.
yang, z.f.
chen, b.
li, j.
chen, s.
liu, h.
yu, x.y.
galloway, j.n.
li, y.
zhang, y.
brown, m.t.
liu, g.
ulgiati, s.
hubacek, k.
guan, d.
liu, y.
xu, y.
huang, s.l.
zhang, q.
chen, j.
hillman, t.
grimmond, c.s.b.
odum, h.t.
wiedmann, t.
geng, y.
gasson, b.
garnier, j.
barrett, j.
chrysoulakis, n.
lenzen, m.
wu, j.
wolman, a.
ramaswami, a.
newman, p.w.g.
dhakal, s.
kennedy, c.
brattebø, h.
newcombe, k.
lobo, j.
pincetl, s.
folke, c.
hashimoto, s.
kenworthy, j.
rosado, l.
barles, s.
tanikawa, h.
muller, d.b.
worrell, e.
haberl, h.
elliott, s.
girardet, h.
wiedenhofer, d.
krausmann, f.
decker, e.h.
eisenmenger, n.
fischer-kowalski, m.
allen, a.
newell, j.p.
castan broto, v.
cousins, j.j.
gandy, m.
brenner, n.
swyngedouw, e.
heynen, n.
sauri, d.

Figure 3 : Co-citation of cited authors map based on bibliographic data (min number = 30) (Source: Scopus; Realization: VOSviewer - Copyright © 2020 Centre for Science and Technology Studies, Leiden University)

Seven scientific clusters were retrieved from this analysis. The first cluster in purple includes the work of Chris Kennedy (at the center of Figure 3), as the author of many highly cited articles including "*The changing metabolism of cities*" (2007) which is the most cited article in our database (608 citations). In this article, the authors define the space on the basis of the circulation of flows between the city and the hinterland: "the vitality of cities depends on spatial relationships with surrounding hinterlands and global resource webs" (Kennedy et al., 2007: 56).

The strong influence of urban political ecology (in yellow) and social ecology (in red) becomes now visible, differently from Figure 2. The urban political ecologists, including the work of Erik Swyngedouw, Nik Heynen, Mathew Gandy and David Wachsmuth (Gandy, 2004; Heynen et al., 2006; Swyngedouw, 2006; Wachsmuth, 2012) rooted in the tradition of urban critical geography, used the UM concept and its spatialization to explore "the transformation of nature (is) embedded in a series of social, political, cultural, and economic social relations that are tied together in a nested articulation of significant, but intrinsically unstable, geographical configurations like spatial networks and geographical scales" (Heynen et al., 2006 :7). The spatial approach therefore makes it possible to understand these metabolic interrelationships among geographical spaces.

The contribution of social ecologists is centered on society-nature interactions reflected in socio-ecological spaces and the assessment of biophysical flows underpinning long-term societal dynamics. The work of Marina Fischer-Kowalski, Fridolin Krausmann, or Helmut Harbel (Fischer-Kowalski and Haberl, 2007, 2007; Krausmann et al., 2009) is very influential in our database, although less visible in Figure 2 for the reasons discussed in III.1. Sabine Barles's work (in red) is also very influential especially with reference to the development of the field of "territorial ecology", which is a response to the need for greater focus on the "socio-spatial dimensions" of metabolic dynamics (Barles, 2010).

The green cluster corresponds to work on carbon emission footprints and urban energy use through multiregional input-output models and includes researchers like Anu Ramaswami, Thomas Wiedmann, Xuemei Bai, Manfred Lenzen, or Julia K. Steinberger. This cluster is related to the field of ecological economics and is tightly interrelated with the social ecology (red) cluster. Finally, our network map features some of the pioneers in the UM field, who have authored seminal articles between 1960 and 2000, including Abel Wolman, Eugene Odum, Ethan Decker, Paulo Ferrão, John E. Fernández, Marina Fischer-Kowalski, Wiliam E. Rees, Gilles Billen, Herbert Girardet, Peter Baccini, Paul H. Brunner and Sergio Ulgiati. These authors are mainly represented in the blue and red clusters. The blue and turquoise clusters represent the environmental modeling community and, in particular, Brian D. Fath (Ecological network analysis) and researchers from the Beijing Laboratory of Environmental Simulation and Pollution Control (cf. III.1).

III.3. A qualitative analysis of the "spatial" themes, recent contributions and perceived limits

As a third step of our bibliometric analysis, we conducted a qualitative analysis of "spatial" themes and emerging notions to go beyond the research networks identified in the scientific landscapes and get deeper insights into our research question: *"What is the place of space in UM research?"*

Our objective was to extract the most relevant spatial notions from all the titles, abstracts and keywords in our database (Table 1), informed by our expert judgment. Table 1 summarizes all notions which, in our opinion, more clearly illustrate the spatial component of the UM articles in our database. Some of them are directly linked to accounting methods such as environmental impacts, material stocks, etc. while others relate to theories and concepts such as society-nature interactions, human practices, vulnerability, spatial and physical patterns, resilience. These notions were then organized in five main categories. For each category, main research issues and the inclusion (or not) of the five approaches of space laid out in our definition were investigated (cf. Table 1):

- 1. *The political approach*, dealing with power relationships, land grabbing, resource exploitation and inequalities, dominant regimes, the reproduction of inequalities within cities and between the city and the hinterland, spatial practices and extra-territoriality.

- 2. *The territorial economic approach*, concerned with the organization of supply chains, territorial economy, and competitions

- 3. *The socio-ecological approach*, highlighting the long-term regimes and the ecological economics of territories, the society-nature interactions across spatial scales, and the material stock accumulation.

- 4. *Governance and planning approaches*, focusing on developing research towards sustainability grounded in territorial-related parameters, spatial patterns, and infrastructure planning.

- 5. *The spatially explicit modeling/accounting approach*, centered on spatial-explicit developments of methods such as Material Flow Analysis, Input-Output model, Emergy, Ecological Network Analysis and Life Cycle Assessment.

Table 1: Categories of "spatial" themes and examples of associated notions

	Examples of emerging notions through keywords	References (5 most cited per category)	Methodological, operational critiques / limits	Theoretical, conceptual critiques / limits (level of sophistication)
1. The political approach	Spatial scales for vulnerability; Spatial Practices; Socio-spatiality of Water Problems; Conflicting urban and rural territorial livelihood; City-hinterland relation; Urban extraterritoriality; Boundary system; Uneven urban metabolisms; Neoliberalisation of	(Heynen, 2014) (Newell and Cousins, 2015) (Wachsmuth, 2012) (Demaria and Schindler, 2016); (Shillington, 2013);	No flow-stock quantitative assessments (providing theoretical insights rather than quantified effects or impacts)	Hinterlands considered only as spaces subordinated to the metropolises

	urban environments;			
2. The territorial economic approach	Reterritorialisation; Territorial competitions; Territorial organization indicators; Territorial-based approach; Multi-scalar; Scale-dependent; Metabolic pathways;	(Kalmykova et al., 2016) (Fung and Kennedy, 2005) (Rushforth and Ruddell, 2015) (Gravagnuolo et al., 2019) (Bahers et al., 2017)	No specific focus on urban systems	Limited insights on the geographical scales of metabolic relocation
3. The socio-ecological approach	Society-nature interactions across spatial scales; Spatial material stocks accumulation; Workplace spatial distribution; Urban growth boundary; Spatial variation in the ecological relationships;	(Golubiewski, 2012) (Augiseau and Barles, 2017) (Haberl et al., 2019) (Miatto et al., 2019) (Gingrich et al., 2012)	Space often intended as geographic distribution of stocks and as a background to the circulation of flows	De-politicized vision of spatialization No differentiation among territories Limited attention paid to the conceptualization and contextualization of space.
4. The governance and planning approaches	Interspatial connections; Spatial patterns; Urban food system in spatialized systems; Resilience spatial planning; Environmental imprint; Infrastructure planning;	(Townsend, 2000) (Pincetl et al., 2012) (Chelleri et al., 2015) (Chrysoulakis et al., 2013) (Ramaswami et al., 2012)	Locking up of the knowledge-transfer processes	Limited analysis of the relationships of domination between the city and the spaces of production natural resources
5. The spatially explicit modeling approach	Spatially explicit network model; Spatial and temporal disparity; Spatial Analysis of Residential GHG; Spatially explicit commodity flow; Spatializing material replacement; Spatial material stock;	(Kennedy et al., 2007) ; (Pauleit and Duhme, 2000) ; (Kennedy et al., 2010) ; (Zhang et al., 2016) ; (Villarroel Walker et al., 2014)	Black-boxing of in-boundary dynamics in mainstream methods Top-down approaches	Limited attention paid to space, largely aterritorial both within the city and beyond. Limited consideration of socio-political drivers of metabolic flows Limited attention paid to the socio-physical

	Spatial variability; Spatial dimension of circularity. Indicators at different spatial levels			transformations of spaces

Research in category 1 refers to the relations of domination between territories. The place of space is therefore at the core of this research strand to understand the territorialities and extraterritorialities of the UM and the link with the social dynamics (including conflicts) in cities (Demaria and Schindler, 2016; Bahers et al., 2019). Gandy's narrative is centered on the idea of the UM as a dimension to urban space ("metabolic dimension to urban space", Gandy 2018) rather than on the spatial dimension of UM, which resonates with Neo-Marxian readings of the UM (e.g. Swygedouw, 2006). Understanding the UM as a dimension of the urban space allows to move away from a managerial and technocratic metaphor (the urban space as a "metabolic system which can be examined in isolation from wider processes of historical change", Gandy, 2004, p. 374), as in Wolman and initial "industrial metabolism" approaches. What are the spatial dimensions of the relations of power and vulnerabilities, which the circulation of flows generates? The concepts of metabolic relationships, metabolic rift and metabolic vulnerabilities (Wachsmuth, 2012) are among the most recent contributions in this theme. Although questions related to the spatial distribution of resources and unequal access to them are central to it, this research strand does not always engage, in terms of methodological limitations, with the results of quantitative assessments of flows and stocks, which can hardly be used in urban planning and public policy evaluation. The relatively recent field of political-industrial ecology (Newell and Cousins, 2015) has started catalyzing efforts in this sense, i.e. "calculat[ing] and map[ping] out the uneven spatiality of environmental and social impacts associated with production and consumption" (Newell and Cousins, 2015), but is far from mainstream. Another criticism is that the hinterland is considered only as spaces dominated by the metropolises, and the points of view and internal logics of these supply territories are only hardly investigated. This is the other side of what is called the 'Methodological cityism' (Wachsmuth, 2012), as discussed theoretically in more recent works in this field (Arboleda, 2016).

A recent debate in category 2 (the territorial economic approach) is the development of economic activities aiming at the relocalisation (or internalization) of the UM. What model of metabolic relocalisation could be implemented? While the predominant historical tendency has been the externalization of the UM, new local value chains are starting to emerge for flows such as excavated earth, organic waste or urban wood (Kampelmann, Raufflet, Scialpi, 2021). This strand often lacks a systematic approach to the urban system in its entirety and mainly works "by value chain" or "by product" (privileging a single flow/service/product rather than their tradeoffs/interactions in the city). Another criticism is that this domain often refers to circular economy strategies, whereas with the latter, space and territories are totally absent from the definition. Most circular economy strategies focus on the valorization and recycling of resources, without no systematic consideration

of the geographical scales which may be involved in such processes. The recurrent claim to relocate the UM is only rarely based on an understanding of the spatial scale at which this should be implemented. From a theoretical point of view, the notion of space is not systematically discussed and spatiality remains a factor or consequence of value creation (the organization of the city is an economic resource to be developed).

The socio-ecological approach of category 3 can be understood through an analysis of the long-term metabolic regimes. What is the place of space in these socio-ecological regimes? During the agrarian socio-ecological regime, the cities are double space-dependent: as a result of a socio-spatial specialization, depending on food produced elsewhere and through a partial externalization of the UM (Billen et al., 2012; Haberl et al., 2016). With the industrial socio-ecological regime, the cities are still space-dependent, because of the total externalization of the UM (inputs and outputs) and of the splintered and globalized UM (Barles, 2014). One criticism that can be made of this research is that it does not study the socio-ecological relations at multiple geographical scales. Space is seen as a depoliticized entity, without taking into account the conflicts that take place there. In these works, the relationships between actors that lead to alliances, struggles and negotiations for the governance of metabolic flows are not always taken into account. Some authors have developed a political approach to social-ecological metabolism through political economy and regulation theory at macro level (Schaffartzik, Duro, Krausmann, 2019), but this does not involve a political understanding of space. The conceptualization of the political space as a social product organized by actors is missing. Hence, there is a limited attention to the way in which the relationships between actors influence the circulation/spatial distribution of flows and stocks. Moreover, this approach lacks a specific focus on urban systems as such. Here "space" is often intended as geographic distribution of stocks within national or regional systems (cf. material stocks studies in our definition of "spatial dimension" above). Therefore, there is only limited consideration of the territorial differentiation within these systems, the heterogeneity of urban spaces and their links to different types of networks. Other dimensions to urban space (cf. above, Gandy, 2018) are left out of the analysis. A few exceptions are more recent land use and land system studies, which are presented as a strategy to "open the black box" (cf. Human Appropriation of Net Primary production, HANPP tool, Erb et al. 2016) although these are mostly performed at global or national (rather than urban) scale (Dorninger et al. 2021).

The main research question in category 4 is: how can UM studies be coupled with urban and infrastructure planning? The sustainability of urban systems is assessed based on cross-scale interactions among the ecosystems, the transboundary infrastructures, and the multiple social actors and institutions that govern these infrastructures (Ramaswami et al., 2012). One policy-relevant criticism is that although this approach is operationally oriented, in most cases, urban planners/designers do not take into account the spatial dimension of UM, often due to a lack of education (Perrotti, 2019), and mostly consider it as a homogeneous set of processes at the urban and metropolitan scale. The appropriation of the UM concept by designers remains at the level of building/site and construction (and waste) flow management. The interdependencies among supply flows and the role of local actors in the decision-making processes influencing UM dynamics are only rarely analyzed. In addition, this approach does not engage systematically with the relationships of domination of the city on the spaces of production of natural resources through the deployment of socio-technical networks. Yet this is an important feature of the spatiality of UM, since this involves analysis of the impacts on the productive ecosystems.

Category 5 (spatially explicit modeling approaches) concerns a small industrial ecology community whose research attempts to track the deployment of metabolic flows beyond cities, through identification of their hinterland. Indeed, much of the research in industrial ecology is largely aterritorial. The hinterland is a vague space near the city or far from it; it is neither described nor analyzed and with no systematic consideration of the humans and non-humans living in it. However, this category does not conceptualize space as a production or driver of inequalities, but only as a location of infrastructures and flows. This black-boxing of space does not allow to theorize the spatiality of the UM, nor to understand the organization of space through urban flows and resources. A recent work in category 5 refers to the visualization of data on material stocks and flows on a fine-grained level (for example through the Metabolism of Cities Data Hub). The territorial subdivision is therefore very important to develop maps which generate quick visual insights into differences within areas. How to develop indicators at different spatial levels? This work aims to open the black box of cities through the collection of data on individual infrastructure/site level (e.g. individual wastewater treatment plant or food market). However, from a methodological point of view, some internal urban dynamics are still black-boxed as in traditional modeling methods. The interrelation between the city and its hinterland is not detailed and remains at a superficial level of flow tracing. Moreover, these methods remain top-down approaches, which do not mobilize an analysis and differentiation of the (socio-economic) dominant vs dominated actors. From a theoretical point of view, this approach lacks a deeper consideration of the socio-political drivers of UM flows, governance systems, and the consideration of the planner/designer perspectives on metabolic infrastructure and landscapes. This approach can also result in prescriptive and techno-centric policy recommendations, with limited understanding of the territorial dynamics on the ground and of the socio-physical transformations of spaces (which are not neutral from a political and environmental point of view).

IV. Discussion: an outreaching and future agenda for incorporating the space more systematically into UM studies

The bibliometric analyses illustrate academics' growing interest in incorporating spatial challenges in traditional UM studies. Nevertheless, as underlined in the previous section and similarly to UM research at large, the point of view and the end use of space for each researcher and research sub-discipline can widely vary. In fact, while some researchers focus on the methods making the spatialization of the UM possible, others focus on the landscapes current UMs create both locally and globally, or even on the uneven spatial distribution of flows within a city. We have described approaches where spatiality is considered at higher sophistication levels and others where it is only minimally conceptualized. Thus, a theoretical framework of the spatiality of UM needs to incorporate the various dimensions of space which have emerged through our research.

To facilitate the articulation of these different representations of space and accelerate their consolidation and conceptualization by the disciplines that develop them, a definition is proposed:

Space in UM is *a physical and conceptual construct which considers space as a 1) political space, in the sense that material relationships of domination, ecological inequalities and strategies of actors*

are played out, 2) as a territorial economic space in which raw materials, goods, waste, and value-chains are organised, 3) a socio-ecological space which reflects society-nature interactions through local and global biogeochemical cycles, 4) a space for planning urban metabolic infrastructures and socio-technical networks, and 5) a space of flows which concerns the circulation of materials, energy and waste between the city and its hinterland (including the spatial footprint of urban resource use and pollution emissions).

This integrative definition combining flows, actors, governance, infrastructures and modeling techniques attempts to provide an interface over which research can converge and build new cumulative insights.

A simplified schematic of space in UM studies (Fig. 4) provides the reader with an illustration of the different approaches of space identified. It includes the political space (in purple), represented by the material relationships of domination between the city and the hinterland, and the ecological inequalities within the society, whether urban or rural. The territorial economic space (blue) refers to the organization of the supply chain that crosses the territories, from the hinterlands to the consumption areas. The socio-ecological space (green) is represented by the society-nature interactions through the externalization of the UM in hinterlands. This includes the external supply of food, minerals, and energy. The space of planning (brown) encompasses urban infrastructure and socio-technical networks such as buildings, transportation networks, waste and energy utilities, within the city, but also outside it, via the material extraction and processing infrastructure. Finally, the space of flows (gray) is represented by the arrows between the hinterlands and the city (and vice versa), which show the exchange of commodities and secondary materials, agricultural products and organic waste, energy imports and exports, construction materials and bulk waste, manufactured products and equipment waste, wood and wood waste.

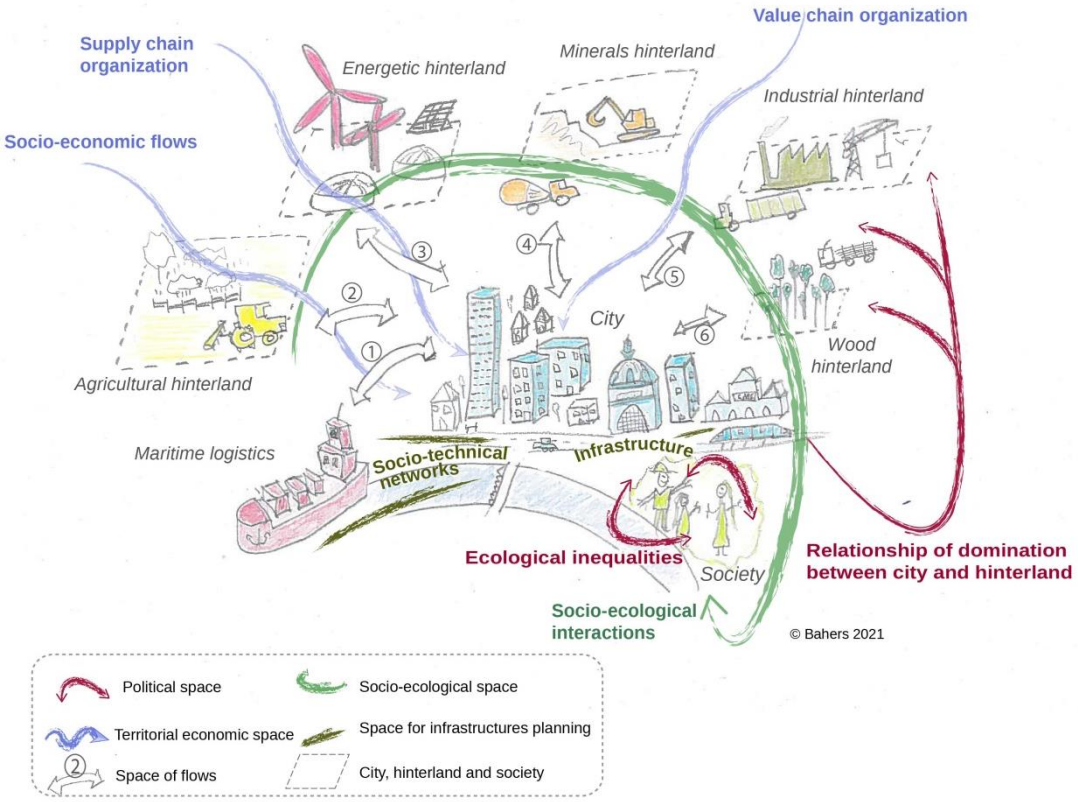

Figure 4: Graphical representation of space in urban metabolism (legend: 1. commodities and secondary materials; 2. agricultural products and organic waste; 3. energy imports and exports; 4. construction materials and bulk waste; 5. manufactured products and equipment waste; 6. wood and wood waste) (Source: Authors)

Building on the definition and criticisms (cf. table 1), we identify a few themes for converging research on spatializing the UM towards a higher level of sophistication in the definition of this notion. In addition, the potential contribution of each approach was described, especially from a theoretical point of view. Some of the new notions describing the spatial UM could be further consolidated (meaning that they have already been used but not collectively embraced by the UM research community at large). These include metabolic infrastructures, metabolic spaces and landscapes, and metabolic interterritorial relationships.

Interrogating the role of metabolic infrastructures (places where flows are transformed from one state/function to another) within a territory would characterize the networks that enable the transformation and paroxysmal circulation of flows within and among cities. These infrastructures can also determine who has the right to some flows but also to produce the city (in the Lefebvrian sense) and the urban space (Gandy, 2014). They can also be drivers of the several inequalities (Schaffartzik, Duro, Krausmann, 2019) that exist among individuals and social groups (category 1). This positioning would help to overcome the criticism in category 2 that infrastructure is not enough politicized. Moreover, locating and better characterizing these infrastructures also enables one to understand whether a city has the sufficient capacity to become self-sufficient and how dependent it

is to external supply chains (category 2). In addition, deeper knowledge on current and needed metabolic infrastructure is a necessary step to plan and orchestrate land use, economic and network planning (category 4). Finally, locating metabolic infrastructures ranging from waste, energy, water infrastructures to manufacturing plants helps to open the “black box” from current UM studies and link flows to users and activities (category 5). For example, one critical research frontier under this emerging notion is the role of urban ecosystems and the “services” they provide towards the mitigation of the energy demand and GHG emissions in cities. Growing evidence demonstrates that assessing the impacts that Ecosystem Services have on the metabolism of cities (e.g. through Drivers, Pressures and State indicators) contributes to a deeper understanding of flow and stock dynamics within urban systems and provides alternative pathways into sustainable resource management at city level (Perrotti and Stremke, 2018; Cardenas-Mamani, U. and Perrotti, 2022). This notion echoes the call for a “resource-sensitive" turn in infrastructure studies (Coutard and Florentin, 2022), which can contribute to the urban political ecology agenda by bringing resource issues, in their material, political, and spatial dimensions to the center of scientific attention. Spatially-explicit metabolic studies can inform novel green and blue infrastructures policies to jointly address environmental performance targets and the fulfillment of human wellbeing and ecosystems’ health (Galan and Perrotti, 2019; Perrotti and Iuorio, 2019)

Analyzing metabolic spaces and landscapes can illustrate the transformation and redefinition of natural ecosystems into the urban fabric and built environment (Gandy, 2003) while shedding light on the environmental and spatial quality of new, designed metabolic landscapes (wastescapes, waterscapes, energyscapes, etc.) (Amenta & Van Timmeren, 2018). By defining the metabolic landscapes and hinterlands of resources and waste, questions of land appropriation and exploitation can equally emerge revealing colonial or imperialistic traits of current urban functioning (theme 1). In addition, when delimiting the spaces of resource extraction, manufacturing and waste treatment, the social condition of workers along supply chains of materials and goods consumed in cities can be revealed and traced (category 2). Using a modeling approach (theme 5) to analyze socio-economic consequences could be an interesting contribution in this view. This question can also welcome landscape architects, urban planners and designers to propose alternative strategies to the production of urban landscapes that could minimize the impacts on local and remote natural ecosystems (theme 4). A research agenda at the intersection of landscape ecology and urban studies could unpack how the value systems that have emerged around urban resources can inform wider debates on urban sustainability (decentralization of urban management, locally controlled resources, regenerative urban landscapes) (category 2).

The metabolic interterritorial relationships are another research notion that could also be further explored. Territorializing the UM can reveal the interconnections and dependencies between territories for resource extraction and manufacturing, as well as waste management. These relationships are, in some cases, characterized as predatory, colonial and unidirectional (Arboleda, 2016) (category 1). In the future, it would be extremely relevant to explore how to adjust these relationships into more inter-territorial cooperation models. Indeed, hinterlands are not only dominated by the metropolises, but also in the ability to formulate socio-economic and collaborative strategies or, on the contrary, strategies of rupture and opposition (category 2). What type of governance for inter-territorial relationships can be proposed at *glocal* level and what forms of

negotiations possibly remain to be analyzed? It is also a question of recognizing that cities do not aim to become completely autonomous and must build their inter-territoriality with surrounding territories. This research strand could study the triple space-dependence of cities (Barles, 2014), in order to measure the urban environmental imprint and ecosystem services (theme 4) and to identify urban hinterlands. Consequently, it would be necessary to consider socio-political drivers of urban metabolic flows and socio-physical transformations of spaces (category 3). There is therefore a need to develop methods that can trace urban flows from extraction and processing hinterlands (category 5), to overcome black-boxing of in-boundary dynamics of mainstream modeling methods. It is essential to measure and understand the indirect environmental effects of urban affairs. This notion could articulate traditions in territorial ecology (Barles, 2014) and political ecology (beyond the urban) (Wachsmuth, 2012), in revealing the spaces and scales of these territorial interdependencies..

As these examples show, further work on novel, "hybrid" concepts and the testing of their relevance to UM researchers can not only provide greater scope for integrating the multiple facets of space (its dimensions and qualities) at the outset of applied UM studies. It can also leverage more far-reaching collaborative research endeavors that can, in turn, stimulate new cross-thematic questions yet under-explored in the current state of the art.

V. Conclusion:

Through this paper, we have proposed a bibliometric analysis illustrating the multiple meanings and relevance of "the spatialization of UM" across research communities. This bibliometric analysis also points to a potential "spatial turn" in UM research, in the sense of an increasing consideration of the spatial dimension of metabolic phenomena in those communities. Although far from being dominant, this perspective seems already quite established to date with 448 publications found in Scopus including the terms "space" or "spatial" (in the title, abstract and keywords) out of total 724 "urban metabolism" entries. The results of our three-layered scientific landscape analysis (author's co-authorship and co-citations and themes) have led to the identification of five main research themes as a means to summarize major efforts towards the systematization of knowledge regarding space in UM studies. These include approaches focusing on: urban political critique and analysis of power relationships and inequalities in cities and their hinterlands; governance models and urban planning for sustainability; socio-ecological and long-term environmental analysis; socioeconomic systems and value-chain configurations in a territorial economic perspective; and spatially explicit modeling of urban systems. We have exemplified main concepts, methods and ambitions within the three new notions through examples drawn from our analysis. The mapping of differences and complementarities has not only allowed us to identify areas for further development and ways into the consolidation of emerging research concepts and trends. It has also opened a broader spectrum of cross-thematic approaches that can better express the multiple facets of space dimensions and qualities and potentially meet the growing need to embed space more consistently as an essential "matter of concern" for UM research. The value of our analysis and discussion is primarily exemplificatory and surely not exhaustive. Similar efforts can be replicated and augmented through a new agenda of research, which will potentially include novel, hybrid concepts currently under-explored or still unknown in the literature. In the end, it is its relative unpredictability in terms of future lines of research and action that, we believe, constitutes one of the clearest expressions of dynamism characterizing the UM. From the heterogeneity of meanings associated with the "metabolism" concept to the diversity of the disciplines involved in it, the UM has, since its inception,

never stopped surprising its tenants and lovers. We are sure even more surprises lie ahead if the field celebrates its diversity and ever-increasing intellectual creativity and adventurousness as one of its main strengths and, perhaps, its richest legacy for the next generation of metabolic studies.

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