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

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

3

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12

### 13 **Highlights**

- 14 - **We conduct a bibliometric analysis of spatialization in UM**
- 15 - **448 publications are analyzed**
- 16 - **We identify five main research themes**
- 17 - **20 research communities are involved in the spatial debate**
- 18 - **A spatial turn in UM research seems a possible horizon**

19

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

21

22

### 23 **Abstract**

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

34

### 35 **I. Introduction**

36 The world is rapidly urbanizing, resulting in ever-increasing resource requirements and pollution  
37 flows. It is now estimated that cities are responsible for 80% of global energy consumption and more  
38 that 40 billion tons per year (since 2010) of materials are extracted-transformed-transported by  
39 urban technical networks (IRP 2018). As a consequence of this mobilization of matter and energy,  
40 cities are also responsible for 65% of global atmospheric emissions (IRP 2018). Urban Metabolism  
41 (UM) is an interdisciplinary concept that studies how cities interact with the environment and more  
42 specifically how they use resources and emit pollution flows as well as the associated societal,  
43 economic and environmental challenges around these flows. UM research thus attempts to better  
44 understand the functioning of cities by characterizing and understanding all socio-technical and  
45 socio-ecological processes by which flows of materials, energy and water are consumed, transformed  
46 and rejected in different forms by cities. Over the last century, the UM concept has been profusely  
47 used to describe, by various academic disciplines, the above-mentioned urban socio-technical  
48 phenomena. Josh P. Newell and Joshua J. Cousins (2015) have highlighted that within UM, different  
49 disciplinary fields exist which in turn have created islands of knowledge with quite distinct  
50 boundaries between them. Yet, one recurring aspect that can be found in each of these islands of  
51 knowledge is to acknowledge the importance of the spatial dimension of UM. Reciprocally, UM is for  
52 some authors seen as "a series of intersections between capital and nature encompassing  
53 infrastructure, technological networks, and other functional components of urban space" (Gandy  
54 2018, p. 102).

55

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

63

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

79

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

83

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

92

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

98

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

- 101 - To introduce a bibliometric analysis on the topic of “spatializing UM” and better understand  
102 what researchers mean by this notion. In addition, we will investigate how UM researchers  
103 mobilize the notion of spatialization and space.
- 104 - To highlight how different disciplinary vantage points can broaden current understanding of  
105 space as well as its meaning and use in UM research. The differences, limits and  
106 complementarities among these different perspectives will also be described.
- 107 - To identify emerging notions which could consolidate research on space in UM studies as  
108 well as suggest new perspectives and research areas based on the combination of themes  
109 that have emerged through our bibliometric analysis.

110 The novelty of this paper is therefore to establish a state of the art of research on the spatialization  
111 of UM, by including a broad spectrum of disciplines (and not only the dominant fields of accounting  
112 and modeling) and by drawing from it a new integrative definition of space in UM. Section 2 presents  
113 the bibliometric and qualitative methods. Section 3 shows the results of the scientific landscape  
114 analysis and the qualitative analysis of the “spatial” themes and emerging notions. Finally, in section  
115 4, new research avenues to establish interdisciplinary collaborations around novel cross-thematic  
116 research areas are proposed based on current limits of 5 identified compartmentalized approaches  
117 and our own definition of space in UM.

## 118 **II. Methods**

119 A bibliometric analysis was carried out to study the potential spatial turn in UM research as well as  
120 map the boundaries between the different scientific communities. The bibliometric analysis was  
121 performed using Scopus. Unlike Web of Science, it allows direct search of papers’ bodies of text and

122 not only from their titles or abstracts. In fact, using Web of Science, only 80 papers could be found  
123 which were all already present in Scopus. In addition, we chose to limit our study to works published  
124 between 1980 and 2020 in all English-language publications. Once the articles identified and  
125 selected, their references were analyzed. Finally, a qualitative analysis of recurrent themes was  
126 conducted.

127

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

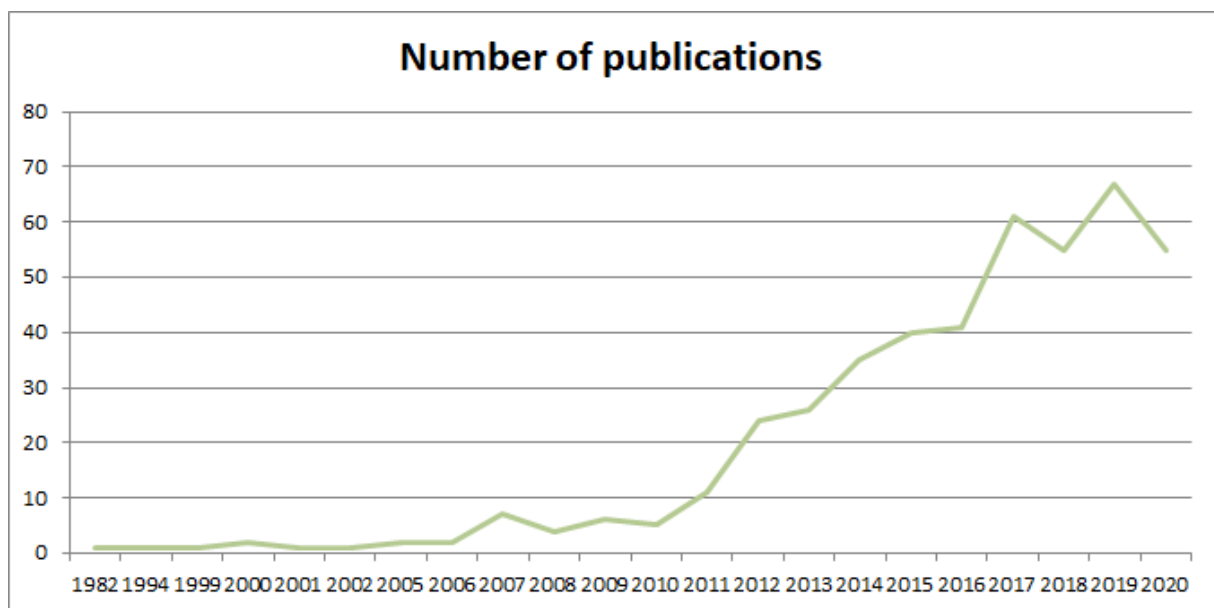
129 Firstly, a literature dataset from the following Scopus search string was built:

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

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

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

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



144

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

146

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

152

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

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

160

## 161 **II.3. A qualitative analysis of urban metabolism “spatial” themes and emerging notions**

162 Results shown in Figures 2 and 3 focus on the quantity of scientific production, rather than quality,  
163 novelty and their influence within the scientific community. The bibliometric study of keywords did  
164 not yield interesting results, as it only highlighted banal and generic words (such as “sustainability” or  
165 “urban planning”). We therefore did not pursue this step, which did not provide any detailed analysis  
166 of the important concepts and themes characterizing the spatial dimension of UM. To better  
167 understand the different themes of this dataset, we conducted a qualitative analysis by extracting  
168 the most relevant spatial notions of all titles, abstracts and keywords (Table 1), informed by our own  
169 judgment. As such, Table 1 gather notions which, in our opinion, best illustrated the spatial  
170 components of the UM articles identified in the dataset.

171

## 172 **III. Results: the research on “spatializing the urban metabolism”**

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

176

### 177 **III.1. The scientific landscape analysis**

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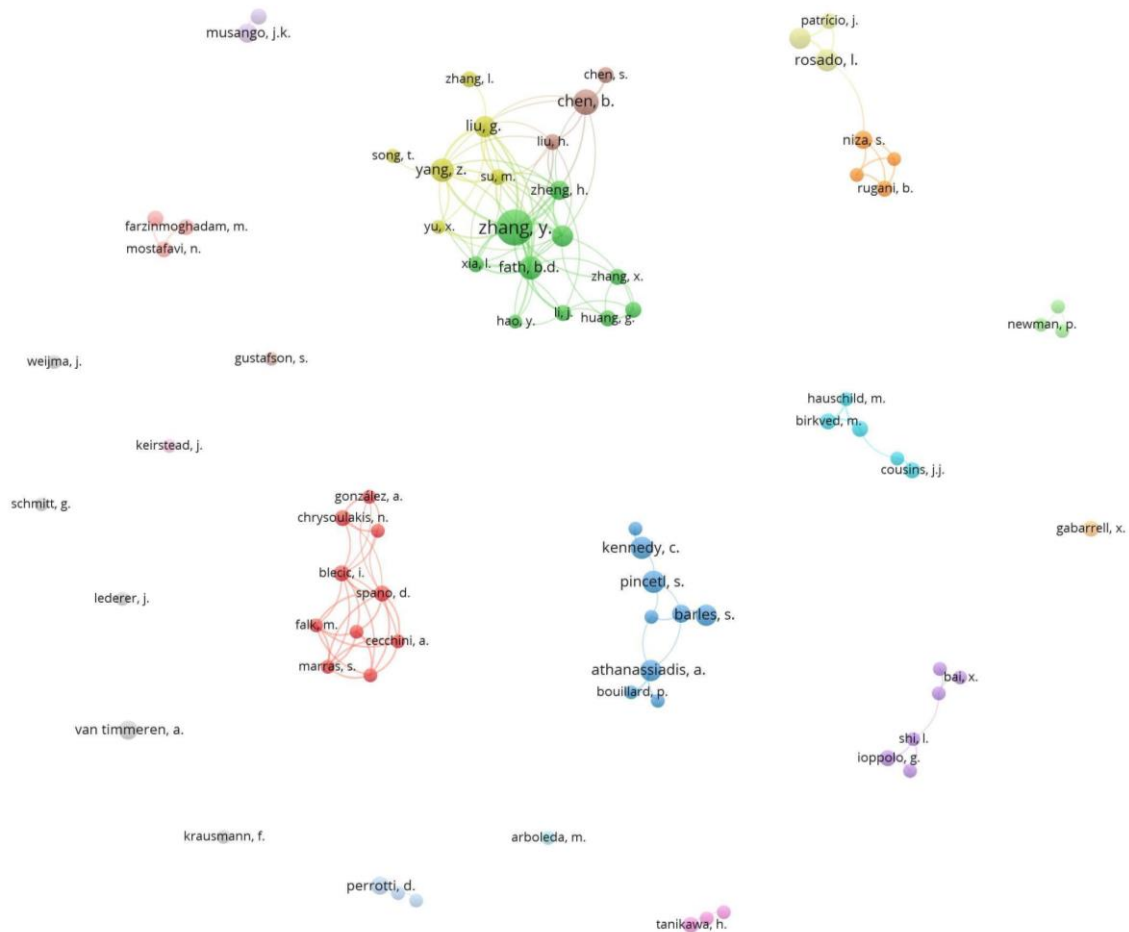
<sup>1</sup> Thus, after a quick calculation based on Scopus data of all publications, we obtain the same order of magnitude of increase for the 1st (+5.1) for the “Journal of Industrial Ecology”, and much lower (+40 and +530) for “Resources, Conservation and Recycling” and “Journal of Cleaner Production”.

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

181

182

183



184

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

188

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

197 The blue community includes some of the foundational figures of UM such Chris Kennedy and Sabine  
198 Barles as well as some of their collaborators (Barles, 2010; Pincetl et al., 2012; Kennedy et al., 2011,  
199 2015). Their cluster of articles has a predominant urban planning and civil engineering perspective,  
200 with a focus on megacities. For them, space is characterized in particular by the links between the  
201 city and the hinterland, through the concept of “environmental footprints or imprints [which] is,  
202 however, particularly important for characterizing the impacts of metabolism (urban in the context  
203 of this article) on the biosphere. The term ‘footprint’ (or imprint) is used to designate the spatial  
204 dimension of the impacts” (Barles, 2010: 450). The spatial dimension is also investigated through  
205 comparison of cities’ metabolic profiles, the study of hinterland characteristics and spatial indicators  
206 (e.g. local versus international supply), as well as the identification of social and spatial drivers of  
207 energy metabolism.

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

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

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

232 The figure also shows smaller communities such as those gathered around: i) Mostafavi’s work on an  
233 integrated UM analysis tool which “includes different scales of spatial interaction that dynamically  
234 influence how urban system parameters are affected” (Mostafavi et al., 2014), ii) Weijma and his  
235 team on spatial nutrient supply through agricultural demand (Wielemaker et al., 2020), iii) Newman  
236 and his work on the spatial fabric and the concept of regenerative cities (Thomson and Newman,  
237 2018), iv) Tanikawa’s spatial analysis of material stock accumulation (Tanikawa and Hashimoto,



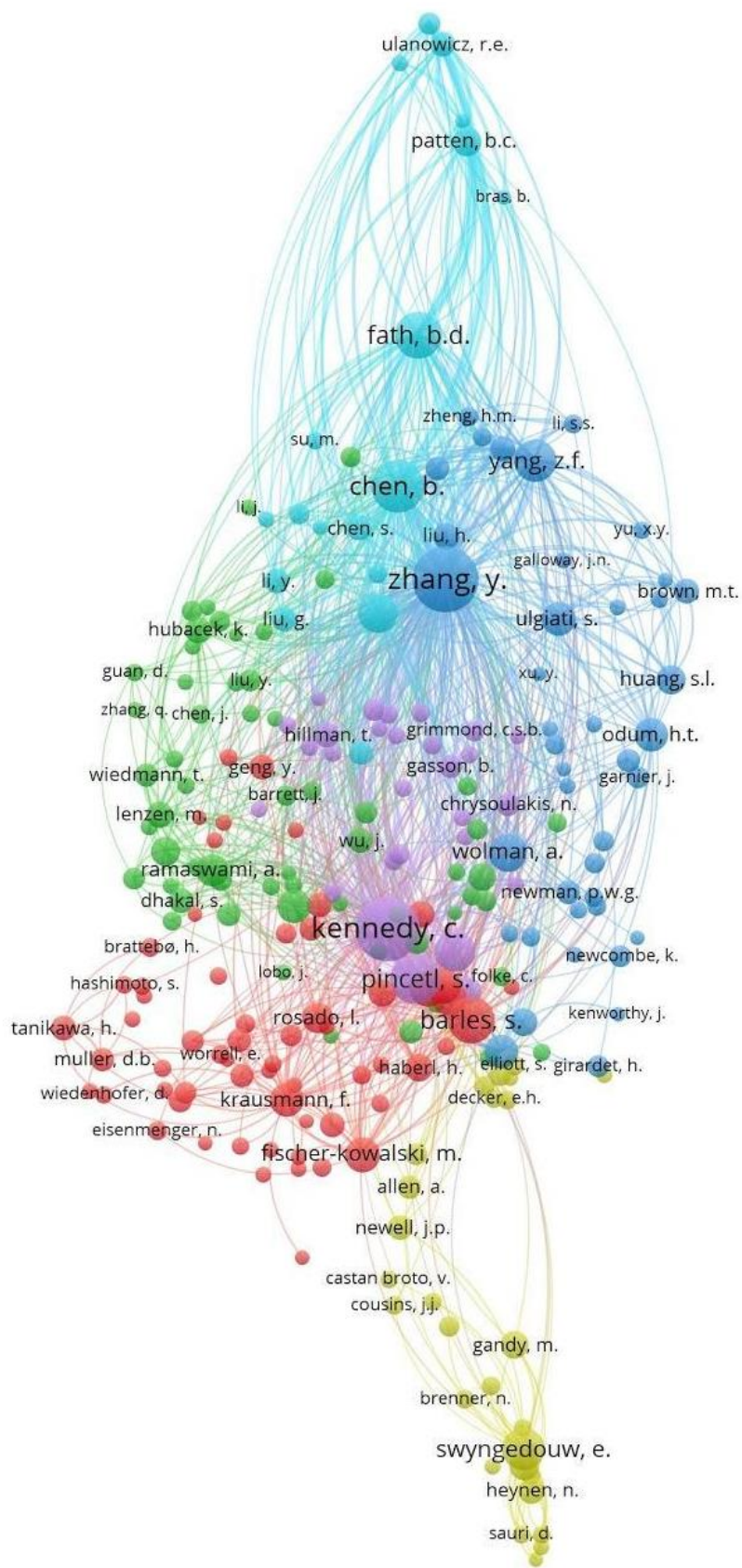
238 2009), v) Arboleda's work on urban political ecology and spaces of planetary urbanization (Arboleda,  
239 2016), vi) as well as a few other smaller communities.

240 All in all, our map features three larger communities, four medium and 13 small ones from a variety  
241 of disciplinary fields and domains, showing the dynamism of the spatial dimension research strand in  
242 the broader UM field. These communities are also relatively young. Nevertheless, some of these  
243 groups can sometimes hide larger and more established communities in the fields of social and  
244 industrial ecology, which might not have a distinct focus on spatial UM (e.g. Kraussmann and van  
245 Timmeren). Similarly, we can observe that these communities are relatively fragmented with few  
246 links existing between them. Through this first step, we could identify the research networks working  
247 in the direction of a spatial turn in UM studies. The next step is to investigate the main research fields  
248 influencing these relatively young (and still compartmentalized) small communities.

249

### 250 **III.2. The scientific landscape analysis of the dataset references**

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



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

261

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

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

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

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

295

### 296 **III.3. A qualitative analysis of the “spatial” themes, recent contributions and perceived limits**

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

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

- 308 - 1. *The political approach*, dealing with power relationships, land grabbing, resource  
 309 exploitation and inequalities, dominant regimes, the reproduction of inequalities within cities  
 310 and between the city and the hinterland, spatial practices and extra-territoriality.
- 311 - 2. *The territorial economic approach*, concerned with the organization of supply chains,  
 312 territorial economy, and competitions
- 313 - 3. *The socio-ecological approach*, highlighting the long-term regimes and the ecological  
 314 economics of territories, the society-nature interactions across spatial scales, and the  
 315 material stock accumulation.
- 316 - 4. *Governance and planning approaches*, focusing on developing research towards  
 317 sustainability grounded in territorial-related parameters, spatial patterns, and infrastructure  
 318 planning.
- 319 - 5. *The spatially explicit modeling/accounting approach*, centered on spatial-explicit  
 320 developments of methods such as Material Flow Analysis, Input-Output model, Emergy,  
 321 Ecological Network Analysis and Life Cycle Assessment.

322

323 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)
<b>1. The political approach</b>	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;			
<b>2. The territorial economic approach</b>	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
<b>3. The socio-ecological approach</b>	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.
<b>4. The governance and planning approaches</b>	Interspatial connections; Spatial patterns; Urban food system in spatialized systems; Resilience spatial planning; Environmental imprint; Infrastructure planning;	(Townsend, 2000) (Pincetl et al., 2012) (Chellersi 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
<b>5. The spatially explicit modeling approach</b>	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
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324

325 Research in category 1 refers to the relations of domination between territories. The place of space is  
 326 therefore at the core of this research strand to understand the territorialities and extraterritorialities  
 327 of the UM and the link with the social dynamics (including conflicts) in cities (Demaria and Schindler,  
 328 2016; Bahers et al., 2019). Gandy’s narrative is centered on the idea of the UM as a dimension to  
 329 urban space (“metabolic dimension to urban space”, Gandy 2018) rather than on the spatial  
 330 dimension of UM, which resonates with Neo-Marxian readings of the UM (e.g. Swygedouw, 2006).  
 331 Understanding the UM as a dimension of the urban space allows to move away from a managerial  
 332 and technocratic metaphor (the urban space as a “metabolic system which can be examined in  
 333 isolation from wider processes of historical change”, Gandy, 2004, p. 374), as in Wolman and initial  
 334 “industrial metabolism” approaches. What are the spatial dimensions of the relations of power and  
 335 vulnerabilities, which the circulation of flows generates? The concepts of metabolic relationships,  
 336 metabolic rift and metabolic vulnerabilities (Wachsmuth, 2012) are among the most recent  
 337 contributions in this theme. Although questions related to the spatial distribution of resources and  
 338 unequal access to them are central to it, this research strand does not always engage, in terms of  
 339 methodological limitations, with the results of quantitative assessments of flows and stocks, which  
 340 can hardly be used in urban planning and public policy evaluation. The relatively recent field of  
 341 political-industrial ecology (Newell and Cousins, 2015) has started catalyzing efforts in this sense, i.e.  
 342 “calculat[ing] and map[ping] out the uneven spatiality of environmental and social impacts  
 343 associated with production and consumption” (Newell and Cousins, 2015), but is far from  
 344 mainstream. Another criticism is that the hinterland is considered only as spaces dominated by the  
 345 metropolises, and the points of view and internal logics of these supply territories are only hardly  
 346 investigated. This is the other side of what is called the 'Methodological cityism' (Wachsmuth, 2012),  
 347 as discussed theoretically in more recent works in this field (Arboleda, 2016).

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

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

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

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

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

425

426

#### 427 **IV. Discussion: an outreaching and future agenda for incorporating the space more systematically** 428 **into UM studies**

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

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

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

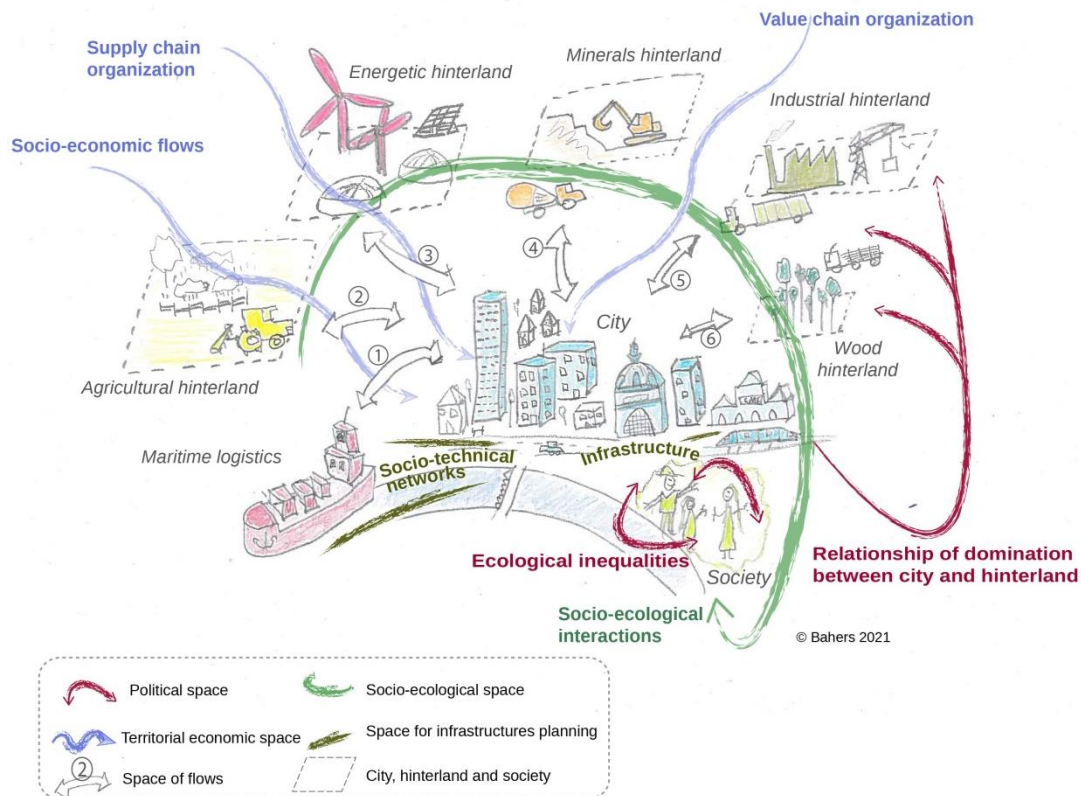


442 *are played out, 2) as a territorial economic space in which raw materials, goods, waste, and value-*  
443 *chains are organised, 3) a socio-ecological space which reflects society-nature interactions through*  
444 *local and global biogeochemical cycles, 4) a space for planning urban metabolic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

448  
449 This integrative definition combining flows, actors, governance, infrastructures and modeling  
450 techniques attempts to provide an interface over which research can converge and build new  
451 cumulative insights.

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

466



467

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

472

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

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

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

506  
507 Analyzing metabolic spaces and landscapes can illustrate the transformation and redefinition of  
508 natural ecosystems into the urban fabric and built environment (Gandy, 2003) while shedding light  
509 on the environmental and spatial quality of new, designed metabolic landscapes (wastescapes,  
510 waterscapes, energyscapes, etc.) (Amenta & Van Timmeren, 2018). By defining the metabolic  
511 landscapes and hinterlands of resources and waste, questions of land appropriation and exploitation  
512 can equally emerge revealing colonial or imperialistic traits of current urban functioning (theme 1). In  
513 addition, when delimiting the spaces of resource extraction, manufacturing and waste treatment, the  
514 social condition of workers along supply chains of materials and goods consumed in cities can be  
515 revealed and traced (category 2). Using a modeling approach (theme 5) to analyze socio-economic  
516 consequences could be an interesting contribution in this view. This question can also welcome  
517 landscape architects, urban planners and designers to propose alternative strategies to the  
518 production of urban landscapes that could minimize the impacts on local and remote natural  
519 ecosystems (theme 4). A research agenda at the intersection of landscape ecology and urban studies  
520 could unpack how the value systems that have emerged around urban resources can inform wider  
521 debates on urban sustainability (decentralization of urban management, locally controlled resources,  
522 regenerative urban landscapes) (category 2).

523  
524 The metabolic interterritorial relationships are another research notion that could also be further  
525 explored. Territorializing the UM can reveal the interconnections and dependencies between  
526 territories for resource extraction and manufacturing, as well as waste management. These  
527 relationships are, in some cases, characterized as predatory, colonial and unidirectional (Arboleda,  
528 2016) (category 1). In the future, it would be extremely relevant to explore how to adjust these  
529 relationships into more inter-territorial cooperation models. Indeed, hinterlands are not only  
530 dominated by the metropolises, but also in the ability to formulate socio-economic and collaborative  
531 strategies or, on the contrary, strategies of rupture and opposition (category 2). What type of  
532 governance for inter-territorial relationships can be proposed at *glocal* level and what forms of

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

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

#### 549 **V. Conclusion:**

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

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

579

580

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