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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**

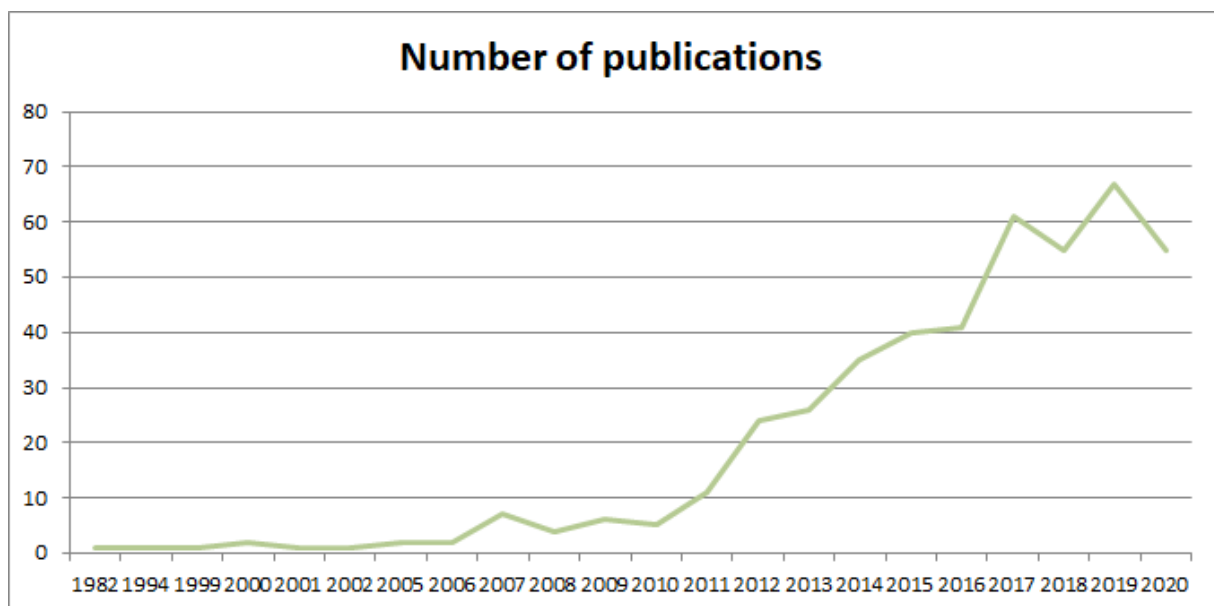
129 Firstly, a literature dataset from the following Scopus search string was built:

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 field¹ 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**

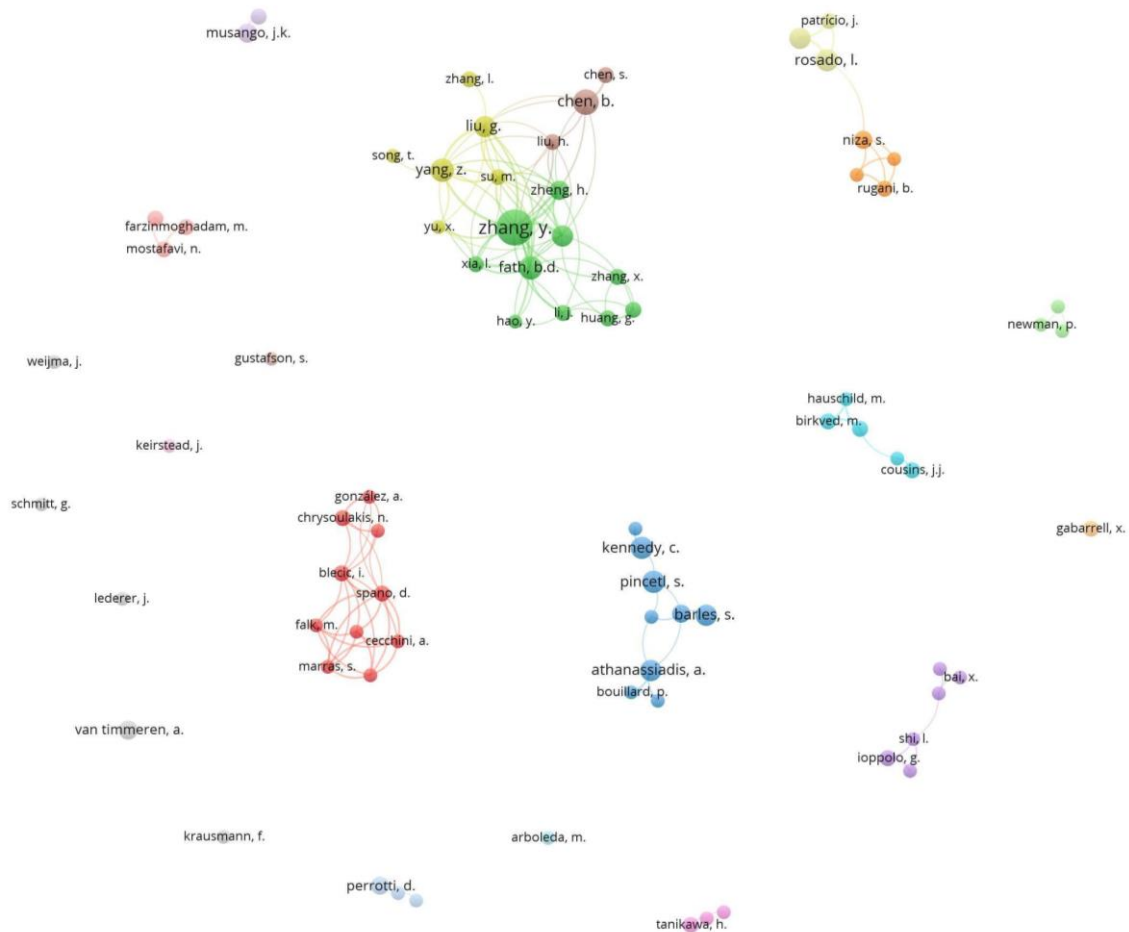
¹ Thus, after a quick calculation based on Scopus data of all publications, we obtain the same order of magnitude of increase for the 1st (+5.1) for the “Journal of Industrial Ecology”, and much lower (+40 and +530) for “Resources, Conservation and Recycling” and “Journal of Cleaner Production”.

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,

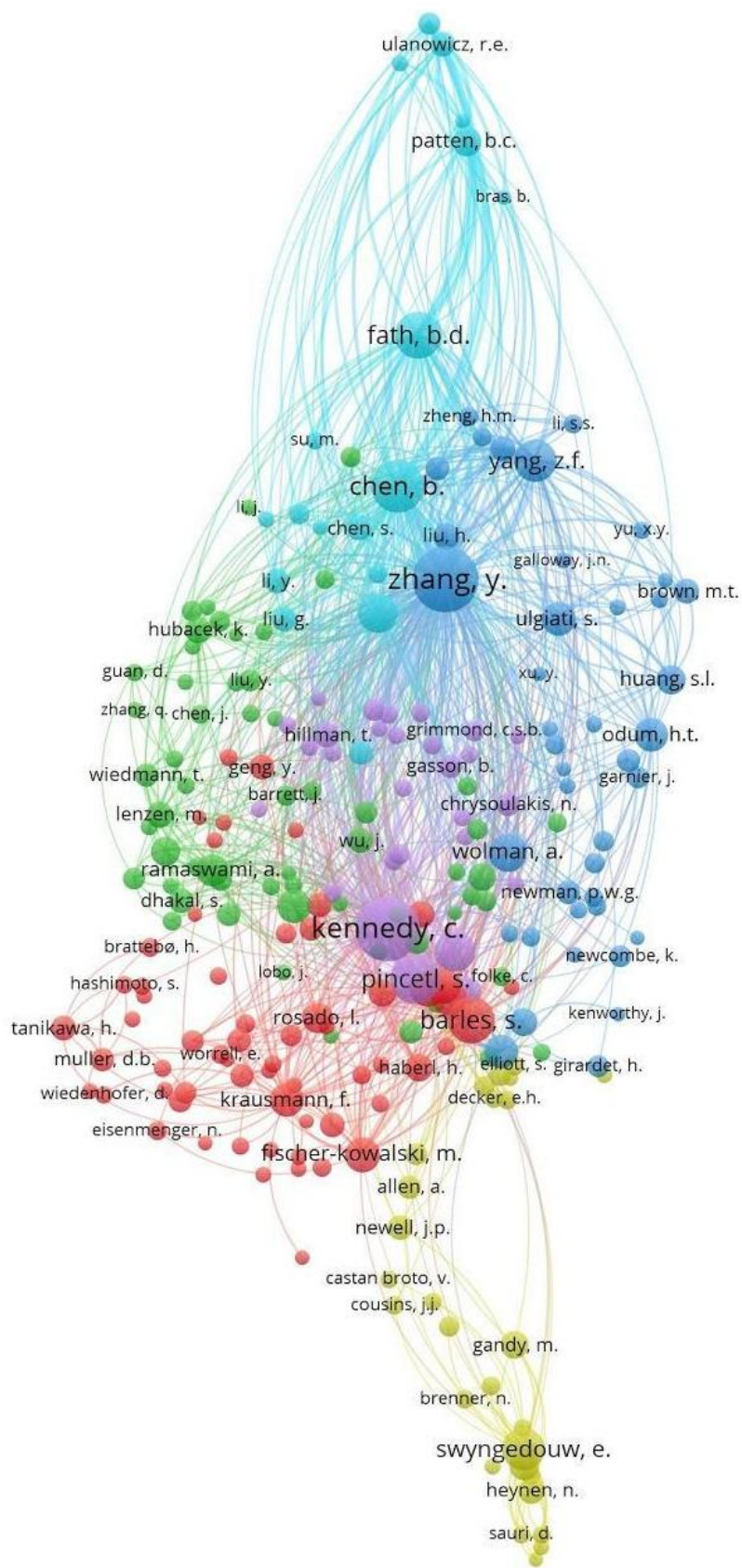
238 2009), v) Arboleda's work on urban political ecology and spaces of planetary urbanization (Arboleda,
239 2016), vi) as well as a few other smaller communities.

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)
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) (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
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
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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*

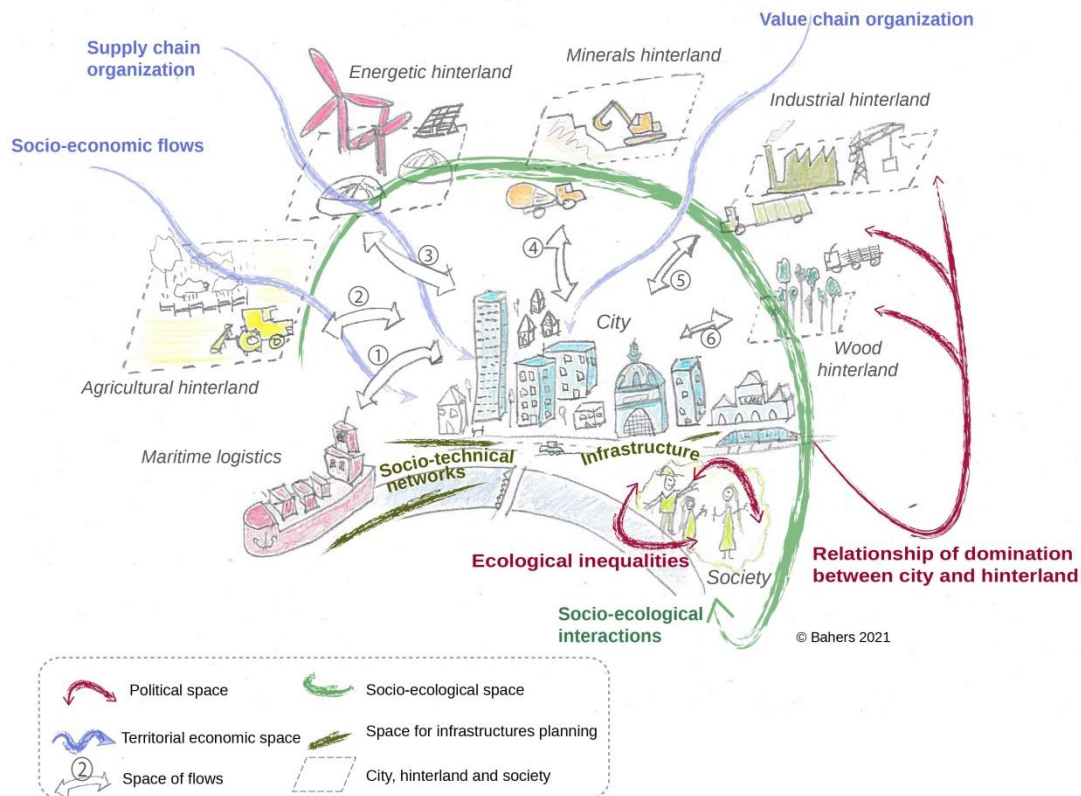
442 *are played out, 2) as a territorial economic space in which raw materials, goods, waste, and value-*
443 *chains are organised, 3) a socio-ecological space which reflects society-nature interactions through*
444 *local and global biogeochemical cycles, 4) a space for planning urban metabolic infrastructures 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.
 471 wood and 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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