The Boundaries of Urban Metabolism: Towards a Political-Industrial Ecology

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The boundaries of urban metabolism: Towards a political–industrial ecology

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Abstract
This paper considers the limits and potential of 'urban metabolism' to conceptualize city processes. Three 'ecologies' of urban metabolism have emerged. Each privileges a particular dimension of urban space, shaped by epistemology, politics, and model-making. Marxist ecologies theorize urban metabolism as hybridized socio-natures that (re)produce uneven outcomes; industrial ecology, as stocks and flows of materials and energy; and urban ecology, as complex socio-ecological systems. We demarcate these scholarly islands through bibliometric analysis and literature review, and draw on cross-domain mapping theory to unveil how the metaphor has become stagnant in each. To reinvigorate this research, the paper proposes the development of *political–industrial ecology*, using urban metabolism as a boundary metaphor.

Keywords
boundary object, industrial ecology, interdisciplinary research, metaphor, political ecology, urban ecology, urban metabolism

I Introduction

Theory of metabolism in formalized written word dates back to at least the time of Sanctorius (1712 [1614]), who spent some 30 years eating, working, and sleeping on his famous balance seat, meticulously weighing his dietary intake and bodily excretions. He concluded that a substantial portion of his food was lost through his skin as *perspiratio insensibilis* or 'insensible perspiration' (Figure 1). Much later, in his treatise on cells, Schwann (1839, 1847) first used the term *metabolische*, from which metabolic derives. And of course Marx famously deployed metabolism (*stoffwech sel*) to characterize complex nature–society relationships, borrowing heavily from Moleschott's (1852) work on cycling and exchange of energy–plant–animal nutrients and from chemist Justus von Liebig's (1842, 1859) use of 'metabolic rift' to characterize declining soil conditions due to the intensification of agriculture and the corresponding spatio-temporal disconnects between urban and rural (Swyngedouw, 2006a).

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Figure 1. Sanctorius (1561–1636) at his famous balance seat, where he spent the better part of 30 years measuring his body's metabolism.
Source: University of Kansas Medical Center Clendening Library, 2000.

Geographers are well familiar with Burgess (1925) and other human ecologists in the Chicago School of Sociology, who theorized a transposition of ecological theory onto society to explain (and in cases predetermine) urban social structure and spatial pattern. In 1965, sanitary engineer Abel Wolman wrote a seminal article in *Scientific American* that quantified the metabolic inputs (e.g. water, food, and fuel) and outputs (e.g. waste) of a hypothetical American city. Meanwhile, the Metabolist movement in Japan brought an avant-garde approach to urbanism as organic process, where buildings and other features of the city exhibited metabolic cycles. Although only a single building, the Nakagin Capsule Tower in Tokyo, was built (1972), the utopian visions of the organismic city – replete with prefabricated modules to replace outdated elements of the urban form – continues to influence architecture today (Lin, 2010).

From these intellectual legacies, academia has witnessed a remarkable resurgence of 'urban metabolism' over the past two decades, sparked by increased attentiveness to processes of urbanization, to material and cultural consumption, and to notions of sustainability. However, scholars deploying the metaphor ascribe very different meanings and models to it. Building from Marx, human geographers and sociologists use it to denote the interwoven knots of social and natural processes, material flows, and spatial structures. Industrial ecologists in the Wolman tradition use mass–balance accounting methodologies such as material flow analysis (MFA) to quantify metabolism's 'stocks' and 'flows'. Then, there is the 'emergy' research strand stemming from Eugene Odum's systems ecology and metabolism theory.

These diverse uses of urban metabolism beg the following questions: Given that scholarly communities share the metaphor, do they have similar intellectual lineages? Do these communities interact? If not, why? How might geographers apply theories and approaches in industrial ecology and urban ecology to advance understanding of urban space?

To begin to answer these questions, this essay reviews 47 years of academic literature on urban metabolism (1965–2012) by using bibliometrics to map the boundaries of scholarly communities deploying the metaphor (Section II). We delineate and analyze the emergence of three 'ecologies' of urban metabolism: industrial ecology, Marxist ecologies, and urban ecology (Section

III). As the bibliometric analysis reveals, these thought traditions have effectively formed islands of urban metabolism, with little cross-fertilization. The urban political ecology (UPE) metabolism community, relatively small in terms of scholars and citations, is especially isolated from the other clusters.

These clusters are bounded by the ways in which theories of metabolism are transposed on the city as metaphor. Stemming from the Latin *metaphora*, meaning ‘to carry over’ or ‘to transfer’, metaphor literally means to understand and experience one thing in terms of another. Metaphors like urban metabolism have the power to structure entire research paradigms through metaphorical redescription (Hess, 2010). Geography is filled with such *large* metaphors (Barnes and Curry, 1992), from assemblages, networks, cyborgs, hybrids and circulation, to coupled natural–human systems, the Anthropocene, adaptation, and resilience. The metaphorical generation process makes the unknown more familiar, yet results in an inevitable *partiality* (Richards, 1936; Lakoff and Johnson, 1980; Smith and Katz, 1993). Just as focusing light on part of a room highlights certain features, while hiding others, the partiality of metaphors gradually becomes canonized through habitual use. As Barnes (1996: 154) explains, the initial ‘murkiness’ of the chosen metaphor is cleared up, moving from hermeneutic-to-epistemological. In the end, metaphors become literal, in essence ‘dead’.

In this essay, we expose the partiality endemic to urban metabolism in the three ecologies and argue that the metaphor has reached the point of maturity, becoming *stagnant* – in some instances, ossified (Section IV). In the case of geography, Marxist urban political ecologists have so successfully forged the conceptual and methodological apparatus for urban metabolism that it has become almost synonymous with urban socionatural transformations wrought by the uneven processes of capitalist development.

But just as broader Marxist theory has struggled to move beyond strictly a ‘social theory’ (Swyngedouw, 2006a), there is an absence of ‘ecology’ in much of the UPE metabolism research. In addition, UPE urban metabolism typifies other perceived shortcomings in ‘first wave’ UPE scholarship (Heynen, 2014), including a preponderance of qualitative approaches and a ‘methodological cityism’ that ends up privileging a traditional, bounded conception of the city (Angelo and Wachsmuth, 2014).

To reinvigorate the urban metabolism metaphor in geography and move UPE forward as a part of a ‘second wave’ research agenda, we propose the development of *political–industrial ecology* through the creative infusion of ideas and approaches from the other two ecologies (Section V). Industrial ecology offers a suite of untapped methods, such as material flow analysis (MFA) and life cycle assessment (LCA), with which to map out and quantify the networks of flows that circulate within and beyond the city. Urban ecology, meanwhile, provides the theory necessary to explore the ecological and biophysical properties of urban space and is nested in an ontological nature–society construction that resonates with UPE.

Cognizant of the challenges of interdisciplinary scholarship, including the difficulty in reconciling the divergent spatial politics that underlie the respective metaphorical deployments, we are not proposing any sort of framework that presupposes an integrative approach to studying urban metabolism. Instead, urban metabolism can be collectively conceptualized as a ‘boundary metaphor’ – drawing on the concept of boundary objects (Star and Griesemer, 1989), whereby scholarly communities might interact through empirical practice and as a means to explore the friction between the varied epistemologies, methodologies, and framings of urban metabolism. Towards that end, we provide a hypothetical case of the political–industrial ecology of urban water supply. Through these interdisciplinary engagements, a more robust metaphor of urbanization can emerge: the metabolism of the urban ecosystem.

II Mapping disciplinary worlds

Scholars use bibliometrics to map the dynamics of research fields and to situate scholarly work in relation to their academic communities (see Morris and Van der Veer Martens, 2008, and Persson et al., 2009, for basic guidance on how to conduct a bibliometric analysis). The results provide a map of scientific knowledge that Small (1999: 799) describes as 'a spatial representation of how disciplines, fields, specialties, and individual articles or authors are related to one another as shown by their physical proximity and relative locations'. As with cartography, bibliometric techniques map known structures of a system and reveal a limited view of elements. Our analysis focused on mapping the structure and interconnections between authors around the base concept of urban metabolism at a certain level of detail and inclusiveness so as to better understand the extent to which scholarly communities are acting independently from each other and the degree to which cross-fertilization occurs around the concept. Inherently a subjective process, choices to remove or add links within the maps were based on a desire to balance the highest possible number of data points with visual clarity. The bibliometric software BibExcel (Persson et al., 2009) was used to prepare the network data from the collected records; Pajek (2012) software was used to map the field.

To ensure germaneness to urban metabolism, we performed a keyword search using the Institute of Scientific Information's (ISI) Web of Science™ (WoS) database. WoS was chosen over Google Scholar because the former allows downloading full citation records, including cited references and cited reference counts, into a .txt file compatible with BibExcel. In WoS we searched for articles with 'metabolism' or 'metabolic' in the topic or title, plus one of the following terms: city, cities, urban, rift, social, socio-economic, society, and industrial. These terms enabled the widest range of citation data possible to capture key papers, yielding 696 entries. Then, to narrow the focus to relevant subject areas in the social sciences, physical sciences, and engineering, articles from fields such as toxicology and pharmacology were excluded. For example, we removed a technical study using urban samples to analyze the human metabolism of a substance. This process reduced the total to 311 articles in the following ISI-defined subject areas: environmental sciences (59%), engineering (24%), business economics (12%), geography (11%) and urban studies (8%).

WoS does not include citations outside of the WoS-registered journals, which eliminated some influential articles, such as Fischer-Kowalski (1998), from the initial keyword search. WoS also excludes many trade journals, books, and book chapters, making citation counts in WoS smaller than in Google Scholar. WoS is also primarily an English-language database, giving the results an Anglo-American bias. For this reason, Chinese and Japanese urban metabolism scholarship, which is fairly active, is underrepresented in the bibliometric mapping. To ensure inclusion of as many publications as possible, we used the 'create citation report' function and selected 'full record' with 'cited references' to download the citation data of all articles that cited the original 311 articles. These cited references, including books and non-English journals, provided as robust a picture of the structure and evolution of the fields employing the metaphor as possible, given the limitations of WoS.

To map scholarly networks, the bibliometric analysis incorporated three measures: direct citations, co-citations, and weighted-direct citations (Figure 2). Direct citation analysis is especially helpful for identifying emerging research trends (Shibata et al., 2009) and clarifying information flows between two articles (Persson and Ellegård, 2012). To identify the specific direct

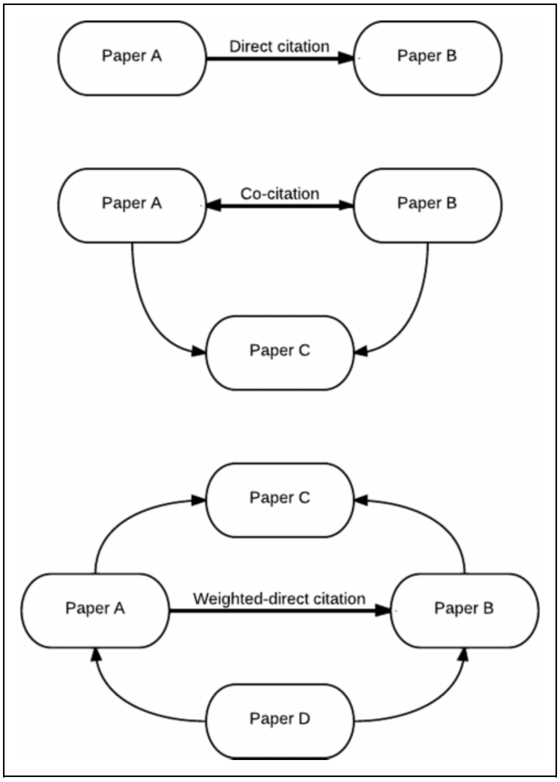

Figure 2. Bibliometric analysis measures: direct citation; co-citation; and weighted-direct citation.

citation links among the downloaded articles, we omitted the second initial of the author's first name, thus minimizing the chance of missing a link due to spelling variations. We then linked articles based on author last name and first initial, year, journal, volume, and start page. To illustrate the most influential scholars and publications in the field, the results were plotted over time.

Co-citation links, introduced by Small (1973), posit that a stronger relationship is established between articles if they appear in the references of a third document. This technique highlights instances of dense direct citation, enabling the network to be broken up into meaningful groups or components (Small, 1999). The result is a more nuanced view of the interaction structure between scholarly communities and the groups of authors who typically collaborate. To identify the primary works influencing the research field, we required a minimum of ten citations among the reference list. The co-citation network was mapped in Pajek using the Kamada-Kawai layout algorithm, a forced-directed layout utilized for graphing networks in two-dimensional space; it improves map readability by reducing the number of overlapping and crossing links. After data importation, complexity was further reduced by removing edges, or lines, with a value less than five (i.e. papers sharing fewer than five references). This improved legibility and highlighted the more prominent groups within the network, while retaining its overall structure.

To identify additional research communities, the third step used weighted-direct citations, which integrates direct and co-citations with shared references (so-called bibliographic couplings) into a single metric of citation strength and further decomposes the network of papers (Persson, 2010). This is based on the rationale that the more shared references between two papers, the more similar they are in topic (Kessler, 1963). The strongest direct citation links between papers are those that share many references and are frequently co-cited. Weighted-direct citations calculate these relationships by assigning values to the citations. A direct citation link between two articles would be assigned a value of one, for example, but more shared references and co-citations can strengthen the link. Thus, if a direct citation link is accompanied by one shared reference and one co-citation, the weighted-direct citation has a value of three; for each additional co-citation or shared reference, the value grows by a factor of one. Again using the Kamada-Kawai layout in Pajek to map the network, we removed the weaker components to improve map clarity and to maintain consistency with the co-citation map by requiring a minimum value of four.

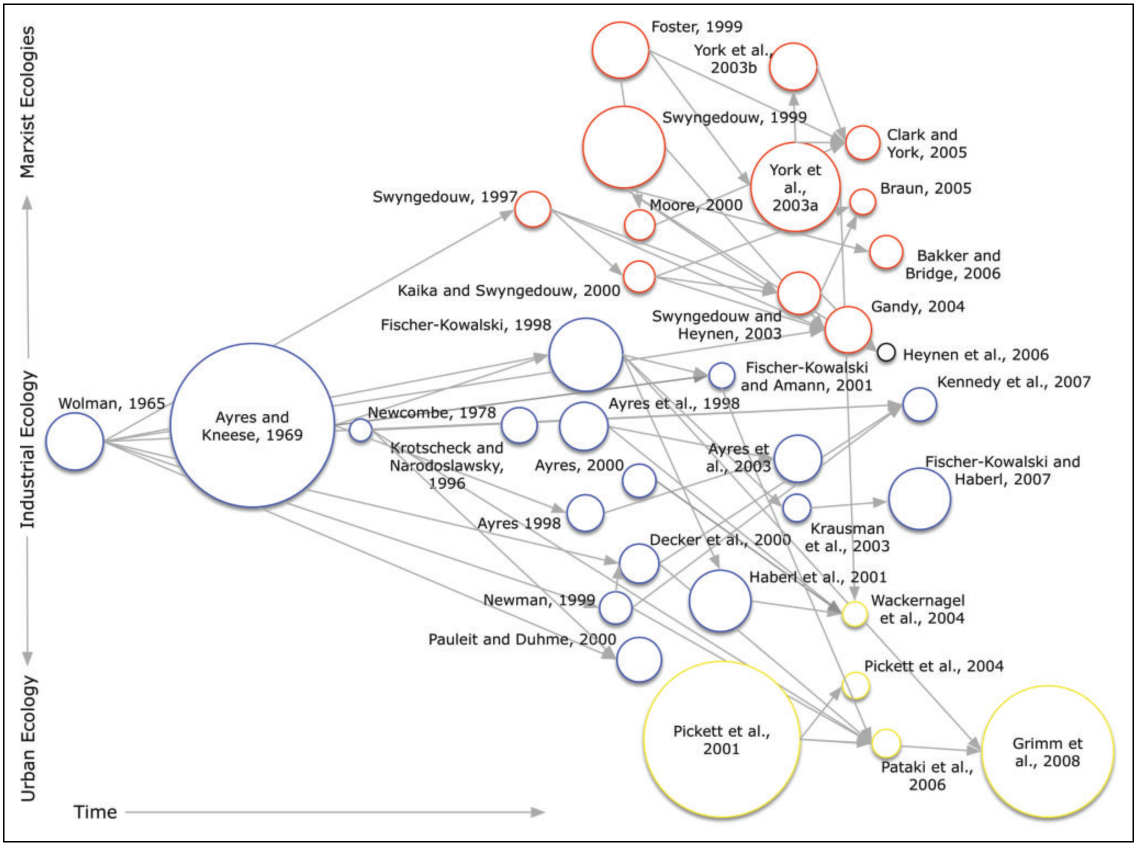

Figure 3. The three thought traditions of urban metabolism research: Marxist ecologies, industrial ecology, and urban ecology. The figure illustrates the direct citation network of the 35 most cited articles informing theory on urban metabolism. Arrows indicate a direct citation, and node size is proportional to the number of citations.

III Three distinct 'ecologies' emerge

The bibliometric analysis, with subsequent mapping, indicates three *ecologies* – industrial, Marxist, and urban; each includes strands from multiple disciplines but can be traced to a common lineage.[1] Labeling these three thought traditions as such took careful consideration. A case could be made for urban planning rather than urban ecology. Girardet (1992) used linear vs. circular metabolism as a heuristic device to link ideas of sustainable development to cities. Wackernagel and Rees (1996) used the metaphor symbolically to characterize the ecological footprint of cities, and Newman (1999) proposed extending metabolism to include livability and health. But in the end, planning was excluded because the metaphor is not infused with the same theoretical or methodological rigor and is not consistently visible in the bibliometric analysis.

Based on citations of the 35 most cited books and articles, the most influential of these ecologies in the urban metabolism field is industrial ecology (49%), followed by the Marxist ecologies (29%) and urban ecology (16%), which are briefly characterized in the next section. Fields such as architecture and urban planning (6%) form the bulk of the remaining citations. Figure 3 illustrates the most influential thinkers, as indicated through citations. Wolman and Robert Ayres appeared early on and were seminal to industrial ecology formulations. By the late 1990s, urban metabolism in Marxist ecologies began to emerge with works by Swyngedouw and John Bellamy Foster, followed by those of Gandy, Kaika, Heynen, and York. By the early 2000s, notable urban ecologists such as Steward Pickett and Nancy Grimm were employing the metaphor.

I Industrial ecology

Pioneered by physicists and engineers (Ayres and Kneese, 1969) in the late 1960s, industrial ecology is largely a normative project whereby 'nature' serves as a model, both in terms of structure and function, for the analysis of existing industrial systems and for guiding new, more efficient and resilient forms (Jelinski et al., 1992; Frosch, 1992). Building from Wolman, Ayres (1989, 1994) developed conceptual foundations for 'industrial metabolism' that specified more concretely how industrial systems were analogous to organisms in terms of processing waste and energy. Within industrial ecology, urban metabolism is defined as 'the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste' (Kennedy et al., 2007: 44).

Intellectual underpinnings for industrial ecology stem from Lavoisier's Law of the Conservation of Mass (1789). Stating that in chemical reactions mass is neither created nor destroyed, the law provides the basis for the mass-balance approaches and methodologies driving industrial ecology. In urban metabolism research, the most widely used is material flow analysis, or MFA (Baccini, 1996; Baccini and Brunner, 1991), which is a fundamental tool for facilitating industrial symbiosis (Chertow, 2000, 2008) – the strategic co-location of industrial activities that enable waste from one factory (e.g. fly ash) to be an energy or material source for another (e.g. forging of bricks).

The co-citation network map (Figure 4), which provides insight into the intellectual terrain of the metaphor and respective knowledge structures, indicates two dense but distinct network clusters in industrial ecology. We label the first as 'traditional' urban metabolism and the second as the Vienna School of socio-economic metabolism, developed by sociologist (and former president of the International Society of Industrial Ecology) Marina Fischer-Kowalski and her colleagues at Vienna's Institute of Social Ecology (Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1998). As illustrated by the weighted-direct citation analysis map (Figure 5), Fischer-Kowalski's (1998) intellectual history of urban metabolism links the two clusters. Nonetheless, the Vienna School has evolved into being largely distinct.

'Traditional' urban metabolism. The densest networks of scholarly interaction are in this network cluster (Figure 5). MFA is traditionally used to develop strategies to gradually dematerialize the metabolism by optimizing resource use. An influential early case study was the metabolism of Hong Kong (Newcombe et al., 1978), which Warren-Rhodes and Koenig (2001) bookended, leading them to conclude that Hong Kong's 'metabolic rates' had increased substantially. Similarly, in a meta-analysis, Kennedy et al. (2007) concluded that eight metropolitan regions across five continents exhibited 'increasing per capita metabolism'. But most case studies – Tokyo (Hanya and Ambe, 1976), the Swiss Lowlands (Baccini, 1997), Paris (Barles, 2007a, 2007b, 2009), Vienna (Hendriks et al., 2000), Stockholm (Burström et al., 1997), Toronto (Sahely et al., 2003), Singapore (Schulz, 2007), Beijing (Zhang et al., 2011), and Lisbon (Niza et al., 2009) – have been temporal snapshots, with varying degrees of flow inclusiveness (usually water, materials, and energy, sometimes food).

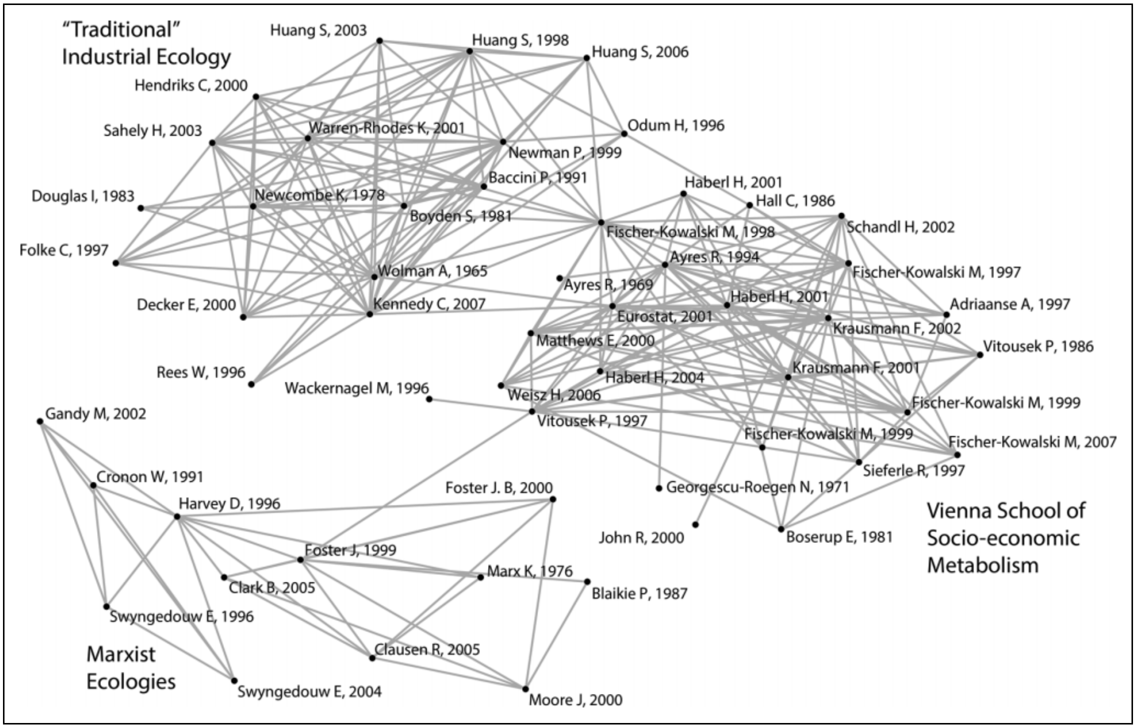

Figure 4. This co-citation map illustrates three network clusters that inform the urban metabolism knowledge base: 'traditional' industrial ecology, Vienna School of socio-economic metabolism, and Marxist ecologies. Note the important linkage played by Fisher-Kowalski (1998) between the two industrial ecology network clusters. The density of the interconnections indicates a greater degree of co-citation strength.

Within this cluster, an interesting research strand combines MFA with Eugene Odum's systems ecology (1953, 1969) and H.T. Odum's concept of 'emergy' (1983, 1996) – a measurement unit for a system's energy (expressed as solar energy equivalents). Early case studies included Miami (Zucchetto, 1975) and 1850s Paris (Stanhill, 1976), and the most highly cited works are of Taipei, Taiwan, by Huang (1998) and Huang and Hsu (2003).

Vienna School of socio-economic metabolism. This second network cluster is smaller, but according to the bibliometric analysis scholars within it are some of the most prolific (Haberl and Krausmann with 17 records, Fischer-Kowalski with 10). Their metabolism work also uses MFA to quantify stocks and flows, but it is far more ambitious in that sweeping historical materialism explains how socio-economic transitions (such as from agrarian to industrial) have shaped stock–flow trajectories. The analyses make heavy use of metabolism as metaphorical expressions ('socio-metabolic regimes', 'metabolic rates' and 'metabolic profiles') and consider issues of labor, capital, property, income distribution, and consumption. Some research links changes in land use to metabolism dynamics, but those changes are rarely made spatially explicit, perhaps because the analytical frame often extends to broader spatial scales: the socio-economic energy metabolism of Austria from 1830 – 1995 (Krausmann and Haberl, 2002; Krausmann et al., 2003); changes in societal metabolism and

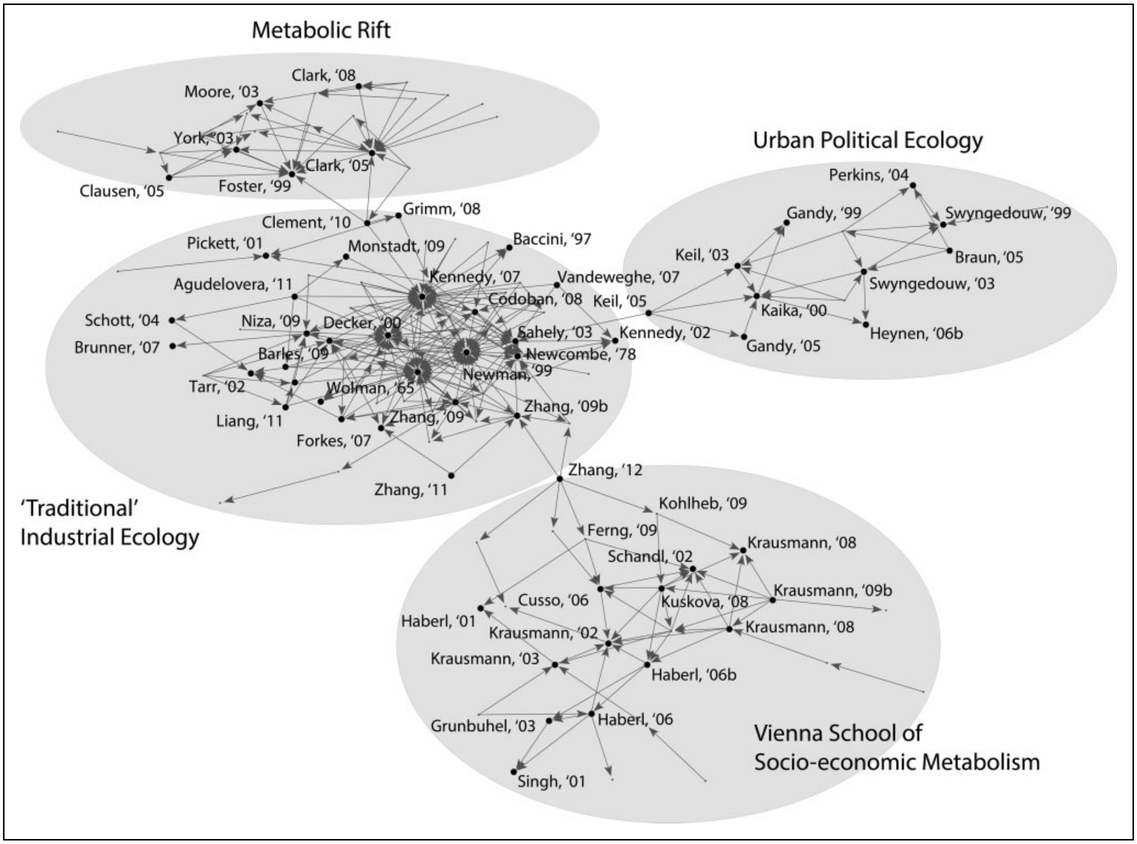

Figure 5. This weighted-direct citation map expands urban metabolism research into four network clusters. The Marxist ecologies thought tradition is now divided into two network clusters: metabolic rift and urban political ecology. Primary nodes are labeled by author and date. Arrows represent direct citation links.

land use in the United Kingdom from 1950 – 2001 (Schandl and Schulz, 2002); social metabolism in agrarian Catalonia from 1860 – 1870 (Cussó et al., 2006); and even the socio-metabolic transition of the globe (Haberl, 2006).

Although the Vienna School draws strategically from the social (e.g. sociology, history, economics, anthropology, geography) and natural (e.g. biology, ecology) sciences (Fischer-Kowalski, 1998; Fischer-Kowalski and Weisz, 1999), their theorization of the socio-economic metabolism as a process of nature–society coevolution is rooted in sociology; Luhmann's (1984) theory of social systems is particularly influential, as is the work of Boyden, Godelier, and Sieferle (Weisz, 2011; Weisz and Clark, 2011).

2 Marxist ecologies

Two isolated clusters, one on UPE and the other on Foster's theory of metabolic rift (Figure 5), utilize metabolism to investigate a range of related themes inspired by Marx's theorizations on metabolism[2] – from broad tensions between nature and society (Cronon, 1991; Gandy, 2002) to the role of social power in shaping urban space and access to resources (Swyngedouw, 2004) and the ruptures between human production and the natural world wrought by urbanization and growth in long-distance trade (Broto et al., 2012; Foster, 1999; Moore, 2000).

Urban political ecology. Urban political ecologists use metabolism to characterize nature–society relationships as dynamic and networked circulations that reorganize social and physical environments into socionatural assemblages (Swyngedouw, 2006a). Highly influential in the 'first wave' of UPE (Heynen, 2014) and development of the metaphor is Harvey's (1996) notion of a 'created ecosystem' (which interprets the ecology of cities in a manner reflective of Marx's metabolism as a nature–society dialectic), Smith's (2008) theorizations of the metabolism of nature as embedded in the production of nature, and Cronon's (1991) vivid account of how the urbanization of Chicago transformed both city and countryside to produce a unique political ecology.

The outcome has been a robust scholarship that shows urban space to be a socionatural hybrid. Scholars have used the concept to explore both how nature is transformed by and enrolled into the political and socio-economic practices that shape urban form and its metabolic relationship to other geographies (Gandy, 2002) and how the flows of water (Swyngedouw, 2004), fat (Marvin and Medd, 2006), alcohol (Lawhon, 2013), and the technologies and infrastructures connecting these objects and places (Gandy, 2005; Kaika and Swyngedouw, 2000; Monstadt, 2009) form a 'socio-environmental metabolism' entangled with the dynamics of social power and capital. Collectively, this community of scholars utilizes the metaphor to destabilize binaries (e.g. nature–society, city–countryside) and unveil uneven power relationships shaping urban space with the normative goal of fostering more sustainable and democratic forms of urban environmental governance and policy-making (Keil and Desfor, 2003; Swyngedouw, 2004; Swyngedouw and Heynen, 2003).

Metabolic rift. The second cluster also uses metabolism to characterize intertwined nature–society relationships but differs due to a sustained focus on the metabolic rift between town and countryside. Drawing on Marx's writings, Foster (1999, 2000) frames this as an antagonistic human–environment binary that emerges due to the processes of capitalism (such as how capitalist forms of urbanization create this rift). Collectively, as indicated in Figure 5, Foster's elaborations on the rift have informed case studies in a range of 'spatio-temporalities' (Sheppard, 2010), from Clausen and Clark's (2005) examinations of depleted fish stocks and the expansion of aquaculture in relation to capitalist production to Wittman's (2009) illustrations of how peasants' movements can bridge the rift. In this vein, McClintock's (2010) work illustrates the potential for linking metabolic rift with core UPE concerns as he reveals from ecological, social, and individual perspectives how urban agriculture is both an outcome of the rift's alienating forces and an attempt to ameliorate it by reconnecting urbanites with food production.

3 Urban ecology

Evidenced by the lack of large network clusters (Figures 4 and 5), urban ecology has used the metaphor with less persistence, initially surprising given the highly cited work on urban metabolism by ecologists (Figure 3) and system ecologist EP Odum's continued influence in industrial ecology. Golubiewski (2012a) maintains industrial ecologists misread Odum's work, asserting he referred to the metabolism of an individual organism, not the level of community. But a close reading of Odum's texts reveals numerous references to a more extensive metabolism (e.g. the 'community metabolism of self-sustaining micro-ecosystems' (1968: 16).

For many ecologists, Odum's ideas are outmoded and misapplied with respect to the ecology of the city. A reading of the highly cited work indeed reveals ambivalence towards the metabolism concept, deploying it for its metaphorical power yet being cognizant of its contested status vis-à-vis cities within the ecology discipline. Thus Grimm et al. (2008) acknowledge the debate about its appropriateness but highlight its utility as a method to quantify resource consumption trends. Decker and colleagues (2000) use the term similarly in their synthesis of the material and energy flows of 25 world cities, as do Ngo and Pataki (2008) in their longitudinal mass-balance analysis of Los Angeles County's fuel, water, and food flows.

Nevertheless, given the importance of ecological metabolism theory, the presence of highly cited works, and the engaged debate by ecologists over the metaphor's appropriateness, we include urban ecology as the third 'ecology'. Let's now analyze how epistemology, politics, and model-making are intertwined with the construction of the metaphor in each of the three ecologies.

IV Islands of urban metabolism

Purcell (2003) used a debate over scale, between Marston and Brenner, to make the case that 'islands of practice' form not because of competing epistemologies but instead because of research *practices* (e.g. data collection, analysis, and discourse) that gradually limit outside engagement. Purcell was referring specifically to schisms within human geography, while our analysis spans disciplines and thought traditions that exhibit a divide between more positivist approaches in urban ecology and industrial ecology and the range of critical realist, materialist, and constructivist approaches found in the Marxist ecologies.

Epistemological differences clearly shape the research questions posed, the processes by which data are collected, and the parameters for what counts as valid knowledge. But how does one explain the separate islands between 'rift' sociologists and urban political ecologists despite a shared Marxist legacy? Scholarly islands extend beyond epistemology, ranging from the object and method of study to the disciplinary-bound reward structures of the academy; all combine to form a process of exclusion stemming from knowledge production in disciplinary cultures (Schoenberger, 2001).

Space limits a detailed excavation of how and why metabolism islands have emerged. The focus here is on the use of metaphor because, unlike in more Kantian traditions where its role might be circumscribed to metaphorical expression (e.g. 'it's raining cats and dogs'), we view the metaphorical process as fundamental to scientific theorizing. This aligns with work on metaphor by Richards (1936) and Lakoff and Johnson (1980), by critical realist philosophers who view it as the generative basis for making sense of the world (Lewis, 1996), and by geographers who write of its conceptual power and therefore the importance of exposing the politics associated with their construction and use (Barnes and Curry, 1992; Smith and Katz, 1993; Robbins, 2013).

Just as metaphors are inseparable from their ascribed meanings and politics, so too are the models generated from them that make meaning of the world. Black (1962: 40) recognized this early on: 'to speak of "models" in connection with a scientific theory already smacks of the metaphorical'. As structured simplifications of complex phenomena, models need not only refer to statistical equations, graphs, flow charts, or maps (Pickett et al., 2004).

Richards (1936) identified metaphor as having a 'tenor' (its underlying subject) and a 'vehicle' (the terms for presenting that subject). Thus, in the example, 'the city is a metabolism', the tenor is 'the city', and the vehicle is 'metabolism'. The generative power of metaphor is through *interaction* or *interanimation* of these words and their associations. Richards (1936: 94) describes the process as 'a borrowing between and intercourse of thoughts, a transaction of context (rather than mere substitutions)'.

Thus, the emergent cognitive power of metaphor lies in its ability to conceptualize a murky subject in a novel way. Tenor and vehicle, therefore, co-construct each other to give more varied and powerful meaning to both (Richards, 1936: 108). In this intercourse of thoughts, there are not two subjects per se (urban and metabolism), but rather just one (urban), and this subject is described in lexicon appropriate to a description of a metabolism.

Lakoff and Johnson (1980) would later famously build off of Richards' interaction theory of metaphor, replacing vehicle with *source domain* and tenor with *target domain* and characterizing the metaphorical process as 'cross-domain mapping', whereby a fixed set of 'ontological *correspondences*' between entities in the source domain are mapped onto entities in the target domain (Lakoff, 1993). Lakoff and Johnson (1980) would also helpfully point out that by making a lesser known domain better understood, metaphor has a *utility*, but the process invariably results in *partiality*. Cresswell (1997: 334) conveys this partiality in spatial terms: 'Many metaphors are distinctly geographical acts that encourage spatial thoughts and actions while prohibiting others.' Thus, constructions of the urban metabolism metaphor are useful but inevitably partial, asymmetrical representations of particular phenomena, processes, sets of practices, and situated knowledge (Haraway, 1988).

Using interaction theory of metaphor and the cross-domain mapping concept, we now analyze the source and target domains in the three ecologies of urban metabolism and the varied epistemologies, politics, models, and methods that undergird deployments of the metaphor. This is a discussion informed by the few instances where the three thought traditions have engaged each other in the literature over appropriate use of the term, namely Syngedouw, Keil and Boudreau (UPE), Kennedy (industrial ecology), and Golubiewski (urban ecology). This section illustrates the ways in which the urban metabolism metaphor has become stagnant, due to repeated use through particular disciplinary constructs and situated knowledge. Table 1 summarizes the theoretical influences, emphases, lexicon, methods/models, and critiques or perceived limitations of urban metabolism in the three ecologies.

1 'Input–output model of the flow of things'

> Studies on urban metabolism have often uncritically pursued the standard industrial ecology perspective based on some input–output model of the flow of 'things.' Such analysis merely poses the issue and fails to theorize the making of the urban as a socio-environmental metabolism. (Swyngedouw, 2006b: 35)

In 'traditional' industrial ecology, the vehicle or *source domain* stems from an Odum-informed ecology of metabolism as simplified biological organism, with some internal complexity to be sure, but primarily organized around a series of inputs and outputs. This source domain selection is influenced by a normative priority to quantify urban resource consumptions patterns, so as to reduce material 'throughput'.[3] As the *target domain*, the city has organismic qualities in that it consumes resources to sustain itself, transforms energy, and eliminates waste. The industrial ecologist generates and applies a mass-balance model (e.g. MFA) to particular urban phenomena, namely by quantifying as many flows and stocks as available data allow. The industrial ecology urban metabolism metaphor is thus functional, linear, organismic and based on an ontological construction of nature as distinct from society, in which nature is largely abstracted as a supply source of natural resources.

Table 1. Characteristics of the three ecologies of urban metabolism.

	Marxist ecologies	Industrial ecology	Urban ecology
Metaphorical conception	Metabolism as nature–society relations	Metabolism as biological organism	Metabolism as ecosystem
Network clusters	1) Urban political ecology 2) Metabolic 'rift'	1) 'Traditional' urban metabolism 2) 'Vienna School' of socio-economic metabolism	—
Theoretical influences/key figures	Marx; Harvey; Bellamy-Foster; Smith; Swyngedouw; Gandy; Kaika; Keil; Heynen	Lavoisier; EP Odum; HT Odum; Wolman; Ayers; Kennedy; Fisher-Kowalski; Weisz; Schandl	Complex systems theory; EP Odum; Pickett; Grimm; Alberti
Emphases	• How dynamic nature–society relationships shape outcomes, including (re)production of inequality and rift • Social power	• Quantifying 'flows' and 'stocks' • Optimizing and reducing material 'throughout'	• Internal complexity of urban ecosystem processes • Sub-system interactions • Ecosystem function to inform sustainability
Language	• Movement as networked circulations • Urban as created ecosystems • Nature–society dialectic • Production of nature	• Movement as input–output • Flows as throughput • Beyond the city as 'hinterland'	• Movement as feedback loops • Flows as structure–function linkages • Internal transformations • Nature–society hybridity
Methods/models	• Historical materialism • Qualitative approaches	• Mass-balance approaches • Material flow analysis (MFA) • Emergy analysis • Life cycle assessment (LCA)	• Ecologically informed complex systems models
Critiques/ perceived limitations	• Isolated scholarly network • 'Methodological cityism' • Social at expense of ecological • Marxist dominated	• 'Black boxing' of urban processes • Aspatial rendering of 'hinterland' • Nature–society dualism • Flows instead of stocks • Apolitical	• Bounded sense of 'urban' • Apolitical • Complexity at expense of distal flows

Although the resource flows are hypothetically connected to distal production spaces (e.g. 'the hinterland'), the work has been largely aspatial with respect to grounding the origins of water, food, materials, and energy flows in specific geographies. In addition, by privileging the flows, the internal processes within the city are 'black-boxed' in that the 'stocks' that gradually accrue in the urban space receive short shrift, as do the socio-economic and ecological processes that principally shape stock–flow dynamics. Reduced to a series of input and outputs, the city, as Swyngedouw points out, is divorced from the historical materialism and power geometries perpetually [re]shaping urban material and energy flows over time–space.

In this conceptualization, space is treated as 'absolute', relegating the city to a 'field, a container, a coordinate system of discrete and mutually exclusive locations' (Smith and Katz, 1993: 73). This apparent apolitical construction is actually highly political. As Smith and Katz (1993: 73) explain, 'absolute space is politically charged', whereby 'a specific tyranny of power is expressed through the capitalist production of it and in which the spatial metaphor is implicit'. In UPE discourse, therefore, the industrial ecology enterprise is framed as a naïve promoter of capitalism, and more specifically a weak form of ecological modernization (Desfor and Keil, 2004; Gibbs and Deutz, 2005) – that is, techno-managerial approaches that endorse market environmentalism as a means to create win–win scenarios between economic growth and environmental sustainability, but preserve the status quo by failing to identify or challenge the structural changes necessary to address the underlying problem of uneven capitalist development (Harvey, 1996; Swyngedouw, 2013). Thus, following Swyngedouw (2006b), Keil and Boudreau (2006: 43) prescribe a political ecology of flows that pays attention to 'political context', analyzes the 'capitalist systems driving these flows', and addresses 'social factors', such as habits of consumption and modes of regulation. Although not because of the underlying spatial politics, urban ecologists also take issue with the 'black-boxing' of urban nature–society processes, which we turn to next.

2 City as ecosystem vs. organismic metabolism

Rather than an organismic metabolism, urban ecologists such as Golubiewski (2012a, 2012b) propose 'ecosystem' – an assemblage of organisms interacting with the physical environment within a specified area (Likens, 1992; Tansley, 1935) – as the appropriate metaphor to characterize and model urban space. Although industrial ecology and urban ecology are both rooted in systems thinking, the source domain differs in that the ecosystem metaphor Golubiewski proposes is informed by a complex systems theorization in which humans are integral components of an urban socio-ecological matrix (Alberti, 1999; Grimm et al., 2000). Biotic and abiotic entities interact within a fairly bounded system to generate the emergent patterns and processes that define an urban ecosystem (Golubiewski, 2012a).

The city is conceptualized as a relational, hybridized set of nature–society processes. Cities, writes Alberti (2008: 252), are 'hybrid phenomena' that emerge from 'interactions between human and ecological processes'. These urban ecosystems are contingent, constantly [re]shaped by drivers, patterns and processes. The likeness of language ('assemblages', 'emergent properties', etc.) is striking and, in stark contrast with industrial ecology, it is an ontological construction of nature–society that resonates not only with UPE (Gandy, 2005; McFarlane, 2011, 2013; Swyngedouw, 2006a; Whatmore, 2002), but also with co-constructivist actor–network theory and, to a lesser degree, with the Vienna School.

Through ontological *correspondence*, 'ecosystem' becomes the preferred metaphor, focusing attention on a *target domain* of pattern and process of biotic and abiotic interactions in a city that is complex, adaptive, and emergent. Thus, ecosystem-based urban models focus on simulating dynamic interactions between these socio-ecological entities. When operationalized empirically as a model, the ecosystem metaphor results in a *partiality* of a different sort, one that privileges urban ecosystem complexity (and spatially bounded processes) at the expense of the more unbounded flows coursing through the city.

As with industrial ecology, the urban ecology enterprise is largely devoid of political concerns (e.g. uneven capitalist development, equality, and justice), but it resonates in that its epistemological foundations in systems thinking leads to similar metaphorical optics politically. Despite the conceptual hybridity, the urban ecosystem is nonetheless composed of identifiable and discrete subsystems that are quantifiable within a larger systemic whole. As Robbins (2013: 313) explains, 'People, trees, monkeys, and carbon all enter a system mix', and those nature–society relationships that resist quantification are typically excluded (Robbins, 2012). The political implications of systems metaphors are problematically reductionist in the sense that the outcomes from the models can be used to reproduce a narrow technocratic agenda in support of state and expert power, thereby silencing other forms of knowledge and action (Robbins, 2012). This can have disastrous consequences, as Robbins (2013: 314) insightfully recognizes, in situations where the 'behavior of real-world socio-environments' is incongruent with policies and approaches rooted in the 'meta-technics of system logic.'

Let's now turn to urban political ecology, the third ecology of urban metabolism, and consider what cross-domain mapping reveals about its use of the metaphor.

3 Marxist urban metabolism

To build the initial architecture for the UPE urban metabolism, Swyngedouw (1996) fused traditional Marxist discourses with lexicon from actor–network theory (e.g. networks, assemblages, cyborgs). Nevertheless, Marxist logic has so successfully permeated the metaphor that it is hard to imagine it without this epistemological apparatus. The generative source domain is dominated by a framing of metabolism as an ongoing dialectical process of transforming the raw materials of nature into 'things' through human labor and their circulation within and through urban socio-natures. Hybridized nature–society relations of these perpetually emerging things – whether they be water mains, concrete, urban green space, or some other object of focus – are excavated to pursue a particular political project: namely to unveil the unevenness and power relations behind their production and consumption under capitalism, all in the pursuit of a more egalitarian politics. For some, the predominance of Marxist framing hinders future development of the UPE field. Holifield (2009), for example, rejects a synthesis of Marxism and actor–network theory (ANT), in favor of an elaborated ANT approach when tackling questions of urban environmental justice and politics. In a related vein, Grove (2009) argues that UPE extend theorizations beyond a Marxist epistemology by including conceptual approaches offered by post-structural and feminist political ecology and critical geopolitics.

In addition to the permeation of Marxist framings, three emphases have gradually imbued the metaphor and typify first-wave UPE: 1) a privileging of the 'social' at the expense of the 'ecological'; 2) a methodological cityism (Angelo and Wachsmuth, 2014); and 3) the preponderance of qualitative approaches.

First, although theorized as a hybridized socio-natural process, the focus is clearly on the social and political dynamics shaping urban metabolisms. 'Environment' and 'nature' are often used interchangeably with 'ecology' to foreground or provide context for an urban environmental politics. For example, drawing on Latour (1993) and Haraway (1991), Loftus (2012) describes the cyborg relationships that link social and ecological processes around water in Durbin, South Africa, but throughout the text the actual biophysical properties of water are largely absent. Concerns about access to and struggles over water provide the context to propose an environmental politics situated in the everyday experience. Similarly, the urban ecology of Los Angeles and Toronto explored by Desfor and Keil (2004) relies on a discursive analysis of the politics of urban environmental change, but neglects how the city's biophysical ecology might co-construct the various social and political struggles over the environment. Other examples that explore the politics of urban environments without a strong emphasis on biophysical ecology include representations of post-industrial ruin (Millington, 2013), the role of social power in shaping access to water (Swyngedouw, 2004; Kaika, 2005), the politicization and maintenance of urban infrastructures (Broto and Bulkeley, 2013; Domínguez and Fogué, 2013) and gentrification (Quastel, 2009), among others.

Second, a methodological cityism that theorizes the spatio-temporal dimensions of planetary urbanism, but paradoxically maintains an empirical focus that privileges bounded conceptualizations of the city, prevails in UPE (Angelo and Wachsmuth, 2014). The city becomes reified as a specific socio-natural artifact produced through the metabolization of nature (Heynen, 2006; Swyngedouw and Heynen, 2003) – ironic given the spatial dimensions the metabolism metaphor implies (Heynen et al., 2006) and the widespread understanding in UPE that globalized socio-natural relationships are integral to contemporary urbanism. Methodological cityism does not permeate all UPE scholarship, as Cronon (1991) and Gandy (2004) provide two excellent examples to the contrary. But across a large swath of UPE, the ontological correspondence is indeed a particular thesis of urban space that is contrasted with generally presumed nonurban spaces (e.g. farms, forests, mines, or dams) (Brenner, 2013). This has resulted in case studies that focus on the city proper (e.g. Cooke and Lewis, 2010; Gandy, 2002; Hagerman, 2007; Heynen et al., 2006; Desfor and Keil, 2004), rather than how the processes of urbanization occur at other sites and scales, or in delineating and interrogating spatiotemporal linkages between cities and the more distal sites of resource extraction and production that help sustain them.

Third, qualitative approaches dominate most UPE frames of urban metabolism, relying on either some combination or individual aspects of discourse and document analysis, archival methods, interview data, and participatory observation (e.g. Grove, 2009; Ioris, 2012; Lawhon, 2013; Kooy and Bakker, 2008). Some UPE does engage with quantitative approaches (e.g. Heynen et al., 2006; Buzzelli, 2008; Cousins and Newell, 2015), but these studies are a minority in the tradition.

V Advancing urban metabolism in geography and beyond

So how might, but the urban metabolism metaphor be reinvigorated in geography (and the broader academy)? As noted earlier, post-structural, ANT, and feminist political ecology offer vehicles (i.e. source domains) in which to do so. But if one observes the three emphases (social at the expense of the ecological, methodological cityism, and preponderance of qualitative approaches) as shortcomings to be addressed in a 'second-wave' UPE research agenda, then urban ecology and industrial ecology are especially well-suited for such an effort. Indeed, growing numbers of scholars are calling for interdisciplinary collaboration under the urban metabolism banner so as to leverage respective disciplinary strengths associated with diverse theorizations of the city (Broto et al., 2012; Pincetl, 2012; Pincetl et al., 2012; Kennedy et al., 2011, 2012; Ramaswami et al., 2012).

Building from a shared theorization of urbanization as hybridized socio-ecological processes, urban ecology provides an important grounding to explore the 'ecology of cities' and how the aggregated human and non-human systems sum in the urban environment (Grimm et al., 2008). Given the dualistic formulations of nature–society relations, the initial utility of industrial ecology for geographers is likely methodological. Specifically, quantitative approaches to measure stocks and flows could be used to advance understandings of the networked impacts of urbanization processes on ecologies, people, and places. In addition to MFA, LCA offers possibilities for spatializing metabolisms, not necessary for inputs–outputs as a whole, but instead for specific water, food, wood, waste, and energy flows that link (and potentially destabilize) notions of urban and rural (Newell and Vos, 2011, 2012). The Vienna School metabolists have long coupled the quantification of flows using MFA with core themes of critical social science. Although the underlying teleology and sweeping historical narratives of socio-economic metabolic transitions that permeate much of this work is tendentious, the Vienna School metabolists nonetheless demonstrate the potential of IE tools for progressive praxis, such as the development of a 'geographical politics of consumption' (Hartwick, 2000).

Recent calls in geography for epistemological and methodological pluralism and bridging qualitative–quantitative divides are helpful when considering such collaboration (Barnes and Sheppard, 2010; Sui and DeLyser, 2011). Geographers are combining diverse intellectual traditions, such as mathematical theory and critical human geography (Bergmann et al., 2009; Bergmann, 2013), leading Barnes (2010: 3) to assert that 'one can be a Marxist, postmodernist or post-structural critic and make use of mathematics and formal theory'.

For all the well-trumpeted benefits of interdisciplinary research (National Academies, 2005), however, the challenges are often underestimated (Lau and Pasquini, 2008; Massey, 1999; Schoenberger, 2001). Shared spaces of protected intellectual experiment need to be created to foster real engagement (Brenner et al., 2011; Lele and Norgaard, 2005; Schoenberger, 2001; Wolman, 1997). Therefore, we propose urban metabolism be conceptualized as a boundary metaphor, much like the concept of a boundary object.

1 Urban metabolism as a boundary metaphor

Boundary objects are concepts or items (such as policy documents or maps) that have a malleability or 'plasticity' so that they 'inhabit several intersecting social worlds ... *and* satisfy the informational requirements of each of them' (Star and Griesemer, 1989: 393). By enabling heterogeneity and multiple attitudes to co-exist, boundary objects enable 'collaboration without consensus' on difficult epistemological issues between disciplines (Clarke and Star, 2008: 222). Similar to watersheds (Cohen, 2012), resilience (Brand and Jax, 2007; Brown, 2014) or conservation corridors (Goldman, 2009), urban metabolism as a boundary metaphor offers the potential to bring together multiple attitudes and beliefs around a shared and recognizable concept, while allowing the metaphor to maintain its particular meaning in each social world or island of disciplinary practice.

Although boundary metaphors (and objects) are meant to enable translation and communication across thought traditions, their interpretive flexibility requires a focus on a particular object of study to retain some degree of coherence of the metaphor across scholarly communities. Socio-technical infrastructures such as water and energy systems and highways and streets are a material set of objects with which research paradigms might fruitfully interact. Explored as a series of shared empirical experiments, these objects of study could provide the conditions for a useful 'friction' between often contested and unequal interactions across epistemological differences (Tsing, 2005).

2 An urban political–industrial ecology: The case of water

Water provides an excellent initial object of study for deploying urban metabolism as a boundary metaphor. In contrast to globalized product commodities, urban water flows are spatially bounded by proximate ecosystems, providing a definite set of hydrological systems for urban ecologists to study and a relatively constricted system boundary for industrial ecologist to locate (and quantify) flow origins. Water is also the most well-studied flow in UPE (Gandy, 2002; Kaika, 2005; Desfor and Keil, 2004; Swyngedouw, 2004), thereby leveraging a rich body of work, such as emergent research on the 'hydro-social cycle', which recognizes the circulations of these flows as dependent upon the hydrological cycle as well as institutions, infrastructures, and social practices (Bakker, 2003, 2005, 2013; Budds, 2009, 2013; March, 2013; Swyngedouw, 2009). To give the reader a sense of how collaboration might proceed, we expand on our own efforts to develop a political–industrial ecology using urban water supply as the object of focus.

In a typical study of the urban water metabolism, the industrial ecologist would first delineate the system boundary by identifying the life cycle phases (sourcing, conveying, treating, etc.) of water supply sources (e.g. imported, groundwater, recycled) to be quantified using MFA or life cycle assessment (LCA). This would include selection of 'activity data' and 'emissions factors', usually based on regional or national averages, to quantify the carbon footprint of the supply system, broken down by water source and life cycle phase (Newell and Vos, 2011, 2012). Recommendations would then follow, such as a shift away from high-carbon water sources and technological fixes to make water supply more efficient. As discussed earlier, this traditional industrial ecology approach 'black boxes' the city, both in terms of the lack of areal differentiation in the LCA modeling used to quantify the carbon footprint and in rendering opaque the urban processes that drive these flows.

As an antidote, we crafted an urban political–industrial ecology approach to analyze the water supply metabolism of Los Angeles (Cousins and Newell, 2015). To better delineate the supply system, including 'downscaling' to ascertain the specific grid mixes that drive the pumping and treatment plants along the water infrastructure network, we coupled LCA with GIS. This intervention led to two major outcomes. First, it unveiled how aspatial assumptions about the system boundary, activity data, and emissions factors embedded in conventional urban water metabolism modeling can fundamentally shape the end result. The outcome provides a means of opening up the black box of the carbon modeling, measurement, and calculation processes that drive urban climate governance. Second, it makes LCA more political by revealing the uneven spatiality of water supply burdens (and carbon emissions) across demographics, along supply chains, and among resource users.

These results were then linked to a broader qualitative analysis of the socio-economic and political factors that shape how geographic complexity is scoped in the production and application of industrial ecology approaches, thereby providing important insights into its political role in (re)configuring urban water metabolisms and the production of science (Forsyth, 2003). The metrics used to measure urban water metabolisms support urban infrastructural transitions that are embedded within a broader political economy and reflect the social histories of place, discourses of development, and the networks of power that solidify urban water supply networks (Cousins and Newell, 2015). Linking these complex socio-political issues to a quantitative measure required a careful analysis of the discursive strategies, both historical and contemporary, employed to build social consensus so as to facilitate the transformations of urban water metabolisms (Kaika, 2003) and to deflect attention away from potential issues of social justice, land distribution, and the environment to benefit elite actors. For example, the legacy of the Los Angeles Aqueduct continues to shape water politics in both Los Angeles and California as a whole through regulatory drivers that reallocate water for environmental mitigation to control dust on the dried up portions of Owens Lake. Yet other strategic new paradigms have emerged in the Los Angeles region, from stormwater capture to water recycling, which impact socio-ecological systems while reshaping urban carbon emissions in potentially contradictory ways.

This coupling of urban metabolism approaches provides a means for the field of UPE to move beyond a 'methodological cityism' by addressing the networked impacts of urban metabolisms on ecologies, peoples, and places both inside and outside of the 'city'. The approach infuses UPE with a new set of quantitative methods (e.g. MFA, LCA) to calculate and map out the uneven spatiality of environmental and social impacts associated with production and consumption. From the standpoint of industrial ecology, a geographically informed analysis that takes seriously the spatiality and political ecology of GHG emissions destabilizes the apolitical acceptance of technological adoption and innovation to fix the carbon emissions problem.

This is just a brief example of how utilizing urban metabolism as a boundary metaphor offers the potential to advance the concept within geography and to extend the discipline's influence to other scholarly communities. Although three islands or 'ecologies' of urban metabolism have emerged, each with their own framings and understandings, this does not pose an insurmountable barrier to cooperative interdisciplinary work. That the metaphor is employed by scholars with different epistemological and disciplinary commitments highlights its utility in achieving multiple and, likely, contradictory objectives. Similar to traditional formulations of boundary objects, the extent of future engagement among scholarly communities will depend on the informational needs found outside of their traditional discipline and the specific work requirements of those collaborating in an interdisciplinary environment (Star and Griesemer, 1989). Above all, these engagements require moving beyond disciplinary boundaries to embrace multiplicity and a spirit of openness, patience, and even periodic compromise to enable geographers to better capture what Thrift (2002: 297) recognizes as the 'myriad geographies perpetually emerging'.

VI Conclusion

The metabolism metaphor reflects particular lenses through which urban space is comprehended. Through bibliometric analysis and literature review, we have mapped out the evolution and crystallization of three islands of urban metabolism: industrial ecology, Marxist ecologies, and urban ecology. Industrial ecology focuses on quantifying material and energy flowing into, within, and out of cities, using accounting methodologies such as MFA. Urban ecology models the complex patterns and processes of urban human–ecological systems. Marxist ecologies such as UPE emphasize power relations that constitute uneven socio-ecological production.

Interaction and cross-domain mapping theories of metaphor have unveiled how epistemological, methodological, and political commitments and normative priorities shape the urban metabolism of the three ecologies accordingly. Each privileges a particular dimension of urban space, while excluding others. This is endemic to the generative process of metaphors, as is their canonization through habitual use, at which point they often stagnate, their generative power greatly reduced. First-wave UPE urban metabolism has reached this stage, simultaneously empowered and limited by a particular Marxist apparatus that privileges socio-political dynamics and by methodological approaches that are largely qualitative and 'cityist'.

To remain alive and vibrant, metaphors need to be continually infused with creativity, namely through the circulation of new thoughts, ideas, and applications. Interdisciplinary engagement can reinvigorate the urban metabolism metaphor as part of a 'second wave' of UPE that creatively articulates the emergent socio-natures that (re)define urban space and that develops the political and methodological means necessary to produce more sustainable and just urban worlds. As the water supply case illustrates, collaboration with industrial ecology offers a means to spatialize and interrogate the carbon calculus that drives urban climate governance, while simultaneously advancing efforts to quantify the uneven material burdens associated with urbanization processes. Crafting this urban political–industrial ecology entails an importing of method and an exporting of spatial sensitivity and critical political economy. Although beyond the scope of our water case, complex-systems urban ecology would enrich this effort by offering a relational view of socio-ecological systems grounded by knowledge of ecological processes. Scrutiny of urban metabolism as a spatial metaphor vis-à-vis ecological theory accompanies this understanding. Geography has long been rightly suspicious of naturalistic and organismic metaphors, especially when applied to cities, as their use brings to mind the tainted past of their misapplication (e.g. Burgess, 1925; Park, 1936).

Through this engagement, a richer, deeper, more inclusive, and yet still politically engaged metaphorical conceptualization of urban space can emerge. This may even take form as a new metaphor, a *metabolism of the urban ecosystem*, one that blurs boundaries by blending elements of the three ecologies and could be defined as follows: a global circulatory process of socio-natural relations that transforms and (re)creates urban ecosystems through the exchange of resources, capital, humans, and non-humans into and out of the spaces of global urbanization. How exactly this metaphor would take shape hinges on those who would collectively build it.

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Notes

1. Unlike the 'three ecologies' of urban metabolism identified by Wachsmuth (2012), our analysis excludes the 'human ecology' of Burgess and the Chicago School of Sociologists because the bibliometric analysis indicates that it is no longer influential among contemporary metabolism formulations. Instead, we identify the third ecology as urban ecology, whose influence is evident–based on the citation analysis.
2. Marx (1976: 283) uses metabolism to define the labor process as a relationship 'between man and nature, a process by which man, through his own actions, mediates, regulates and controls the metabolism between himself and nature'.
3. Reducing the material and energy burdens associated with resource consumption is a research focus that pervades industrial ecology, beyond work on urban metabolism. See, for example, work by Lugschitz et al. (2011), Konar et al. (2011), and Wiedmann et al. (2013).

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