Interdisciplinary Perspectives on Urban Metabolism

Vanesa Castán Broto, Adriana Allen, and Elizabeth Rapoport

Keywords:
industrial ecology
political economy
social ecology
urban ecology
urban metabolism
urban planning

Summary

The concept of urban metabolism, referring to the exchange processes that produce the urban environment, has inspired new ways of thinking about how cities can be made sustainable and has also raised criticisms about the specific social and economic arrangements in which some forms of flow are prioritized or marginalized within the city. This article explores how the concept of urban metabolism travels across disciplines, using a comparative analysis of different approaches to urban metabolism within industrial ecology, urban ecology, ecological economics, political economy and political ecology. The analysis reveals six main themes emerging within interdisciplinary boundaries in relation to urban metabolism, and how this concept enables new understandings of (1) the city as an ecosystem, (2) material and energy flows within the city, (3) economic–material relations within the city, (4) economic drivers of rural–urban relationships, (5) the reproduction of urban inequality, and (6) attempts at resignifying the city through new visions of socioecological relationships. The article suggests potential areas for cross-disciplinary synergies around the concept of urban metabolism and opens up avenues for industrial ecology to engage with the politics and the governance of urban development by examining the city and its metabolism.

Introduction

Debates on sustainable development have long been influenced by concepts from ecology and biological sciences. One such concept is urban metabolism, referring to the exchange processes whereby cities transform raw materials, energy, and water into the built environment, human biomass, and waste (Decker et al. 2000). This concept has fostered new imaginations of the city and how material and immaterial flows mediate its production and reproduction, both as a biophysical and socioeconomic entity. Urban metabolism has inspired new ways of thinking about how cities can be made sustainable and has raised criticisms about specific social and economic arrangements in which some forms of flow, or of "being in flow," are prioritized and/or marginalized within the city.

To a certain extent, the growth in literature on urban metabolism represents a convergence in the interests of scholars across a range of disciplines. Such studies share common concerns, such as the exploration of the relationships between social and natural systems, cities and their hinterlands (both immediate and global), and sustainability in urban areas. They often have interdisciplinary ambitions: scholars employing the concept of urban metabolism are most often working to push the boundaries of their own disciplines. This raises questions about the value of urban metabolism as an analogy for understanding urban processes and the extent to which urban metabolism bridges theoretical debates and their practical applications.

The objective of this article is to put the literature on urban metabolism within industrial ecology into dialogue with other disciplines, including urban ecology, ecological economics, political economy, and political ecology. A cross-disciplinary

Address correspondence to: Vanesa Castán Broto, Development and Planning Unit, University College London, 34 Tavistock Square, WC1H 9EZ, London, UK *Email:* v.castanbroto@ucl.ac.uk *Web:* www.bartlett.ucl.ac.uk/dpu

DOI: 10.1111/j.1530-9290.2012.00556.x

Volume 00, Number 00

Table 1 Six urban metabolism themes

Theme	*Key question*	*Emphasis on*
The city as an ecosystem	What lessons from the functioning of ecosystems can be applied to design and plan better cities?	Nature-inspired models of development in urban planning and design
Material and energy flows in the city	What methods can account for material and energy flows through the city and can these provide suggestions for their optimization?	Comparative analyses of cities and models of urban planning in relation to their efficiency in allocating materials and energy
The material basis of the economy	What policy measures can break the link between urbanization, economic growth and resource consumption?	The material limits of the economy and macroeconomic models to achieve economic and resource stability
Economic drivers of rural–urban relationships	How do economic relations shape the distribution of flows between urban regions and their surroundings?	Forms of territorial organization in relation to different modes of economic circulation
The reproduction of urban inequality	How do existing urban flows distribute resources across the city and who controls these processes?	Patterns of unequal access to resources and the control of these patterns by urban elites
Resignifying socioecological relationships	What socioecological practices have the potential to reimagine and reconfigure existing socioecological flows?	Alternative visions and models of socioecological flows in cultural production, everyday practices, and policy innovations

literature review examined contrasting theoretical interpretations of urban metabolism on the one hand and foreseen practical applications on the other. Instead of fixing the definition of urban metabolism at the outset, we developed the comparative analysis with reference to key questions that are addressed using this concept (table 1). In this way the analysis revealed six main themes emerging within interdisciplinary boundaries in relation to (1) the city as an ecosystem, (2) material and energy flows within the city, (3) economic–material relations within the city, (4) economic drivers of rural–urban relationships, 5) the reproduction of urban inequality, and (6) attempts at resignifying the city through new visions of socioecological relationships. The analysis investigated their emergence, conceptual basis, normative recommendations, and criticisms, although these aspects vary for each theme depending on how it relates to historical and current debates. Rather than discrete theories, each theme represents an evolving viewpoint that reflects the variety of historical and contemporary debates in relation to urban metabolism. They have developed with reference to each other, and hence there is some overlap between them. Yet, by emphasizing the distinct purposes of each perspective, this analysis highlights how urban metabolism not only illuminates different aspects of the city's sustainability, but also fosters dialogue across apparently disconnected disciplinary bodies of work.

The following six sections explore each of these themes in turn. The comparative exploration offers both an understanding of potential areas for cross-disciplinary synergies around the concept of urban metabolism as well as strategies for industrial ecology to engage with the politics and the governance of urban development by examining the city and its metabolism.

The City as an Ecosystem

The first explicit application of the concept of metabolism to the city was Wolman's study "The Metabolism of Cities," which modeled the metabolism of a hypothetical U.S. city (Wolman 1965). Wolman's approach was published at a time when worries about the impact of humans on the environment were growing rapidly and thus it appealed to those concerned with the existence of limits to the planet's capacity to provide resources and deal with the waste of an ever-increasing human population. A key innovation in Wolman's study was to present the city as an ecosystem. Within urban ecology this meant a move from studies of the "ecology in cities" to analyses of the "ecology of cities" (Grimm et al. 2000). While the former focused on explaining how ecological patterns and processes in cities are different from those in other environments (Marcotullio and Boyle 2003), the latter emphasized how cities process energy or matter relative to their surroundings. This last perspective characterizes the city as an ecosystem embedded in a larger system, and thus employs the concept of metabolism to describe the interactions between subsystems within an urban region.

The idea of the city as an ecosystem was strongly influenced by systems ecology studies, which adopted the ecosystem as the fundamental unit of analysis (Slocombe 1993). A systems approach to the analysis of human–environment relations, proponents argue, enables capturing and interpreting the full complexity of urban systems (Grimm et al. 2000; Mehmood 2010; Newman 1999). They attempted to develop a holistic understanding of the emergent properties and complexities of living systems by "looking at the relationships and interactions between parts, seeking to devise solutions that are integrative rather than merely reductionist" (Newman and Jennings 2008, 92).

Outside academic debates, however, these ideas have sustained two normative implications in urban planning and design emerging from, first, an understanding of ecosystems as providing ideal models of metabolism and, second, the description of a city as a parasite on its immediate environment. The first set of normative recommendations relates to models of urban development that take natural ecosystems as an archetype. These approaches can be regarded as continuing the organicist tradition in urban planning, leading to experiments in which the natural world is taken as a template for architecture and urban development. The Japanese architect Kisho Kurokawa, for instance, developed a metabolic approach to urban design that envisioned cities and buildings as going through the same process of change, renewal, and destruction as other life forms (e.g., Kurokawa 1999). Cities, he argued, should be designed to change over time and be flexible enough to maintain a constant cycle of growth, transformation, and death of its parts without destruction of the whole (Kurokawa 1977). More recently these ideas have led to an increasing interest in biomimicry principles in the professional practice of civil engineering and urban planning in transport, food, waste, water, energy, and communications (e.g., Head 2008).

The second set of normative recommendations relates to the characterization of the city as a parasite. Odum (1989) regarded the city as a parasite because rather than producing its own food, it encroaches on the wider region where it is located, polluting water, air, and other resources. His vision built upon a holistic understanding of the ecosystem in which constituents mediate material and energy flows to create a life support system (Odum 1963). While the notion of the city as a parasite has lost traction among urban scholars and is most often presented as merely describing the relationship between the city and its surroundings (Tarr 2002), this notion has been persistent in urban planning, policy, and design interventions, always linked to arguments about the inherent unsustainability of cities (Doughty and Hammond 2004).

The notion of the city as a parasite highlights the problematic character of the organization of inputs and outputs in urban areas, consuming and producing waste according to a model of "linear metabolism" (Girardet 1992). In contrast, natural systems are seen as cyclical and efficient in their use of materials and energy (Dunn and Steinemann 1998). Thus the long-term viability and sustainability of cities is reliant on them shifting from a linear model to a circular model of metabolism in which outputs are recycled back into the system to become inputs (Girardet 2008). This approach has already been applied in high-profile urban sustainability projects, such as the design of the Hammarby Sjöstad urban district in Stockholm, Sweden, which proposes closing material loops through the development of integrated urban systems (City of Stockholm 2007). American architect William McDonough has advocated building cities along the principles of "cradle-to-cradle design," or as closed metabolic systems that produce no waste (McDonough and Braungart 2009).

These analyses, however, have come under scrutiny from urban ecologists who regard them as relying on an inappropriate understanding of ecosystems (Golubiewski 2012). For example, urban ecologists studying complex systems theory have challenged the focus of urban metabolism on circularity, balance, and order. Complex systems theory regards urban ecosystems as consisting of multiple interlinked subsystems in continual interaction with each other and the outside world (Alberti 1999, 2008). The city is regarded as a dynamic, complex, and adaptive system linking social and ecological systems. Moreover, rather than externalizing human activity from ideal models of ecosystems, complex systems theory recognizes human activity as an integral part of ecosystems (Alberti 1999; Grimm et al. 2000). Models linking the biophysical impacts of human-induced environmental stresses to various types of land use, human activities, and management practices aim to simulate the ecological impacts of urban development patterns to facilitate planning decisions (Alberti 1999, 2008). Complex systems theory challenges the idea that ecological design for urban areas should aim for stability and predictability. Rather than adjusting urban metabolic flows to idealized models of city ecosystems, the proposal here is to achieve greater resilience to the inevitable internal and external shocks that will impact an urban area by reference to detailed urban ecology models.

Following the publication of Odum's study, two approaches to studying urban metabolism emerged. While the first followed Odum to describe urban metabolism in terms of energy equivalents, the second focused on new approaches to account for the flows of materials and energy in the city (Kennedy et al. 2011). This second approach, starting with a wave of empirical studies of the metabolisms of various cities that appeared in the 1970s and 1980s (Boyden 1981; Duvigneaud and Denaeyer-De Smet 1977; Hanya and Ambe 1976), has developed within industrial ecology and cognate disciplines, as the following section explains.

Material and Energy Flows in the City

Industrial ecology has made major contributions to methods for accounting for material and energy flows and optimization of the "metabolism" of industrial systems through industrial symbiosis, whereby the waste output from one industry can become an input for another, providing both cost savings and environmental benefits (Dunn and Steinemann 1998). These approaches focus on quantifying the flows of materials, energy, or the presence of a particular substance (Barles 2010). Material (or substance) flow analysis (MFA), in particular, analyzes social metabolism through the systematic assessment of the flows and stocks of materials within a well-defined system, connecting sources, pathways, and sinks of materials. While MFA has predominantly been applied at the national level, the 1990s saw a resurgence in interest in applying the metabolism concept to cities using an MFA approach (Kennedy et al. 2011), leading to the proliferation of studies of MFA of the city (Bai 2007; Hammer 2006; Kennedy et al. 2007; Schulz 2007).

Industrial ecologists share a view of the city as a system whose metabolism can be understood as "the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al. 2007, 44). In line with MFA principles, the rationale behind this approach is that through the systematic recording of all physical flows to and from an urban area it is possible to describe the relationship between urban systems and their environment (Minx et al. 2011). The application of MFA to cities, however, has been limited by methodological difficulties, such as capturing urban areas as well-defined, bounded systems, and the lack of data at the city level (e.g., Kennedy et al. 2007; Minx et al. 2011).

While most studies of urban material and energy flows are largely "accounting exercises" (Kennedy et al. 2011), they also provide the basis for some practical applications and encourage the use of urban metabolism as a foundation for urban policy (Baccini 1997; Barles 2009; Codoban and Kennedy 2008; Kennedy et al. 2007; Niza et al. 2009). Like some studies in urban ecology, MFA highlights the linear nature of urban metabolisms as a particular source of vulnerability (Brunner 2007; Dunn and Steinemann 1998). Taking natural systems as a model, self-sufficiency is regarded as one of the most important characteristics of a sustainable metabolism, that is, reducing dependence from a wider hinterland for resources extraction or waste disposal (Baccini 1997; Brunner 2007; Niza et al. 2009). MFA is also useful to identify "urban inefficiencies," or suboptimal use of resources (Browne et al. 2009). Overall, MFA is seen as serving both to identify environmental problems and to design more efficient urban planning policies. For example, a study in Toronto, Ontario, Canada, linked the design characteristics of different types of neighborhoods to metabolic flows (Codoban and Kennedy 2008). In practice, when MFAs are linked to policy recommendations they usually advocate market-led solutions rather than traditional command and control environmental regulation (e.g., removing subsidies and taxing resource consumption rather than labor) (Fischer-Kowalski and Hüttler 1998; for an example see Bringezu et al. 2003). This focus has been associated with the type of case studies most commonly studied, which tends to be in service-oriented societies in which consumers, rather than producers, are the primary source of emissions (Brunner 2007). Collaborative environmental management, self-organization, or advocacy programs are rarely considered even though MFA could potentially contribute as an important tool for community-based action or political activism (e.g., by revealing imbalances in the distribution of flows across the city).

Ecological footprinting provides an alternative approach to MFA, focusing on the quantification of land needed to provide resources rather than on the flows of substances through the city. Ecological footprinting methodologies rely on equivalences to calculate the amount of land needed to provide resources and absorb the waste produced within a given territory (Rees and Wackernagel 1995). An alternative to ecological footprinting is provided in energetic metabolism studies that attempt to comprehensively model energy flows in human societies (Haberl 2001, 2006). Ecological footprinting and energetic metabolism studies can be effective in communicating the scale of the imbalance between a city's metabolism and the planet's capacity to sustain this—for instance, London's ecological footprint is said to be 200 times the size of the city itself (Environment Agency 2010). Combining different measures has the potential to compare the energy and resource efficiency of different approaches to urban planning. However, the inherent difficulty of reducing the processes sustaining urban economies to a common unit, whether this is land, energy, or material flows, leads to the realization that these analyses are not sufficient for effective urban policy and planning interventions (Fischer-Kowalski and Hüttler 1998). MFA and ecological footprint analysis "have provided excellent critiques of the impact of cities on the environment, but have been weaker on providing solutions that city managers can use in their daily work" (Marcotullio and Boyle 2003, 15). Knowledge of metabolic inflows and outflows should be linked to how particular things, such as urban forms, lifestyles, and infrastructural landscapes, lead to metabolic differences (Minx et al. 2011). Thus additional methods are needed to develop metabolism models that can examine the relationship between urban and environmental quality and urban drivers, patterns, and lifestyles in metabolic flows (Minx et al. 2011; Newman 1999).

Understanding the spatial characteristics that influence material and energy flows and the development of methods for long-term analysis (Moffatt and Kohler 2008) has already been attempted with the development of a "one system approach" to planning, designing, and managing urban areas, grounded in a view of the city and the urban environment as a complete system (Suzuki et al. 2009). However, less attention has been directed in MFA toward the integration of the social and political drivers of material and energy flows, despite the need to understand "the stakeholders and, more generally, the agents involved in material flows," both questioning their management methods and considering the economic and social consequences of these flows (Barles 2010, 443). In short, MFA requires understanding the socioecological conditions that influence flows (Barles 2009). This implies that a society's metabolism should be regarded as comprising the totality of the energetic and material flows required to sustain the material components of social systems (Fischer-Kowalski 1997).

Overall, this suggests that establishing the metabolism of a society also requires understanding the relationship between societies and the material and energy flows that shape and sustain each other. This relationship can be approached from different perspectives, four of which are presented in the following sections. The first of these perspectives, which has been mainly developed within ecological economics, emphasizes the linkages between the economy and its material basis, paying particular attention to reframing conventional economic analysis by taking into account society's economic dependence on the environment.

The Material Basis of the Economy

The concept of metabolism has influenced the development of theories about economic development, particularly concerned with the relationship between economic growth and urbanization resource depletion and environmental damage (Daly 1996). Here, the concept of metabolism is usually related not to a view of an urban area as an ecosystem, but rather to the prevalence of the laws of thermodynamics on economic flows. The economy is seen as embedded in an "ordered system for transforming low-entropy raw materials and energy into high-entropy waste and unavailable energy" (Daly and Farley 2004, 70). The urban is presented in this work as a key form of organization of the current economic system. Most often these studies assume that urbanization and economic growth have an overall negative impact on the environment.

The normative recommendations of this body of work relate to different theories about how best to optimize economy–environment relations. Dematerialization is one of the approaches that emerges, closely related to industrial ecology analyses of social metabolism. Taking self-sufficiency as an ideal, decoupling economic growth from the use of resources requires reducing the amount of resources used per unit of economic output. This is seen as requiring a change in production and consumption patterns leading to a reduced overall metabolism (Opschoor 1997). Advocates of dematerialization make the case that technological changes and improved business practices make it possible to produce manufactured goods with fewer raw material and energy inputs than in the past. The focus on technological innovation supports the suspicion that industrial ecology studies of metabolism rely on the theory of ecological modernization for justification (Fisher and Freudenburg 2001). Applied studies of material flows and balances that define dematerialization targets for cities such as Stockholm, Sweden, and Geneva, Switzerland (Barles 2010), for example, emphasize more the opportunities for efficiency gains than the need for a transition to a new mode of production and consumption.

The central argument of dematerialization theories—that decoupling growth from environmental degradation is possible—is itself the target of critics who regard unending capital accumulation as the central cause of continued resource depletion and environmental damage (Czech and Daly 2004; Jackson 2009). Such critics highlight that because capital accumulation is characterized by the need for continuous growth and expansion, it is incompatible with the natural limits to growth (White 2006). A sustainable economy thus cannot rely on ever-increasing economic growth (Jackson 2009). Two alternative models emerge for this diagnosis: the steady-state economy and degrowth. The steady-state economy involves stabilizing the economy at a stable level of throughput, maintaining the environmental carrying capacity, and relying on technological progress to increase the ratio of gross domestic product (GDP) per unit of throughput (Czech and Daly 2004; Daly 1992). Achieving this, Jackson (2009) argues, will require new macroeconomic models for achieving economic stability without growth in consumption.

Degrowth theories propose "an equitable downscaling of production and consumption that increases human well-being and enhances ecological conditions at the local and global level, in the short and long term" (Schneider et al. 2010, 512). Degrowth will thus require limiting the scale of production and consumption. Debates focus on how much to downsize in order to achieve sustainability and what might be the optimal scale for the economy (Martinez-Alier et al. 2010b). This line of enquiry has had an important influence in activist forums that do not take degrowth as a theory but as a political slogan, a movement for the reorganization of society around conceptions of well-being that go beyond GDP (Latouche 2010). In this sense, degrowth has been presented as a radical idea beyond the apparent conservatism of the proponents of the steady-state economy. However, while they advocate different solutions for a sustainable economy, the steady-state economy and degrowth may be complementary if degrowth is pursued to a point where a steady-state economy is then feasible (Kerschner 2010).

One challenge to the key arguments put forward by ecological economists is whether they adequately grasp the complexities and subtleties of socioenvironmental relationships (White 2006), including the social and political challenges of maintaining employment levels and social stability while achieving the degrowth transition (Spangenberg 2010), the way in which reducing the economic metabolism will lead to a sense of loss among those who have to reduce their consumption (Matthey 2010), and the implications of transforming the links between consumption patterns and personal identity for degrowth (Hamilton 2010). Ultimately these critiques raise the argument that capital accumulation is related not only to environmental degradation, but also to socioenvironmental relationships. In relation to urban metabolism, this implies interrogating the socioenvironmental patterns generated by capital accumulation in cities. In other words, theories about the material basis of the economy need to be read together with those that seek to explain the spatial distribution of urban flows, as explored in the section below.

Economic Drivers of Rural–Urban Relationships

World systems analysis holds that under capitalism some regions and states on the global "periphery" remain structurally dependent on those in the "core" of developed nations, leading to their continual underdevelopment (Wallerstein 1974). The underlying ecological conditions of human economies determine this unequal distribution of resources. In explaining the connection between urban flows and inequality, cities are presented as dissipative structures, systems sustained through material and energy exchanges with their environments (Hornborg 1998). The continuous demand for energy in the city relates to processes of market exchange and capital accumulation, as "the more energy that has been dissipated by industry today, the more new resources it will be able to purchase tomorrow" (Hornborg 1998, 133). Thus, as centers of capital accumulation and dissipative structures, urban areas will have an ever-increasing demand for resources from the periphery, contributing to structural inequality between the core and the periphery in the world system.

In this perspective, urban metabolisms are of interest because of the way they impact upon and are impacted by broader global systems. An alternative take focuses on the linkages between the accelerated metabolism of cities, their growing demand for resources and production of waste, and the increasing number of ecological conflicts in "commodity frontiers" usually located far from cities (Martinez-Alier et al. 2010a). Studying a society's "social metabolism" directs attention to "the manner in which human societies organize their growing exchanges of energy and materials with the environment" (Martinez-Alier 2009, 153). Rather than seeking to explain environmental problems and conflicts in poor countries as resulting from poor governance or market failure, these perspectives point at a world system in which the metabolism of urban areas relies on areas beyond their boundaries for a constant supply of resources and waste disposal. Conflicts around the social and environmental costs of the extraction of resources maintain urban metabolic processes that produce and reproduce inequality. Within cities, distributional implications of ecological conflicts are closely related to mechanisms that reshape and adjust governance mechanisms, often benefiting those in power, as occurred in the case of a conflict around waste disposal in the metropolitan area of Campania, Italy, in which the actions of public authorities and politicians led to increased social unrest and a consequent erosion of democratic institutions (D'Alisa et al. 2010).

The city is also prominent in neo-Marxist theories of socioeconomic distribution. Marx used the term metabolism to refer to the material exchanges and interdependent relationship between human society and nature occurring through the labor process, described as "a process between man and nature, a process by which man, through his own actions, mediates, regulates and controls the metabolism between himself and nature" (Marx 1976, quoted in Foster 1999, 380). The concept of metabolic rift refers to the notion that, under capitalism, humans have become estranged from the natural conditions of their existence (Foster 1999). From a world systems perspective, the rising costs of ecological exploitation that result from capitalist expansion have led to the repeated reorganization of the world ecology and a metabolic rift—between countries, and between rural and urban areas—that over time has widened and deepened (Moore 2000). For example, the guano and nitrates trade during the mid to late nineteenth century "highlights the unequal exchange and degradation associated with the ecological contradictions of Britain and other dominant countries in the global economy" (Clark and Foster 2009, 330). Marx regarded urbanization as a key process leading to the "metabolic rift" because of the reduced interaction between humans and the earth resulting from the migration of population from rural to urban areas or because of the growth in long-distance trade in food and clothing. The implication of this perspective is that the environmental crisis unfolds in relation to historical and spatial patterns of inequality that, in the context of increasing urbanization, are manifest within the city.

New conceptions of urban metabolism are emerging from these critical approaches that see it as embedded in structures of capital accumulation. For example, several scholars have questioned how relations of dependency are shaped and challenged across multiple scales in the appropriation and transformation of nature through urban processes (Becker and Raza 1999). For instance, Allen (2011) examines how, following the adoption of neoliberal reforms in the last quarter of the twentieth century, the fish processing sector in cities in Argentina shifted from a relatively stable accumulation process—organized around the minimization of industrial costs, domestic capital, wage labor, and an "underexploited" resource base—to a situation of overfishing, internationalization of capital, and flexible production based on the establishment of a precarious labor force. This study reveals another dimension at play shaping urban metabolisms, whereby neoliberal restructuring not only normalizes capitalist accumulation through the production and reproduction of differential sustainability, but also gives rise to new urban-based struggles to confront a governing crisis at multiple scales (e.g., from the workplace to the sea).

These ideas have inspired political ecology studies of the city focused on the reproduction of urban inequality in material and nonmaterial flows mediated both by infrastructure networks and spatial patterns of urbanization. In particular, the following section focuses on patterns of urban inequality within the city and how they are mediated by urban metabolic flows.

The Reproduction of Urban Inequality

Political ecology studies of inequality in urban areas do not always explicitly employ the concept of urban metabolism, and yet they are engaged directly with the question of to what extent urban areas are shaped by socioenvironmental flows and the networks through which they move. Water distribution networks have proved a particularly fertile area for research on urban flows and inequality. Case studies such as the privatization of water networks in Jakarta, Indonesia, have mapped the spatial differentiation in urban areas in the global south in terms of access to water supply (Bakker 2007b; Kooy and Bakker 2008a, 2008b). While urban elites benefit from a relatively plentiful and affordable water supply coming from networked infrastructure, the urban poor typically have limited access to water supply networks, relying instead on water vendors who charge much higher prices (Bakker 2003a). Such studies support that, rather than being the result of resource scarcity or poor management, water poverty is socially produced and reproduced through discriminatory processes (Allen et al. 2006).

One implication of these analyses is that cities have different parallel metabolisms for the same resource (e.g., water). During the last decades, neoliberal reforms in water management have created a range of "alternative community water economies" that "develop new approaches to governing the relationship between the hydrological cycle, and socio-natural economies and polities" (Bakker 2007a, 448). While they may be more visible in cities in the global south, infrastructure networks reflect socioeconomic inequalities both in the south and the north. For example, the evolution of water and wastewater networks during the nineteenth and early twentieth centuries in cities such as Barcelona, Spain, or Pittsburgh, Pennsylvania, USA, shows that urban conflicts over water closely mirror class conflicts (Masjuan et al. 2008; Tarr 2002).

Closely related to debates on the impact of urban flows on inequality is the question of their governance and how power relationships shape urban flows. Control of metabolic flows is essential for the reproduction of structures of power. Urban political ecology studies examine how the material conditions of urban environments are controlled by and serve the interests of elites, at the expense of marginalized populations (Heynen et al. 2006; Swyngedouw and Heynen 2003). The powers of ecological processes are socially mobilized to serve particular purposes, usually associated with strategies of achieving or maintaining positions related to social power. Processes of domination come together in urban areas (Keil and Boudreau 2006). The way in which water has been governed in Jakarta, for instance, has been driven by governmental efforts to differentiate people by race and class, creating and perpetuating inequalities (Kooy and Bakker 2008a). In Barcelona, water supply to the industrial sector was prioritized at the turn of the nineteenth century, but today one of the main objectives of the city's water network is to meet the growing demands of suburban settlements, which reflects a shift in the interests of elites (Masjuan et al. 2008). In summary, although urban metabolisms are also shaped by innumerable and unaccounted urban practices, within existing social relations not everyone can satisfy their needs equally (Zimmer 2010). Certain social classes reap the benefits of the urban metabolism more than others, as "not all actors can mobilise metabolisms in the same way" (Zimmer 2010, 350). Like water flows in Jakarta, Barcelona, or Pittsburg, urban air pollution policies in Delhi, India, since the mid-1990s respond to the values and tastes of an increasingly influential middle class (Vèron 2006).

Infrastructure networks are central to the understanding of metabolic circulation. Modern urbanization depends upon urban infrastructure networks that have allowed cities to extend their "ecological hinterland," both for resource extraction and waste disposal (Monstadt 2009). Through their role in structuring material metabolisms, these networks "constitute one of the most important interfaces between nature and society" (Monstadt 2009, 1926). Understanding how these infrastructure networks reproduce power structures is especially complicated because in modern cities they are out of sight and invisible (Kaika and Swyngedouw 2000).

Politics impact socioenvironmental metabolisms and distributional issues across scales. The physical redistribution of material flows is often accompanied by a change in the mode of social organization accompanying flows (Keil and Boudreau 2006; Tarr 2002). Pittsburg's sewers, for example, were built by local elected representatives to meet the demands of their more well-to-do constituents, while the use of the new wastewater systems, with the associate payment of an access fee, was then enforced by law on all citizens (Tarr 2002). Neoliberal reforms and international finance institutions have led to a new mode of water governance characterized by the privatization of water resources (Allen et al. 2010; Bakker 2003a, 2007a). While private management of the water sector used to be rare, today water systems in more than a hundred cities in developing countries are managed by a few large companies (Bakker 2003a). The facilitation role played by international finance organizations and national governments is crucial to the functioning of the world water market. This dual process of resource regulation and marketization can be conceived in metabolic terms, with resource regulation embodying "the social negotiation of the metabolism of a dynamic resource landscape" and marketization embodying "the reregulation of the social metabolism of nature undertaken by the state" (Bakker 2003b, 49, 52).

While elites and powerful institutions may dominate the governance of urban flows, these may be challenged or subverted by the daily practices of individuals and groups (Bulkeley et al. 2011). Understanding the way in which urban resource flows and the networks that facilitate them are governed also requires examining daily practices and local political economies (Bulkeley et al. 2011; Monstadt 2007). For the urban poor in the global south, for example, service provision often occurs through hybrids of more formal public, public–private, and private arrangements (Allen et al. 2010). This means that urban metabolic flows—water, resources, energy—cannot be solely understood through the mechanisms of domination in the city. A plethora of actors are able to identify alternative courses of action and subvert dominant technological paradigms of nature and human domination. This realization has led political ecology studies that challenge taken-for-granted distinctions between society and the environment and engage with the dialectical production of urban flows both materially and in a plethora of social narratives and everyday practices, a theme which is examined in the next section.

Resignifying Socioecological Relationships in the City

By questioning dualistic conceptions of the relationship between society and nature, political ecology challenges urban metabolism as a mere process of biophysical exchange unrelated to their social and historical context (Gandy 2004; Monstadt 2009). Political ecology argues that urban metabolism often "fails to theorize the process of urbanization as a social process of transforming and reconfiguring nature" (Swyngedouw 2006, 35). Furthermore, the emphasis on biophysical exchange of some methods may depoliticize the urban sphere, naturalizing urban processes "so that urbanization is no longer conceived as the outcome of historical change but rather as a cyclical dynamic alterable through technological modifications rather than by political contestation" (Gandy 2006, 64). Even in the work of scholars who try to integrate the impact of social factors in their models, metabolism is still often used to denote something purely material (Keil 2005). Thus, from a political ecology perspective, attempts to simply "extend" material and energy flow metabolism models to include social and economic issues do not go far enough to explain the complex relationships that shape the city.

Building on Marx's conception of metabolism as a metaphor to analyze human–nature relationships, urban political ecology scholars conceptualize urban metabolism as consisting of as a number of dynamic, interconnected, and mutually transformative physical and social processes. Metabolism is also seen as highly political, because while it may be a process of exchanging material or energy, humans can control their input into this exchange. A key observation is that metabolisms have the potential to express peoples' drives, desires, and imaginations, but they do so in a dialectic way, that is, through the interplay of structure and agency (Swyngedouw 2006).

The characterization of metabolism as related to socioecological interactions and the adoption of a critical political stance has created scope to reimagine relations between social, technical, economic, and ecological forces in urban areas. While some urban ecology, ecological economics, and political economy perspectives on cities have placed cities in opposition to nature, the idea of urban metabolism as consisting of multiple interconnected social and ecological processes argues that flows are shaped by the historical context in which they emerge and the urban practices around them. More generally, human activities cannot be viewed as external to ecosystem function, particularly in urban areas, where the metabolic transformation of nature is highly concentrated (Heynen et al. 2006). Rather than distancing humans from nature, urbanization is seen as "a process by which new and more complex relationships of society and nature are created" (Keil 2003, 729).

Cities are portrayed here as collections of socionatural hybrids, such as "alleys of trees, planned by city councils and planted with the help of scientific knowledge in botany; urban drinking water and waste water that are treated and distributed through pipelines only to be treated again with the help of specific bacteria after us" (Zimmer 2010, 345). As a process of metabolically transformed nature, the city becomes a socionatural hybrid (Kaika and Swyngedouw 2000). In an urban context, hybridity ideas point at the physical infrastructure that "links the human body to vast technological networks" (Gandy 2005, 28). However, these concepts may lead to reproducing the binary representation of the world that comes from a society–nature dualism, as they suggest the mixing of two ontologically distinguishable things (Swyngedouw 2006). Instead, nature and cities are fundamentally heterogeneous, constituted through equally heterogeneous metabolic circulations.

A distinct implication is that the metabolism of the city is not only shaped by visible flows, but also by the ways in which different forms of circulation are imagined and represented through the city. Equally, who governs urban flows is not only relevant in terms of how the distribution of resources across the city occurs, but also in relation to the forms of urban organization that emerge associated to different visions of the ideal or the good city. This reveals greater diversity in the mechanisms shaping these flows, which are seen as being shaped by a wide array of policies, designs, and management styles alongside forms of cultural production, routine interactions, and everyday practices.

In this way, urban political ecology not only highlights the structures of power as they are reproduced in urban flows, but also the potential to subvert such flows in everyday practices. Yet, due to their inherent critical emphasis, the normative and practical applications of this approach are not as obvious as urban ecology and industrial ecology methods. The emphasis of these critical perspectives on urban metabolism is on raising new questions, which require further theoretical development and methodological innovation through enhanced interdisciplinary dialogue on the future of sustainable cities.

Conclusion

The preceding discussion of six different interdisciplinary themes in relation to urban metabolism suggests that this concept can be productive and useful for developing alternative understandings of the functioning of urban areas. For example, MFAs and urban ecology analyses provide tools for the development of social and environmental policy in urban areas. Explorations of the metabolism of urban economies call attention to the environmental and social resources needed to maintain economic growth and how they are manifested in spatial patterns. Critical perspectives on urban metabolism open up new ways of conceptualizing how the urban is produced through social relations and flows of resources and discourses. Major differences are found, however, in terms of thinking about how urban metabolism theories travel into practice, from heterodox approaches that focus on developing tools to support existing expertise in engineering and planning, to approaches that challenge the reengineering of cities and urban life as a means of controlling and maintaining unsustainable and unequal urban metabolisms, whether this is through activism or through academic debates. However, one theme that links most of the approaches in this article is the realization that sustainable urban futures will require a fundamental transformation of existing production and consumption patterns in cities, and that looking into how these patterns are organized into flows—of materials, energy, people, meanings, and power—is a fruitful avenue to investigate such transformation.

Interdisciplinary dialogue is key to developing theoretical and practical approaches to urban metabolism. From the outset, this article has highlighted that each theme was developed in relation to different concerns about urban sustainability, and hence the way in which the concept of urban metabolism is approached and conceptualized serves different purposes. Accounting for the material flows of the city, for example, is different from identifying patterns of urban inequality. Yet, urban development pathways need to engage with the multidimensional nature of sustainability. Through the notions of flow and circulation, the concept of urban metabolism links material flows with ecological processes and social change, and herein is its potential. However, there is a need to find a balance between reflecting urban complexity accurately and developing ideas that can be made operative in policy making, planning, and design processes.

For these reasons, we argue that the potential of urban metabolism to generate ideas to engage with the question of urban sustainability lies in the diversity of studies that emerge associated with this concept. All six themes discussed above may be taken to extremes that make them vulnerable to criticism, whether this is because they negate cities' potential to foster prosperity and sustain populations or because they emphasize socioeconomic and political processes at the expense of material and energy circulation. However, all these themes are also associated with important insights about the material and discursive production of cities. Rather than advocating an amalgamation between all the possible perspectives on urban metabolism, our argument emphasizes the need to recognize a diversity of perspectives as a means of developing common questions that can generate interdisciplinary dialogue and overcome disciplinary barriers. For example, studies of material and energy flows increasingly situate their analyses within well-defined historical and political contexts to ask relevant questions about the circulation of resources. Simultaneously, the quantification of material and energy tools support important arguments about rural and urban tensions and the reproduction of urban inequality patterns. We believe that further productive interdisciplinary dialogue emerging from the diversity of approaches to urban metabolism highlighted in this article has the potential to advance our understanding of how cities work and to generate new ideas about how sustainable urban futures can be accomplished.

Acknowledgments

The research in this article was funded by the University College London (UCL) Environment Institute. The authors wish to thank Andreas Eriksson for his assistance in the project and all the participants within UCL who have shared their views on urban metabolism with us.

References

Alberti, M. 1999. Modeling the urban ecosystem: A conceptual framework. *Environment and Planning B: Planning and Design* 26(4): 605–630.

Alberti, M. 2008. *Advances in urban ecology: Integrating humans and ecological processes in urban ecosystems*. New York, NY, USA: Springer.

Allen, A. 2011. Neoliberal restructuring at work in the urban South: The production and re-production of scarcity and vulnerability in the Argentine fisheries sector. Ph.D. dissertation, Development and Planning Unit, University College London, London, UK.

Allen, A., J. Dávila, and P. Hofmann. 2006. The peri-urban water poor: Citizens or consumers? *Environment and Urbanization* 18(2): 333–351.

Allen, A., P. Hofmann, and H. Griffith. 2010. Moving down the ladder: Governance and sanitation that works for the urban poor. In *Sanitation services for the urban poor: Partnerships and governance*, edited by J. Verhagen et al. The Hague, The Netherlands: IRC International Water and Sanitation Centre.

Baccini, P. 1997. A city's metabolism: Towards the sustainable development of urban systems. *Journal of Urban Technology* 4(2): 27–39.

Bai, X. 2007. Industrial ecology and the global impacts of cities. *Journal of Industrial Ecology* 11(2): 1–6.

Bakker, K. 2003a. Archipelagos and networks: Urbanization and water privatization in the South. *Geographical Journal* 169(4): 328–341.

Bakker, K. 2003b. A political ecology of water privatization. *Studies in Political Economy* 70: 35–58.

Bakker, K. 2007a. The "commons" versus the "commodity": Alter-globalization, anti-privatization and the human right to water in the global South. *Antipode* 39(3): 430–455.

Bakker, K. 2007b. Trickle down? Private sector participation and the pro-poor water supply debate in Jakarta, Indonesia. *Geoforum* 38(5): 855–868.

Barles, S. 2009. Urban metabolism of Paris and its region. *Journal of Industrial Ecology* 13(6): 898–913.

Barles, S. 2010. Society, energy and materials: The contribution of urban metabolism studies to sustainable urban development issues. *Journal of Environmental Planning and Management* 53(4): 439–455.

Becker, J. and W. Raza. 1999. Theory of regulation and political ecology: An inevitable separation? *Ambiente e Sociedade* 5: 5–17.

Boyden, S. 1981. *Ecology of a city and its people: The case of Hong Kong*. Canberra, Australian Capital Territory, Australia: Australian National University.

Bringezu, S., H. Schütz and S. Moll. 2003. Rationale for and interpretation of economy-wide materials flow analysis and derived indicators. *Journal of Industrial Ecology* 7(2): 43–64.

Browne, D., B. O'Regan, and R. Moles. 2009. Assessment of total urban metabolism and metabolic inefficiency in an Irish city-region. *Waste Management* 29(10): 2765–2771.

Brunner, P. H. 2007. Reshaping urban metabolism. *Journal of Industrial Ecology* 11(2): 11–13.

Bulkeley, H., V. Castán Broto, and A. Maassen. 2011. Governing urban low carbon transitions. In *Cities and low carbon transitions*, edited by H. Bulkeley et al. London, UK: Routledge.

City of Stockholm. 2007. Hammarby Sjöstad—A unique environmental project in Stockholm. Stockholm, Sweden: City of Stockholm.

Clark, B. and J. B. Foster. 2009. Ecological imperialism and the global metabolic rift. *International Journal of Comparative Sociology* 50(3–4): 311–334.

Codoban, N. and C. A. Kennedy. 2008. Metabolism of neighborhoods. *Journal of Urban Planning and Development* 134(1): 21–31.

Czech, B. and H. E. Daly. 2004. The steady state economy—What it is, entails, and connotes. *Wildlife Society Bulletin* 32(2): 598–605.

D'Alisa, G., D. Burgalassi, H. Healy, and M. Walter. 2010. Conflict in Campania: Waste emergency or crisis of democracy. *Ecological Economics* 70(2): 239–249.

Daly, H. E. 1992. Allocation, distribution, and scale: Towards an economics that is efficient, just, and sustainable. *Ecological Economics* 6(3): 185–193.

Daly, H. E. 1996. *Beyond growth: Economics of sustainable development*. Boston, MA, USA: Beacon Press.

Daly, H. E. and J. C. Farley. 2004. *Ecological economics: Principles and applications*. Washington, DC, USA: Island Press.

Decker, E. H., S. Elliott, F. A. Smith, D. R. Blake, and F. S. Rowland. 2000. Energy and material flow through the urban ecosystem. *Annual Review of Energy and the Environment* 25: 685–740.

Doughty, M. R. C. and G. P. Hammond. 2004. Sustainability and the built environment at and beyond the city scale. *Building and Environment* 39(10): 1223–1233.

Dunn, B. C. and A. Steinemann. 1998. Industrial ecology for sustainable communities. *Journal of Environmental Planning and Management* 41(6): 661–672.

Duvigneaud, P. and S. Denaeyer-De Smet. 1977. L'ecosysteme urbain bruxellois [The Brussels urban ecosystem]. In *Productivite en Belgique*, edited by P. Kestemont and P. Duvigneaud. Paris, France: Edition Duculot.

Environment Agency. 2010. *State of the environment report 2010*. London, UK: Environment Agency.

Fischer-Kowalski, M. 1997. Society's metabolism: On the childhood and adolescence of a rising conceptual star. In *The international handbook of environmental sociology*, edited by M. R. Redclift and G. Woodgate. Cheltenham, UK: Edward Elgar.

Fischer-Kowalski, M. and W. Hüttler. 1998. Society's metabolism: The intellectual history of materials flow analysis, Part II, 1970–1998. *Journal of Industrial Ecology* 2(4): 107–136.

Fisher, D. R. and W. R. Freudenburg. 2001. Ecological modernization and its critics: Assessing the past and looking toward the future. *Society & Natural Resources* 14(8): 701–709.

Foster, J. B. 1999. Marx's theory of metabolic rift: Classical foundations for environmental sociology. *American Journal of Sociology* 105(2): 366–405.

Gandy, M. 2004. Rethinking urban metabolism: Water, space and the modern city. *City* 8(3): 363–379.

Gandy, M. 2005. Cyborg urbanization: Complexity and monstrosity in the contemporary city. *International Journal of Urban and Regional Research* 29(1):26–49.

Gandy, M. 2006. Urban nature and the ecological imaginary. In *In the nature of cities: Urban political ecology and the politics of urban metabolism*, edited by N. C. Heynen et al. Abingdon, UK: Routledge.

Girardet, H. 1992. *The Gaia atlas of cities: New directions for sustainable urban living*. London, UK: Gaia Books.

Girardet, H. 2008. *Cities, people, planet: Urban development and climate change*, 2nd ed. Chichester, UK: John Wiley.

Grimm, N., M. Grove, S. Pickett, and C. Redman. 2000. Integrated approaches to long-term studies of urban ecological systems. *BioScience* 50(7): 571–584.

Golubiewski, N. 2012. Is there a metabolism of an urban ecosystem? An ecological critique. *Ambio* 41(7):751–764.

Haberl, H. 2001. The energetic metabolism of societies, part I: Accounting concepts. *Journal of Industrial Ecology* 5(1): 11–33.

Haberl, H. 2006. The global socioeconomic energetic metabolism as a sustainability problem. *Energy* 31(1): 87–99.

Hamilton, C. 2010. Consumerism, self-creation and prospects for a new ecological consciousness. *Journal of Cleaner Production* 18(6): 571–575.

Hammer, M. 2006. Die ökologische Nachhaltigkeit regionaler Metabolismen: Materialflussanalysen der Regionen Hamburg, Wien und Leipzig [Ecological sustainability or regional metabolisms: Material flow analyses of the regions of Hamburg, Vienna and Leipzig]. *Natur und kultur* 7(2): 62–78.

Hanya, T. and Y. Ambe. 1976. A study on the metabolism of cities. In *Science for a Better Environment*, edited by HESC Science Council of Japan. pp. 228–233. Kyoto, Japan: HESC Science Council of Japan.

Head, P. 2008. *Entering the ecological age: The engineer's role*. London, UK: Institute of Civil Engineers.

Heynen, N., M. Kaika, and E. Swyngedouw. 2006. Urban political ecology: Politicising the production of urban natures. In *In the nature of cities: Urban political ecology and the politics of urban metabolism*, edited by N. Heynen et al. Abingdon, UK: Routledge.

Hornborg, A. 1998. Towards an ecological theory of unequal exchange: Articulating world system theory and ecological economics. *Ecological Economics* 25(1): 127–136.

Jackson, T. 2009. *Prosperity without growth: Economics for a finite planet*. London, UK: Earthscan.

Kaika, M. and E. Swyngedouw. 2000. Fetishizing the modern city: The phantasmagoria of urban technological networks. *International Journal of Urban and Regional Research* 24(1): 120–138.

Keil, R. 2003. Urban political ecology. *Urban Geography* 24(8): 723–738.

Keil, R. 2005. Progress report—Urban political ecology. *Urban Geography* 26(7): 640–651.

Keil, R. and J.-A. Boudreau. 2006. Metropolitics and metabolics: Rolling out environmentalism in Toronto. In *In the nature of cities: Urban political ecology and the politics of urban metabolism*, edited by N. C. Heynen et al. Abingdon, UK: Routledge.

Kennedy, C., J. Cuddihy, and J. Engel-Yan. 2007. The changing metabolism of cities. *Journal of Industrial Ecology* 11(2): 43–59.

Kennedy, C., S. Pincetl and P. Bunje. 2011. The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution* 159: 1965–1973.

Kerschner, C. 2010. Economic de-growth vs. steady-state economy. *Journal of Cleaner Production* 18(6): 544–551.

Kooy, M. and K. Bakker. 2008a. Splintered networks: The colonial and contemporary waters of Jakarta. *Geoforum* 39(6): 1843–1858.

Kooy, M. and K. Bakker. 2008b. Technologies of government: Constituting subjectivities, spaces, and infrastructures in colonial and contemporary Jakarta. *International Journal of Urban and Regional Research* 32(2): 375–391.

Kurokawa, K. 1977. *Metabolism in architecture*. London, UK: Studio Vista.

Kurokawa, K. 1999. *Kuala Lumpur International Airport*. Stuttgart, Germany: Axel Menges.

Latouche, S. 2010. Degrowth. *Journal of Cleaner Production* 18(6): 519–522.

Marcotullio, P. J. and G. Boyle. 2003. *Defining an ecosystem approach to urban management and policy development*. Tokyo, Japan: United Nations University Institute of Advanced Studies.

Martinez-Alier, J. 2009. Social metabolism, ecological distribution conflicts, and languages of valuation. *Capitalism Nature Socialism* 20(1): 58–87.

Martinez-Alier, J., G. Kallis, S. Veuthey, M. Walter, and L. Temper. 2010a. Social metabolism, ecological distribution conflicts, and valuation languages. *Ecological Economics* 70(2): 153–158.

Martinez-Alier, J., U. Pascual, F.-D. Vivien, and E. Zaccai. 2010b. Sustainable de-growth: Mapping the context, criticisms and future prospects of an emergent paradigm. *Ecological Economics* 69(9): 1741–1747.

Marx, K. 1976. *Capital: A critique of political economy*, volume 1. London: Pelican Books.

Masjuan, E., H. U. G. March, E. Domene, and D. Saurí. 2008. Conflicts and struggles over urban water cycles: The case of Barcelona 1880–2004. *Tijdschrift voor economische en sociale geografie* 99(4): 426–439.

Matthey, A. 2010. Less is more: The influence of aspirations and priming on well-being. *Journal of Cleaner Production* 18(6): 567–570.

McDonough, W. and M. Braungart. 2009. *Cradle to cradle: Remaking the way we make things*. London, UK: Vintage.

Mehmood, A. 2010. On the history and potentials of evolutionary metaphors in urban planning. *Planning Theory* 9(1): 63–87.

Minx, J., F. Creutzig, V. Medinger, T. Ziegler, A. Owen, and G. Baiocchi. 2011. *Developing a pragmatic approach to assess urban metabolism in Europe: A report to the European Environment Agency*. Stockholm, Sweden: Stockholm Environment Institute & Technische Universität Berlin.

Moffatt, S. and N. Kohler. 2008. Conceptualizing the built environment as a social-ecological system. *Building Research and Information* 36(3): 248–268.

Monstadt, J. 2007. Urban governance and the transition of energy systems: Institutional change and shifting energy and climate policies in Berlin. *International Journal of Urban and Regional Research* 31(2): 326–343.

Monstadt, J. 2009. Conceptualizing the political ecology of urban infrastructures: Insights from technology and urban studies. *Environment and Planning A* 41(8): 1924–1942.

Moore, J. W. 2000. Environmental crises and the metabolic rift in world-historical perspective. *Organization & Environment* 13(2): 123–157.

Newman, P. and I. Jennings. 2008. *Cities as sustainable ecosystems: Principles and practices*. Washington, DC, USA: Island Press.

Newman, P. W. G. 1999. Sustainability and cities: Extending the metabolism model. *Landscape and Urban Planning* 44(4): 219–226.

Niza, S., L. Rosado, and P. Ferrão. 2009. Urban metabolism: Methodological advances in urban material flow accounting based on the Lisbon case study. *Journal of Industrial Ecology* 13(3): 384–405.

Odum, E. P. 1963. *Fundamentals of ecology, 2nd ed.* Philadelphia, PA, USA: Saunders.

Odum, E. P. 1989. *Ecology and our endangered life-support systems*. Sunderland, MA, USA: Sinauer Associates.

Opschoor, J. B. 1997. Industrial metabolism, economic growth and institutional change. In *The international handbook of environmental sociology*, edited by M. R. Redclift and G. Woodgate. Cheltenham, UK: Edward Elgar.

Rees, W. and M. Wackernagel. 1995. *Our ecological footprint: Reducing human impact on the earth*. Gabriola Island, British Columbia, Canada: New Society Publishers.

Schneider, F., G. Kallis, and J. Martinez-Alier. 2010. Crisis or opportunity? Economic degrowth for social equity and ecological sustainability. Introduction to this special issue. *Journal of Cleaner Production* 18(6): 511–518.

Schulz, N. B. 2007. The direct material inputs into Singapore's development. *Journal of Industrial Ecology* 11(2): 117–131.

Slocombe, D. 1993. Environmental planning, ecosystem science, and ecosystem approaches for integrating environment and development. *Environmental Management* 17(3): 289–303.

Spangenberg, J. H. 2010. The growth discourse, growth policy and sustainable development: Two thought experiments. *Journal of Cleaner Production* 18(6): 561–566.

Suzuki, H., A. Dastur, S. Moffatt, N. Yabuki, and H. Maruyama. 2009. *Eco2 cities: Ecological cities as economic cities*. Washington, DC, USA: World Bank.

Swyngedouw, E. 2006. Circulations and metabolisms: (Hybrid) natures and (cyborg) cities. *Science as Culture* 15(2): 105–121.

Swyngedouw, E. and N. C. Heynen. 2003. Urban political ecology, justice and the politics of scale. *Antipode* 35(5): 898–918.

Tarr, J. A. 2002. The metabolism of the industrial city. *Journal of Urban History* 28(5): 511–545.

Vèron, R. 2006. Remaking urban environments: The political ecology of air pollution in Delhi. *Environment and Planning A* 38(11): 2093–2109.

Wallerstein, I. 1974. The rise and future demise of the world capitalist system. *Comparative Studies in Society and History* 16(4): 387–415.

White, D. F. 2006. A political sociology of socionatures: Revisionist manoeuvres in environmental sociology. *Environmental Politics* 15(1): 59–77.

Wolman, A. 1965. The metabolism of cities. *Scientific American* 213(3): 179–190.

Zimmer, A. 2010. Urban political ecology. Theoretical concepts, challenges, and suggested future directions. *Erdkunde* 64(4): 343–354.

About the Authors

Vanesa Castán Broto is a lecturer in Environment and Sustainable Development at University College London (UCL), London, UK. **Adriana Allen** is a senior lecturer and director of the masters program in Environment and Sustainable Development at the Development and Planning Unit at UCL. **Elizabeth Rapoport** is a doctoral candidate in the engineering doctorate (EngD) program in Urban Sustainability and Resilience at UCL.