Is There a Metabolism of an Urban Ecosystem? An Ecological Critique

Nancy Golubiewski

Received: 23 November 2010 / Revised: 18 September 2011 / Accepted: 21 December 2011 / Published online: 20 January 2012

Abstract The energy and material flows of a city are often described as urban metabolism (UM), which is put forward as a way to link a city's ecology and economy. UM draws parallels to the biology of individual organisms, yet the analogy is misapplied. In striving to be interdisciplinary, UM makes this organismic comparison rather than identifying the city as an ecosystem, thereby ignoring developments in ecological theory. Using inappropriate rhetoric misdirects researchers, which influences scientific investigation—from problem statements to interpretations. UM is valuable in quantifying the city's use of natural resources but does not achieve a comprehensive, integrated analysis of the urban ecosystem. To realize an interdisciplinary, perhaps transdisciplinary, understanding of urban ecology, researchers need to emphasize the essential tenets of material flows analysis, view the city as an ecosystem, and use language that properly reflects current knowledge, theory, and conceptual frameworks in the foundational disciplines.

Keywords Urban metabolism · Urban ecosystem · Material flows analysis · Urban ecological model · Urban ecology theory · Socio-ecological system

INTRODUCTION

Cities are part and parcel of global environmental change. To meet the challenges of understanding urban systems in this context and of achieving sustainable solutions for cities and the planet as a whole, appeals for interdisciplinary research and action commonly, if not ubiquitously, are made. *Interdisciplinarity* (coordination among disciplines,

using knowledge and epistemologies of one or more disciplines within another to address issues) is situated on a continuum between *multidisciplinarity* (the knowledge and understanding of more than one discipline applied to a subject without cooperation) and *transdisciplinarity* (a multi-level, integrative approach to develop new concepts). Interdisciplinarity, in effect, is crucial for moving toward transdisciplinary integrative frameworks, such as sustainability science.

Implementing interdisciplinary research and acquiring integrated understanding is much more difficult than using the rhetoric that invokes them. How do ecological measures of the urban ecosystem join together with socio-economic methodologies and perspectives? The language used in these ventures critically influences how a problem is conceptualized and, thus, pursued.

Urban metabolism (UM) exemplifies the inherent prospects and the challenges of interdisciplinary research as it attempts to understand cities as biophysical systems. It is considered by some to be a promising methodological tool to bridge the gap between ecological and socio-economic approaches to urban systems (Boyle et al. 2003; Haberl 2005). The concept refers to organismal metabolism, drawing parallels to the inputs (food) and outputs (wastes) of a human body as well as its circulatory system, to place the city within its environmental context.

Although readily adopted by some researchers, the relevance and appropriateness of UM remain largely unscrutinized (Burney 2004; Swyngedouw 2006). Only a few UM studies exist, and none gives more than a cursory explanation and justification of the analogy. It is timely and necessary to undertake a thorough examination of its theoretical and practical aspects (e.g., Lifset 2004; Swyngedouw 2006).

CONCEPTUALIZATION AND EMERGENCE OF UM

UM has been defined as the material and energy flows through a city. It quantifies the balance of a city's resource inputs (e.g., fuel and food) and waste outputs (e.g., air pollution and refuse). The concept draws on the first law of thermodynamics' conservation of energy: the amount of waste depends on inputs, which are the sum of outputs and the stock increase (Newman 1999; Sahely et al. 2003). Emphasis is placed on the efficiency with which resources are used. Rather than develop a theory of UM, though, researchers have explicated the concept through its usage.

Origin: The Hypothetical City

In a paper considered seminal, Wolman (1965) first invoked metabolism to describe a hypothetical city. His premise was to examine inputs and outputs—provision of an adequate water supply, effective disposal of sewage, and control of air pollution—as part of a city's socio-economic functioning. To set the stage, he asserted:

The metabolic requirements of a city can be defined as all the materials and commodities needed to sustain the city's inhabitants at home, at work and at play. Over a period of time these requirements include even the construction materials needed to build and rebuild the city itself. The metabolic cycle is not completed until the wastes and residues of daily life have been removed and disposed of with a minimum of nuisance and hazard (Wolman 1965).

An input–output (I–O) analysis summed the water, food, and fuel required by the city as well as the resulting sewage, refuse, and air pollutants (Wolman 1965).

Though the UM analogy provided a platform for discussing resources quantitatively, strict parallels to organismic metabolism were not drawn. Indeed, Wolman only mentioned the concept; he did not expound a theory. He simply referenced metabolism to explain I–O analysis: “The output side shows the metabolic products of that input in terms of sewage, solid refuse, and air pollutants” (Wolman 1965). Instead of elucidating the reference to metabolism, Wolman (1965) considered how urban infrastructure dealt with throughput required by the city's population.

Implementation: Case Studies

After Wolman's introduction of the phrase, a study of Hong Kong offered the first description of UM: “We must come to understand and appreciate the nature of the inputs of urban settlements; their transportation networks; the

capacity of their natural and man-made circulatory systems; the generation, disposal and resource potential of their wastes—in short, we must become familiar with the metabolism of our cities” (Newcombe et al. 1978). If Wolman labeled the reliance of urban environments upon the natural world as metabolism, the Hong Kong study operationalized it by cataloging the rates of resource consumption and waste production, with additional analyses of energy, food, nutrients, and water supply (Boyden et al. 1981). This pioneering case study used previous mass-balance studies to characterize physical indicators of flows through the city and social variables affecting the population (Newcombe et al. 1978). The research considered the flow and end use by looking at the composition of the built environment, energy use, “metabolic consumption” (i.e., energy), nutrients, flows of phosphorus and water, flow of materials, the “circulatory system” (i.e., transport), air systems, sewage, aggregates, and solid waste (Newcombe et al. 1978). This analysis was used to project the effects of urbanization on resource requirements for the turn of the century.

Warren-Rhodes and Koenig (2001) updated the study to compare flows in 1971 and 1997, explaining that UM “measures quantitatively a city's load on the natural environment”. The trend analysis showed increases in material usage and pollutant generation, leading the authors to conclude, “systemic overload of land, atmospheric and water systems has occurred” (Warren-Rhodes and Koenig 2001). They suggested “high metabolic rates can be beneficial to a city's survival” in terms of efficient resource consumption but noted that a high environmental cost outweighed any benefits in Hong Kong.

A metabolic study of Tokyo considered the health and ecosystem risks of various material stocks and flows (Akiyama 1994). It quantified the accumulation, and calculated the residual time, of chemical elements in urban waterways and synthetic compounds. The study noted the high energy consumption in the city and the large amount of materials rapidly moving through the transport system, highlighting two approaches to UM: the black box and subsystem models (Akiyama 1994). The former considered city-level macroscopic indicators and the latter looked at flows of materials and their controls.

Twenty-five years after the Hong Kong study, material flow analysis and emergy evaluation were contextualized with the UM analogy: “The metabolism of a city can be seen as the process of transforming all the materials and commodities for sustaining the city's economic activity” (Huang and Hsu 2003). Newman (1999) presented material flows for Sydney, Australia in 1970 and 1990, showing an increase through time in per capita resource inputs and most waste outputs.

Hendriks et al. (2000) described the metabolism of Vienna by using a material flows analysis. Several metabolic concepts were considered, including the anthropogenic metabolism (i.e., flows within the city), which was linked to natural metabolism (i.e., the environment). The metabolism of the city was then linked to the hinterland.

A UM study of Toronto estimated the inflows of food, water, and manmade energy and the outflows of air emissions, residential solid waste, and wastewater (Sahely et al. 2003). This served the authors' definition of UM as "a means of quantifying the overall fluxes of energy, water, material and wastes into and out of an urban region" (Sahely et al. 2003). The study showed inputs increased more than outputs between 1987 and 1997 and also compared the per capita material flow for Sydney, Hong Kong, and Toronto in terms of food, water, energy, emissions, solid wastes, discharged wastewater, and biochemical oxygen demand.

Further international comparisons were made by Decker et al. (2000) in a synthesis report, where material and energy flows through 25 megacities were compared using the ideas of "biological metabolism". They defined the UM concept: "Energy and material flows through human settlements are conceived as UM, in which material inputs are transformed into useful energy, physical structure, and waste" and noted this type of analysis has also become known as industrial metabolism, industrial ecology, and regional metabolism (Decker et al. 2000).

These types of analyses show the "sheer magnitude of flow" of resources (Graedel 1999), as well as their composition. Specifically, UM provides a framework for describing the consumption of land and energy and expulsion of waste by economic activity. Usefully, UM has led researchers to catalog the resources used, consumed, and transformed into waste.

The Underlying Biological Analogy

Proponents of UM assert that because it makes explicit the resource/waste pressures of a city, it constitutes an ecological assessment. Newman (1999) explained that UM reveals "the best way to ensure that there are reductions in impact, is to reduce the resource inputs. This approach to resource management is implicitly understood by scientists but is not inherent to an economist's approach which sees only 'open cycles' whenever human ingenuity and technology are applied to natural resources. However, a city is a physical and biological system." Accordingly, the quantification of resource consumption and waste generation is equated to a biological systems way of studying urban settlements (Newman 1999).

UM links the city to the environment by using organismal metabolism to explain the energy and material flows

of the city. In one of the most mild assertions, it is suggested that "somewhat analogous to human metabolism, cities can be analyzed in terms of their metabolic flow rates that arise from the uptake, transformation, and storage of materials and energy and the discharge of waste products" (Sahely et al. 2003). Another explanation provides more detail:

Like human metabolism, the physical and biological processes of a city system transform inflows of energy and materials into useful products, services and wastes. They are based on the laws of thermodynamics and a balance sheet of inputs and outputs can be analyzed. The materials, energy, and food supplies brought into cities, transformed within them and the products and wastes sent out from the cities are often referred to as the urban metabolism (Huang and Hsu 2003).

With such statements, UM research aims to connect ecology and economics.

PRINCIPLES FROM THE NATURAL SCIENCES

That the city is a biophysical system would be agreed to by ecologists, but whether the UM framework implements this concept appropriately or fully is debatable.

Ecological Definitions

Ecology is not synonymous with biology but rather developed into a distinct discipline. In biology, the metabolism of an organism is defined as the total chemical activity and flow of resources that occur within its body. As a general definition, metabolism is the complex of physical and chemical processes involved in the maintenance of life. Metabolism has two aspects: first, anabolism, or constructive activity, involves the transformation of energy and simple organic molecules absorbed from the external environment into more complex macromolecules such as proteins. Second, catabolism, or destructive activity, simplifies complex molecules, such as breaking down toxins into waste products. Metabolism serves the condition of homeostasis in organisms, whereby physiological equilibrium is maintained through the balance of functions and chemical composition.

Whereas biology is the study of living organisms and life processes, the field of ecology comprises the study of interactions *between* an organism and the physical and biological components of its environment. While some of ecology's origins are in biology (e.g., natural history), other elements of ecology arose from the earth sciences (e.g., geochemistry); accordingly ecology overlaps, but is

not a sub-discipline of, biology. A modern, overarching definition of ecology states: “Ecology is the scientific study of the processes influencing the distribution and abundance of organisms, the interactions among organisms, and the interactions between organisms and the transformation and flux of energy and matter” (Likens 1992). Hence, ecology spans a hierarchy of levels of organization, from the organism to the ecosphere (Fig. 1).

At the organismal end of the hierarchy, autoecology focuses on the interactions between an organism and its environment, with a primary focus on physiological responses of the organism to the abiotic environment. The specialized subdiscipline of physiological ecology studies how the bodily processes of organisms are adapted to the physical environment.

Individuals of the same species located in the same area are grouped into a population, which is studied as a whole in relation to the environment in population ecology. In a specific locale, the populations of all species form a community, and community ecology considers the relationships among these populations. Both ecological succession and competition are community-level processes.

An ecosystem comprises the community and its environment: Tansley (1935) coined the term to capture the interchange among organic and inorganic components. Ecosystem ecology constitutes the most inclusive

subdiscipline of ecology insofar as it considers the system perspective of all the abiotic and biotic components of a defined area. Ecosystem interactions can occur at a variety of scales. Systems ecology emerged as a highly mathematical subdiscipline that models the interactions among components of an ecological system, especially energy and materials among biotic and abiotic components of an ecosystem.

Ecology’s broad scope encompasses a range of subdisciplines along a gradient from mostly biotic in focus (e.g., evolutionary ecology) to mostly abiotic (e.g., biogeochemistry) (Likens 1992). A mix of abiotic and biotic vantage points is necessary for most ecological research (Pickett et al. 1994), which investigates structure, function, and the connections between the two in both space and time. Gradients and patch dynamics provide organizing frameworks for the study of spatial relationships. How communities and ecosystems change through time has been a long-standing concern, including successional trajectories, process rates, and residence times. Unique frames of reference emerge where subdisciplines operate at various levels of organization, and functions or processes such as energetics, evolution, and regulation transcend the levels of organization, resulting in a multi-faceted hierarchy (Pickett et al. 1994).

Differentiating the Ecosystem from an Organism

Whereas an organism is a single individual, an ecosystem encompasses a complex assemblage of multiple individuals (often of multiple species) located within their environment. Organismal studies have an inward focus—concerned with the internal functioning of the components that comprise the body. Ecosystem studies incorporate interactions between components within the system as well as connections between the system and wider environment, thus promoting an internal and external focus. Daly (1968) noted the difference in perspectives as “within skin” (biology) and “outside skin” (ecology).

The study of the organism concentrates on how individuals maintain homeostasis in the face of fluctuating environmental conditions as well as their life cycles. While the circulatory system, by definition, encompasses the cyclic flow of blood and lymph through the body, metabolism in the coarsest sense is the linear flow of energy—from ingestion of food to expulsion of its residue—to support the physiological functions necessary for maintaining life (Fig. 2b). The organism’s morphology is pre-determined within a rather narrow range of variation (i.e., juvenile and adult life forms can be predicted from species identification).

In contrast, the study of the ecosystem considers the functional relationships and dynamics of the defined system’s assembled biotic and abiotic entities. Rather than the

Fig. 1 Ecological scope. The levels of organization of biological systems extend from suborganismal (atomic to organ levels) to planetary. Ecology encompasses levels from organisms to the ecosphere. The ecosystem comprises the first complete unit in the hierarchy

Fig. 2 System models: **a** a basic input–output system, **b** a model appropriate for homeostatic, goal-seeking organismal systems (control mechanisms are concentrated in specific structures), **c** a model for “non-teleological” systems, including ecosystems, where controls are internal and diffuse, involving interactions between primary and secondary subsystems (Adapted with permission from Patten and Odum 1981, ©1981 by The University of Chicago. 0003-0147/81/1806-0006\$2.00)

unidirectional flow of the simple I–O model (Fig. 2a), the material processes of ecosystems are varied: outputs become inputs to another flow, cycle in feedback loops, or contribute to a stock with a particular residence time (Fig. 2c). The stocks and flows of energy are studied within and among the various pools that exist in the ecosystem. Though linked, material and energy processes and flows must be treated distinctly because the fundamental laws that govern energy flow and material cycling are different: material cycles, energy does not.

In addition, the ecosystem does not have a predetermined structure or morphology; ecological succession does not operate unidirectionally toward a predetermined climax community (Kingsland 1991). Through the study of disturbance and patch dynamics, community ecology has supplanted the notion of strict equilibrium climax communities with dynamic stable states in ecological succession (Glenn-Lewin et al. 1992).

Ecologists debated the utility and relevance of the organismic metaphor—put forward by Clements, along with climax succession, and critiqued by Cowles, Gleason, and Tansley—in the early twentieth century, ultimately eschewing it by mid-century to concentrate on the ecosystem (Kingsland 1991). Indeed, Tansley chose “ecosystem” to emphasize the functional relationship between a community and its environment, which shifted focus from a biological model to a physical one (Kingsland 1991).

Even so, Odum called upon physiological principles in his efforts to define a holistic view of ecological studies, invoking “metabolism” to describe processes at the ecosystem level and “superorganism” to argue for its stability and emergent properties (Odum 1969; Craige 2001). Ecosystem metabolism has developed into a research area with its own conceptual framework, explicit theory and definitions, and set of methods. It sums the energy processed by all individuals in the ecosystem; the multiplicity of processes are, generally, simplified into categories of production and respiration, often measured in units of carbon rather than energy (Houghton 1999). On the other hand, the superorganism idea proved to be controversial rhetoric, provoking debate that contributed to ecological theory’s progression from an equilibrium orientation to a non-equilibrium one.

For his part, Odum later noted that using the organism to achieve holism had led to confusion, especially regarding system regulation and stability (Patten and Odum 1981; Odum and Barrett 2005). As there are no set-point controls in nature, homeostasis does not govern processes; rather homeorhesis, pulsing states within limits, is generated by interrelationships and feedbacks among material cycles and energy flows (Odum and Barrett 2005). Importantly, the “Failure to recognize this difference...has resulted in much confusion about the balance of nature” (Odum and Barrett 2005). Furthermore, the notion of stability has become more sophisticated to distinguish resistance stability, whereby an ecosystem can resist perturbation and retain its structure and function, from resilience stability, which indicates ability to recover after a disturbance (Patten and Odum 1981; Odum and Barrett 2005). Odum himself relinquished the superorganism idea (Patten and Odum 1981), explicating: “an ecosystem is not equivalent to an organism; because it is not under direct genetic control, an ecosystem is a supraorganismic level of organization, but *it is not a superorganism...*” (Odum and Barrett 2005, emphasis added).

The Urban Ecosystem

It seems rather obvious that a city is a system rather than a body. In actual fact, the urban system is just another type of ecosystem, such as grassland or forest, with the unique

quality that it is controlled and, in part, constructed by humans (Pickett et al. 1997; Redman 1999; Grimm et al. 2000, 2008; Baker et al. 2001; Odum and Barrett 2005). The spatial and temporal scales at which a city operates mirror that of other ecosystems rather than an individual (Table 1).

On spatial scales, the city aligns with an ecosystem. Whereas the organism is clearly bounded—the body versus the environment—the city sits within the environment as an agglomeration. The borders can thus be defined as necessary for the particular study, as is the case with all ecosystem studies. Whereas an organism's circulatory system is clearly defined with specific pathways, the material and energy flows of ecosystems are variable in space and, in fact, are determined by the interactions of organisms with their environment through patch dynamics.

Temporally, the city also functions differently from an organism. Rather than requiring daily intake of a particular suite of nutrients, material and energy flows occur over short and long time scales without specific requirements

(Fig. 2). Whereas an organism has particular life history traits that lead it through various stages toward maturation, a city's growth and development are not predetermined. While particular individuals or entities within the system might die or cease functioning, the city as a whole can continue to exist under a wide range of conditions. Indeed, many individual entities—both organismal and synthetic—comprise the total functioning of the city.

The ecosystem approach (Table 2) is hailed as the tool that will strengthen analyses and understanding of the urban phenomenon (UNU-IAS Urban Ecosystems Management Group 2004). It follows, then, that the ecosystem is the appropriate scale at which to study the subject. Some acknowledge this: “One of the strongest themes running through the literature on urban sustainability is that if we are to solve our environmental problems we need to view the city as an ecosystem” (Newman 1999). Newman (1999) further describes aptly how this can be done, using the appropriate ecological principles at the correct scale:

Like all ecosystems, the city is a system, having inputs of energy and materials, the main environmental problems (and economic costs) are related to the growth of these inputs and managing the increased outputs. By looking at the city as a whole and by analyzing the pathways along which energy and materials including pollutants move, it is possible to begin to conceive of management systems and technologies which allow for the reintegration of natural processes, increasing the efficiency of resource use, the recycling of wastes as valuable materials and the conservation of (and even production of) energy.

This focus on systems, without invoking the strained organismal analogy, would represent the maturation of the approach, if consistently used, as well as lead to the urban ecosystem framework.

EXAMINING THE ANALOGY

To be sure, some UM researchers have associated cities with ecosystems by way of analogy (Costa et al. 2004). Interestingly, Duvigneaud and Denayer-De Smet's early ecological study of the Brussels urban ecosystem, which explicitly set out to apply the concepts of ecosystem ecology (Golley 2003), has been embraced as one of the most comprehensive UM studies, even if some of the flows are deemed too detailed (Kennedy et al. 2007). Decker et al. (2000) described ecosystem analyses well:

Biogeochemical analysis of wild ecosystems is known as ecosystem ecology. Properties studied in

Table 1 Conceptualizations of urban systems differ between organismal and ecosystem approaches to urban studies

	Organismal perspective	Ecosystem perspective
Scientific foundation	Biology	Ecosystem ecology
Disciplinary focus	Life processes	Abiotic/biotic interactions
Orientation	Inward	Internal processes, external linkages
Metabolism meaning	Food/waste	Energy processing, production/respiration (C balance)
Metabolic units	Volume	Energy or carbon (or other materials)
Movement	Input–output	Feedbacks
Flows	Throughput	Structure–function linkages
System regulation	Homeostasis	Homeorhesis
Stability	Resistance	Resilience
Time	Climax succession	Disturbance dynamics
Structure	Morphostatic	Multiple stable states
Space	Uniformity	Fine-scale spatial heterogeneity (patch dynamics and gradients)
Agency	Single actor	Social, biological, and physical entities
Consumption	Heterotrophy	Internal transformations and teleconnections
Scope	Black box	Subsystems
Environmental context of city	Separate but connected, hinterland	Integrated social–biological–physical system

Table 2 Ecosystem versus traditional approaches to studying urban systems (Reprinted with permission from UNU-IAS Urban Ecosystems Management Group 2004)

Ecosystems approach	Traditional approaches
Multiple scales (spatial and temporal)	Remain within municipal boundaries, seek solutions at the scale and level of the problem
Flows/feedbacks	Linear “input–output” approach
Multidisciplinary and multi-sectoral	Dominated by economic planning of sectoral interests (e.g., transportation, solid waste, water supply)
Trade-offs between economic, social and environmental concerns and increasingly between environmental services	Optimization between social, economic and environmental cycles
Plan for less <i>vulnerability</i> , more <i>resilience</i> or urban system	Plan for infrastructure, housing and other system developments to meet consumer demands
Focuses on different roles of and approaches to governance for different types of problems (specifically calls for multi-tiered governance structures)	Focuses on the local level and role of local and citywide decision-makers/stakeholders or prioritizes allocating tasks to as low a government level as possible

this framework include net system productivity, net system respiration, biomass accumulation, nutrient cycling, energy transfer efficiency, and system resilience. The ecosystem analogy draws attention to the differences between urban and wild ecosystems. Further it raises the question of whether city systems undergo succession in any form and provides a framework for addressing urban change.

In fact, ecosystem ecology encompasses “wild”, “natural”, and “managed” ecosystems. Ecologists recognize that very few—if any—places remain on the planet that have not been influenced by human activities.

A Critique of UM

It is important to clarify the difference between analogy and identity. The city is not *analogous* to an ecosystem; it *is* one. By contrast, the UM concept relies on correspondence: Analogies are comparisons that allow inferences to be drawn based on parallels of partial similarity (Ehrenfeld 2003). The underlying problem with using metabolism as an analytic tool for studying cities is that, like all analogies, its usefulness is limited by the differences that underlie the comparison (Gorman 1998), further exacerbated by the fact that the analogy was based on something meant to be a metaphor (Patten and Odum 1981; Craige 2001). In this case, *UM*—while perhaps expedient at first in drawing attention to inflows and outflows—has the effect at times of conflating concepts, limiting analyses, or fostering misleading interpretations.

Conflating Concepts

The UM literature repeatedly cites the need to consider the city as a system in relation to its environment (Akiyama 1994; Newman 1999; Decker et al. 2000; Warren-Rhodes

and Koenig 2001). Even so, a weakness of UM is the tendency to conflate organism and ecosystem (Fig. 2): studies often use the terms interchangeably. For example, “The physical and biological processes of converting resources into useful products and wastes is like the human body’s metabolic processes or that of an ecosystem” (Newman 1999). Throughout the explanations of UM, the simple assertion is made that cities have a metabolism, and the organism and ecosystem levels are used simultaneously without further justification, e.g., “The analogy drawn here between a *large organism* and a city is not misplaced, for the health of the urban *ecosystem* depends very much on a continuing supply of essential materials, energy and information, and on the disposal of unwanted wastes” (Newcombe et al. 1978, emphasis added).

Distortions are further exacerbated when authors compare the organism and the city. Such efforts result in anthropomorphizing the city into a patient:

Drawing parallels between living organisms and urban systems provides insights into how complex, modern cities sustain their populations. Although not fully analogous, there are similarities. Just as materials and energy are required for human metabolism and work, cities rely on a continuing supply of energy, resources and information to function. Cities can therefore be analyzed in terms of uptake, transformation and storage of materials and discharge of waste products.

In humans, food and materials are consumed, energy is utilized or stored, and wastes and heat are released to the air, land, and water. In cities, metabolic flows arise from material use, food consumption and urban development; materials are stored as infrastructure; and materials and wastes are moved through man-made circulatory systems, with pollutants released to air, land, and water systems (Warren-Rhodes and Koenig 2001).

Drawing a tight parallel for something *not fully analogous*, the city is ascribed a physiology: “Like blood in the human body, water functions as one of Hong Kong’s main transport and purifying mechanisms, delivering inputs and outputs, receiving and diluting wastes, and moving human and material cargo through the urban system” (Warren-Rhodes and Koenig 2001). Pushing the analogy to the extreme, the UM study becomes an “urban health check up”, which diagnoses the city as overweight with high blood pressure (Warren-Rhodes and Koenig 2001).

Attempts to work within the confines of the analogy also lead to confusion about scientific fields and principles. As a point of illustration, “At the level of an individual organism, biogeochemistry comprises the metabolic processes: the conversion of water and food into biomass and waste. The parallels to urban systems are obvious and compelling. Cities transform raw materials, fuel, and water into the urban built environment, human biomass, and waste” (Decker et al. 2000). The use of “biogeochemistry” here illustrates the problem of misapplied analogy. At an organismal level, biochemistry affects metabolism; a relationship to the abiotic environment (the “geo”) falls outside an organismal scope. Biogeochemistry, on the other hand, incorporates the material and energy flows through the environment. As these are the phenomena of interest as well as those between organisms and the environment (not within organisms), the ecosystem level is the appropriate one for studying the city within the context of the environment.

Limiting Analyses

Applying the organismal scale to the city creates an artificial boundary problem. The clear delineation of an organism’s body from its environment creates an inward (physiological) focus. The original Hong Kong study exemplifies this: “As urban settlements grow in size, the air and water systems are called on to dispose of more and more waste and the importance of man-made circulatory systems is increased” (Newcombe et al. 1978). This organismal description concentrates on the unidirectional flow of inputs and outputs through the city, acquiring supplies from and expelling waste to the environment, from which it remains separated. Alternatively, an ecosystem perspective considers the socio-ecological system, with both in situ and exogenous socio-economic and ecological factors commingling to influence processes of material and energy flows (Pickett et al. 2008).

Certainly, ecosystem studies can adopt different boundaries, as required by the focus of the analysis. This fluid boundary definition enables multi-scale investigation insofar as ecosystems can be embedded within a larger ecosystem. Importantly, no matter the boundary drawn, the

emphasis remains on the multiplicity of biotic and abiotic interactions.

These interactions are obscured by UM’s organismal focus on sole agency, as exemplified here:

we can manage the wastes produced, but they require energy in order to turn them into anything useful and ultimately all materials will eventually end up as waste. For example, all carbon products will eventually end up as CO₂ and this is not possible to recycle any further without enormous energy inputs that in themselves have associated wastes. This is the entropy factor in metabolism (Newman 1999).

Actually, the story does not stop with the emission of CO₂. In fact, it is an important component of *ecosystem* metabolism. Whereas energy flow is a linear process that involves increasing entropy, materials have cycles and flow into various pools with different residence times.

Similarly, the updated Hong Kong study states fertilizer is stored in land (Warren-Rhodes and Koenig 2001). This is inaccurate; fertilizer does not become, nor join, a single material stock; rather biogeochemical processes operate that further release chemical compounds with varied fates and environmental impacts. By “storing” the “waste products” flowing out of the economy, UM ignores that these products continue as energy and materials in the urban and natural environments, in “consumed” forms, and thus informs little about the systemic overload it purports to demonstrate.

In both cases, the studies ignore biogeochemical processes within the city itself, including the vegetation, animals, soil, water, and air encompassed by the urban ecosystem. Thus, UM falls short in explicating a city’s environmental impact with its macroscopic black box approach, which does not make the city a part of the ecosystem nor consider the spatial heterogeneity and multiple socio-ecological controls influencing material and energy flows in air, water, and land.

Although most UM studies use this black box approach, it is also possible to incorporate subsystem models. As defined, black box approaches to UM show the:

material input and output of a city, and express the intensity and/or the size of urban activities as macroscopic indicators, which are similar to some health-related information such as body weight, body temperature and blood pressure if a city is regarded as a human body by analogy... Another approach to urban metabolism is to build a subsystem model, which enables us to understand the flow of materials and factors controlling the flow, which may be something similar to catalysts or enzymes by analogy to a human body (Akiyama 1994).

This helpfully acknowledges that UM can be extended to look at systemic dynamics, which the macroscopic indicators lack. Yet, the clunky organismal allusion to catalysts and enzymes obfuscates the possibilities for unraveling abiotic/biotic interactions that occur heterogeneously throughout the urban ecosystem (Table 1, Fig. 2).

Misleading Interpretations

With its antiquated analogy, UM misapplies ecology at both practical and theoretical levels. Practical problems arise in the implementation of the research when, rather than allow the city to be an ecosystem, UM analyses replace ecosystem components with other constructs. For instance, “Structural parallels are frequently drawn between natural ecosystems and urban ecosystems, eg between bio-mass [sic] and square feet of floor area in buildings” (Newcombe et al. 1978). The use of floor area as a replacement for biomass ignores the fact that the city already contains its own biomass: vegetation (and other organisms) exists within the city. Other UM studies have used urban biomass to connote accumulated material stock (Baccini 1997; Warren-Rhodes and Koenig 2001). In a truly comprehensive analysis of the city, the pools and processes of vegetative biomass would be considered in addition to buildings and other material stock.

Effectively, UM implements organismal metabolism at the expense of ecosystem metabolism. Warren-Rhodes and Koenig (2001) made a partial analysis by comparing the material resources consumed by the city to those required by inhabitants’ food requirements and material turnover in natural ecosystems as well as contrasting consumed fossil fuel energy with total incoming solar radiation, photosynthetically fixed solar energy, and human respiration. Although interesting, this is neither a full assessment of the city nor an appropriate inter-system comparison. The complete accounting of the energy processed in the *human ecosystem* would include all its components, including primary production (by autotrophs that exist within the city), autotrophic and heterotrophic respiration by all the city’s organisms (including plants, animals, microbes, and humans), and the consumption and emission of imported resources (food, materials, and energy).

With all components accounted for, compelling internal and external assessments can be made. Accumulated material stock could be compared to the city’s vegetative biomass as opposed to substituting for it. It would be informative to compare the city’s primary production to the embodied primary productivity of imported material (thus studying two related processes rather than equating two dissimilar things) in order to understand the city’s reliance on other ecosystems. This would be further supported by assessing the respiration derived from internal production

(i.e., plants, soil, and organisms existing within the city) to that of humans (relying in part on food imports) and manufacturing processes (supported by fossil fuel imports) (e.g., Collins et al. 2000).

Comparisons of the built ecosystem to natural ecosystems can then include both the extant primary productivity in each system as well as the degree of heterotrophy. Material consumption should not be the only component of the city compared to a natural ecosystem. Comparisons of similar stocks and flows—parallel and entirely—need to be made between the human-dominated, synthesized urban ecosystem and other ecosystems, whether managed or natural.

Perhaps such confusions stem from the fact that there is no clear identification of the urban ecosystem itself in the UM literature. One description pulls in various ecological concepts:

If compared with other ecosystems, the urban systems are relatively immature due to rapid growth and inefficient use of resources...cities are one of the heterotrophic ecosystems in the biosphere; the good parasites do not destroy their host, rather, remain in symbiotic relationship with each other. From the point of view of system ecology, cities are self-regulating systems and may be seen as super-organisms... (Huang and Hsu 2003).

Here, the usage of systems ecology is confused, as evidenced by the labeling of a heterotrophic system as parasitic. Cities are heterotrophic; it would be informative to study the degree to which the heterotrophy can be altered as well as contrast it to other heterotrophic ecosystems. Moreover, the idea of equilibrium succession is implied by the description of cities as immature and as superorganisms, pointing to a wider, theoretical problem with UM.

The definition of ecology used by UM researchers seems to reside solely with Odum’s (1969) ecosystem-as-super-organism metaphor—curious, given its outmoded, controversial standing (Brown 1991) as well as the development of the author’s own ideas (Sect. 3.2, Patten and Odum 1981; Odum and Barrett 2005). The city is a system that can take on many forms and functions, quite different from the expected life history of an organism. This point has been recognized by an UM researcher who implements the human metabolism analogy:

when one tries to explain an urban system by the analogy of organic bodies one is obliged to face the risk that an urban system is morphostatic; the final shape and structure are predetermined irrespective of the surrounding environment it is placed in and the historical process it has passed through. Instead, the dynamism and individuality of an urban system

should be more emphasized rather than the static nature and generality (Akiyama 1994).

Such concerns have already been resolved in the field of ecology, which moved away from adopting the organismic metaphor in favor of studying functional ecosystems (Sect. 3.2). Thus, the use of current ecological understanding could help to maintain an appropriate focus and avoid the pitfalls noted above.

Embracing the outdated organismic metaphor also leads researchers to another (itself based on the idea that plant communities are complex organisms): climax-community succession (e.g., Decker et al. 2000). It describes a monotonic process of increasing stability and diversity, toward a stable climax, which relies on outdated equilibrium theories:

it is clear that an adaptive urban management strategy for the future is one which both modifies the operations of present urban systems and designs their expansion to provide for a given level of human well-being at greatly reduced resource inputs. This pattern of development is parallel to ecological succession in natural plant and animal communities. Reduced dependency on external supplies of resources would increase the stability, diversity and resilience of the urban ecosystem (Newcombe et al. 1978).

Modern understanding of succession allows that ecological communities operate in multiple stable states that dynamically respond to a suite of disturbances (DeAngelis and Waterhouse 1987). By emphasizing an organismal perspective, UM researchers more readily link to a narrowly defined climax succession through the logic that, “[c]onceiving urban energy and material flows as an urban metabolism accentuates the fundamental physical processes that govern city growth and functioning. The concepts are not new, and we adapt them as an organizational tool and attempt to expand them. A potentially powerful contribution will be the parallel between urban evolution and succession” (Decker et al. 2000). This parallel may occur—if using the modern definition of multiple stable states rather than seeking the non-existent superorganism.

System Failure

The UM analogy is called upon to operate at three scales simultaneously: organismic (metabolism), community (succession), and ecosystem (systems). Proponents often confound organismal and ecosystem arguments: while calling the city a system, they anthropomorphise it—trying to “take its temperature”—and impose an organismal approach to analyses. They want UM to both describe the city as an ecosystem

and provide a neatly defined organismal model. Two approaches are used: either maintaining allegiance to the analogy so strongly that cities are sent to the doctor’s office, or recognizing the inconsistency of the analogy while using it anyway. This leads to a lack of clarity and a failure to capture a comprehensive biophysical study of the urban ecosystem. Interestingly, the ecosystem health concept suffered the same pitfalls (e.g., Marcogliese 2005).

UM emphasizes an I–O process over interrelationships: only resource inputs and waste outputs are of concern (Table 1, Fig. 2). The treatment of the various flows as independent, mutually exclusive, and additive (Graedel 1999) results in a reductionist consideration of the city at the expense of emergent properties and holism. In all, UM does little more than quantify the resources required by the economy, and, in so doing, expands classical economic analysis in the direction of environmental considerations. Importantly, it identifies and quantifies the biophysical resource stream, but this is treated only as another set of inputs and waste products. Thus, the environment is a locale—a supply source and a waste dump—but processes are not connected to it. Accordingly, UM does not further the prospects of integrating ecology and economics to truly evaluate cities ecologically (Table 2).

SEEKING INTERDISCIPLINARITY

The crux of the issues underlying this critique is the inherent challenge of interdisciplinarity. The UM analogy is a prime example of how the confusion about or misuse of jargon and theory within multidisciplinary research prevents interdisciplinary problem-solving and knowledge-building. Quite simply, metabolism does not mean the same thing to the various participants. In the attempt to make connections across disciplines, the research community clings to misusing a comparison to the body when it should be grappling with the complexity of the ecosystem.

Looking Back: Borrowing Across Disciplines

Although an organism and an ecosystem are not synonymous, each can be conceptualized in context of the other. For example, the human body can be considered a system of functionally related physiological units. Conversely, organicism comprises the school of thought that society is analogous to a biological organism in its development or organization.

Social sciences and economics have a long history of seeking appropriate metaphors and analogies in the biophysical world. In the nineteenth century, the concept of organismal metabolism was developed in the biological sciences at the same time that the nascent field of social

theory applied the term to human social systems (Fischer-Kowalski 2003). Marx and other social theorists understood metabolism to mean exchange of matter between an organism and its environment, rather than the biochemical definitions used in biology; moreover, they used the term literally to mean utilizing nature, rather than metaphorically (Fischer-Kowalski 1998; Heynen et al. 2006).

At the same time, neoclassical economics relied on analogies from physics, including applying nineteenth century principles of classical mechanics and energy to economic functions (Ruth 1993). In the twentieth century, some sought to broaden the scope of economics to include the environment by drawing upon biological, occasionally referred to as ecological, analogies (Daly 1968). In so doing, the idea of metabolism was revitalized and adopted by those with particular interests in material flows analysis and industrial ecology, which then led to UM research (Fischer-Kowalski 1998).

Ecology itself has implemented a number of metaphors to aid conceptual and theoretical development. To be fair, some can be considered mixed or problematic, metabolism included. Those that remain in the lexicon have taken on specific ecological meaning, representing well-developed theory and data (Pickett et al. 2004). Odum, the “father of ecosystem ecology” was influenced by mentors and contemporaneous scientific views and borrowed terminology from other disciplines, including “metabolism”—often colloquially (Craigie 2001). Ecosystem metabolism, though, remains focused on the system’s energetics and materials flows without making an analogy to an I–O flow through an organismal body. This approach is truer to the essence of Odum’s work, who sought system perspectives and used terms metaphorically without intending to adopt organicism (Patten and Odum 1981; Craigie 2001).

The word metabolism becomes problematic through disciplinary space and time: various disciplines use it to denote different ideas, which may become more distinct as conceptual and theoretical developments (e.g., Chapin et al. 2006) do not cross disciplinary boundaries. The interdisciplinary use of a concept can become outmoded, frozen at its initial point of adoption. As a result, “metabolism” can divert, rather than serve, integration among disciplines when used as an attempted lynchpin between nature and economy. Gandy (2004) argues that UM is too simplistic for the complicated modern city, even if it helped to organize studies of the city in the nineteenth century:

With the fading of the bacteriological city and its characteristic modes of urban governance the biophysical conceptions of urban metabolism have become further problematized through an inability to explicate the changing nature of the contemporary city within an

increasingly globalized urban system. The use of biological analogies may serve some heuristic or imaginative value in the context of architectural design for individual buildings but when applied to an entire city or region these essentially arbitrary combinations of scientific metaphors quickly become untenable and lose any analytical utility.

In reality, everything changes: the world has been transformed, cities included. Moreover, scientific perspectives adjust with knowledge acquisition. The analytical tools, and language used to express them, must keep up.

Looking Forward: An Integrative Framework for the Sustainable City

Interdisciplinarity is only achieved when the epistemologies of one field are used within another. This requires appropriate appropriation, rather than, at best, superficially applying obsolete concepts or, at worst, misapplying them. As Pickett et al. (2004) note, “it is extremely important to recognize the difference between creative and provocative metaphors and the rigorous meanings or models that advance scientific understanding of ecological concepts.” The coordination among disciplines requires more purposeful integration.

As “common terms and language” are insufficient, Pickett et al. (2004) suggest that multidisciplinary teams need “[l]ong term dialog...to ensure that the understanding of the shared theoretical base is deep.” This has yet to occur for UM research:

Studies on UM 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... While insightful in terms of quantifying the urbanization of nature, it fails to theorize the process of urbanization as a social process of transforming and reconfiguring nature... it is surely strange to note that relatively little empirical or theoretical work has been undertaken that explicitly attempts to theorize environmental change and urban change as fundamentally interconnected processes (Swyngedouw 2006).

Actually, progress in urban ecological theory is developing a concept of the urban ecosystem that “goes well beyond the early- and mid-twentieth century view of cities as input–output devices driven only by human design and decisions” (Pickett et al. 2008).

Contemporaneous with UM endeavors, urban ecology has pursued empirical research and developed conceptual

frameworks to understand cities as socio-ecological systems, i.e., urban ecosystems (Pickett et al. 1997; Grimm et al. 2000, 2008; Pickett et al. 2001, 2008). With evidence (and, at times, surprising findings) from this work, emerging urban ecological theory is building on contemporary ecological theory to suggest “that urban ecosystems are complex, dynamic biological–physical–social entities, in which spatial heterogeneity and spatially localized feedbacks play a large role” (Pickett et al. 2008). Note that ecological theory is not sufficient for explicating the urban ecosystem, whose processes are influenced by human agents and socio-economic factors (Collins et al. 2000; Kaye et al. 2006); urban ecological theory requires interdisciplinary input and synthesis. Thus, continual dialog is crucial to keep up with disciplinary developments as well as to identify opportunities for epistemological coordination and/or creation.

By adjusting its perspective and focus UM—essentially material and energy flows analysis (MEFA) (Hendriks et al. 2000; Haberl et al. 2004)—may contribute to this socio-ecological integration. MEFA undertakes important accounting of resource flows (Krausmann et al. 2004). It can offer a helpful way to link ecological components and processes into socio-economic models insofar as it could follow the biogeochemical cycles of energy and material within the economy. The work can be made urbanely holistic, by de-emphasizing MFA’s macroscopic I–O framework and enmeshing it within the entire urban ecosystem—the soil, plants, animals, and biogeochemical cycles that exist among the built environment and human population. Indeed, detailed studies of material and energy flows have been made within cities from an urban ecology perspective (e.g., Baker et al. 2001; Pouyat et al. 2002; Groffman et al. 2004).

Thus, it is more appropriate to emphasize mass-balance studies on which UM was predicated in the first place than to seek parallels to an organism. The opportunity exists to create, or understand, a socio-ecological system perspective by studying the linkages of a city to surrounding environments as well as the dynamics among all components within the urban ecosystem. In so doing, more can be elucidated than just the magnitude of the heterotrophy of the city.

Conceptualization of the urban ecosystem offers the opportunity to integrate socio-economic and biophysical factors into urban studies. The ecosystem approach provides the opportunity to bridge disciplines insofar as the “core requirement that a specified physical environment and its associated organisms are functionally linked is central to using this method” (Boyle et al. 2003). Others, too, have assigned the potential to unravel the complexity of urban systems to the ecosystem model: “The conceptualisation of the city as an ecosystem itself and highly

integrated within a wider network of overlapping ecosystems provides a fresh perspective that can be used to identify synergies and interdependencies” (UNU-IAS Urban Ecosystems Management Group 2004). Odum and Barrett (2005) argue that ecology, as the integrative science, allows transdisciplinarity.

CONCLUSIONS

The UM analogy needs to be relinquished to make progress in urban sustainability research: the nineteenth century device should give way to twenty-first century science. Using the analogy limits the potential to link socio-economic and ecologic models and reinforces the linear input–output approach of resource flow through the city. It fails to capture the more complex and sophisticated understanding of the urban ecosystem emerging in urban ecological theory.

Does any of this matter? Is it all just a matter of semantics? Language influences thinking, and imagination is affected by stories and mental images (cf. Larson 2011). (Bad logic begets bad models.) In the case of UM, Newcombe et al. (1978) acquiesced that “Making such analogies is a logically hazardous process”. Clinging to the analogy has resulted in holding on to outdated ideas such as the superorganism and climax succession, which results in missing opportunities to explore the complexity of interconnection and thus manipulates the possibilities for transdisciplinary research.

As a result, it does matter whether “urban metabolism” is used—and abused—because researchers try to connect ecology and economics within this organismal framework rather than an ecosystem one. Ceasing to use the analogy would clarify research priorities, such as homeorhesis, resilience, and feedbacks (rather than homeostasis, stability, and input–output). Ecosystem ecology can thus be merged with established methodologies of material and energy flow analysis in order to transcend disciplines. Perhaps MEFA is actually the better terminology for multi-, inter-, and transdisciplinary work. The issue is not just a matter of semantics, but rather an important conceptual platform upon which to base interdisciplinary, ultimately transdisciplinary, urban research.

Acknowledgments Thanks to those who shared their thoughts on earlier versions of this work, including Joan Martinez Alier, John Ward, and Mitch Pavao-Zuckerman and others who attended conference presentations. I appreciate discussions on the ecological perspective with Nancy Grimm, Mary Cadenasso, and Peter Groffman. Bryan Walpert and others provided helpful comments on manuscript drafts. The thorough and insightful comments offered by several reviewers helped strengthen the argument.

REFERENCES

- Akiyama, T. 1994. Urban metabolism and sustainability. AUICK Newsletter 17. <http://www.auick.org/database/apc/apc017/apc01701.html>. Accessed 26 July 2005.
- Baccini, P. 1997. A city's metabolism: Towards the sustainable development of urban systems. *Journal of Urban Technology* 4: 27–39.
- Baker, L.A., D. Hope, Y. Xu, J. Edmonds, and L. Lauver. 2001. Nitrogen balance for the Central Arizona-Phoenix (CAP) ecosystem. *Ecosystems* 4: 582–602.
- Boyden, S., S. Millar, K. Newcombe, and B. O'Neill. 1981. *The ecology of a city and its people: The case of Hong Kong*, 437. Canberra: Australian University Press.
- Boyle, G., S. Ishii, S.K. Karn, P.J. Marcotullio, K. Suzuki, M. Abu Yusuf, and S. Zandaryaa. 2003. Defining an ecosystem approach to urban management and policy development, 22. United Nations University-Institute of Advanced Studies, Tokyo.
- Brown, J.H. 1991. New approaches and methods in ecology. In *Foundations of ecology*, ed. L.A. Real, and J.H. Brown, 445–455. Chicago: The University of Chicago.
- Burney, G.M. 2004. Summary of RCP(04)606: An Overview of the literature on urban environments. Royal Commission on Environmental Pollution, Urban Environments Well-Being and Health, RCP(04)612, Westminster, 9.
- Chapin, F.S., G.M. Woodwell, J.T. Randerson, E.B. Rastetter, G.M. Lovett, D.D. Baldocchi, D.A. Clark, M.E. Harmon, et al. 2006. Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems* 9: 1041–1050.
- Collins, J.P., A. Kinzig, N.B. Grimm, W.F. Fagan, D. Hope, J. Wu, and E.T. Borer. 2000. A new urban ecology. *American Scientist* 88: 416–425.
- Costa, A., N. Marchettini, and A. Facchini. 2004. Developing the urban metabolism approach into a new urban metabolic model. In *The sustainable city III: Urban regeneration and assessment*, ed. N. Marchettini, C.A. Brebbia, E. Tiezza, and L.C. Wadhwa, 31–40. Southampton: WIT Press.
- Craige, B.J. 2001. *Eugene Odum: Ecosystem ecologist and environmentalist*, 226. Athens: The University of Georgia Press.
- Daly, H.E. 1968. On economics as a life science. *Journal of Political Economy* 76: 392–406.
- DeAngelis, D.L., and J.C. Waterhouse. 1987. Equilibrium and nonequilibrium concepts in ecological models. *Ecological Monographs* 57: 1–21.
- 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.
- Ehrenfeld, J. 2003. Putting a spotlight on metaphors and analogies in industrial ecology. *Journal of Industrial Ecology* 7: 1–4.
- Fischer-Kowalski, M. 1998. Society's metabolism: The intellectual history of materials flow analysis, part I, 1860–1970. *Journal of Industrial Ecology* 2: 61–78.
- Fischer-Kowalski, M. 2003. On the history of industrial metabolism. In *Perspectives on industrial ecology*, ed. D. Bourg, and S. Erkman, 35–45. Vienna: Greenleaf Publishing.
- Gandy, M. 2004. Rethinking urban metabolism: Water, space and the modern city. *City* 8: 363–379.
- Glenn-Lewin, D.C., R.K. Peet, and T.T. Veblen. 1992. *Plant succession: Theory and prediction*, 368. London: Chapman & Hall.
- Golley, F.B. 2003. Urban ecosystems and the twenty-first century—a global imperative. In *Understanding urban ecosystems: A new frontier for science and education*, ed. A.R. Berkowitz, C.H. Nilon, and K.S. Hollweg, 401–416. New York: Springer.
- Gorman, M.E. 1998. *Transforming nature—ethics, invention, and discovery*, 408. Norwell, MA: Kluwer Academic Publishers.
- Graedel, T.E. 1999. Industrial ecology and the ecocity. *The Bridge* 29: 10–14.
- Grimm, N.B., J.M. Grove, S.T.A. Pickett, and C.L. Redman. 2000. Integrated approaches to long-term studies of urban ecological systems. *BioScience* 50: 571–584.
- Grimm, N.B., S.H. Faeth, N.E. Golubiewski, C.L. Redman, J.G. Wu, X.M. Bai, and J.M. Briggs. 2008. Global change and the ecology of cities. *Science* 319: 756–760.
- Groffman, P.M., N.L. Law, K.T. Belt, L.E. Band, and G.T. Fisher. 2004. Nitrogen fluxes and retention in urban watershed ecosystems. *Ecosystems* 7: 393–403.
- Haberl, H. 2005. From LTER to LTSE. The socio-economic dimension of long-term socio-ecological research. *IHDP Newsletter*: 14.
- Haberl, H., M. Fischer-Kowalski, F. Krausmann, H. Weisz, and V. Winiwarter. 2004. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. *Land Use Policy* 21: 199–213.
- Hendriks, C.H., R. Obernosterer, D. Muller, S. Kytizia, P. Baccini, and P.H. Brunner. 2000. Material flow analysis: a tool to support environmental policy decision making. Case studies on the city of Vienna and the Swiss lowlands. *Local Environment* 5: 311–328.
- Heynen, N., M. Kaika, and E. Swyngedouw. 2006. Urban political ecology: Politicizing the production of urban natures. In *In the nature of cities: Urban political ecology and the politics of urban metabolism*, ed. N. Heynen, M. Kaika, and E. Swyngedouw, 1–20. London: Routledge.
- Houghton, R.A. 1999. Ecosystem metabolism. In *Encyclopedia of environmental science*, ed. D.E. Alexander, and R.W. Fairbridge, 172–175. Dordrecht: Kluwer.
- Huang, S.-L., and W.-L. Hsu. 2003. Materials flow analysis and emergency evaluation of Taipei's urban construction. *Landscape and Urban Planning* 63: 61–74.
- Kaye, J.P., P.M. Groffman, N.B. Grimm, L.A. Baker, and R.V. Pouyat. 2006. A distinct urban biogeochemistry? *Trends in Ecology & Evolution* 21: 192–199.
- Kennedy, C.A., J. Cuddihy, and J. Engel-Yan. 2007. The changing metabolism of cities. *Journal of Industrial Ecology* 11: 43–59.
- Kingsland, S.E. 1991. Foundational papers: Defining ecology as a science. In *Foundations of ecology*, ed. L.A. Real, and J.H. Brown, 1–13. Chicago: The University of Chicago Press.
- Krausmann, F., H. Haberl, K.-H. Erb, and M. Wackernagel. 2004. Resource flows and land use in Austria 1950–2000: Using the MEFA framework to monitor society-nature interaction for sustainability. *Land Use Policy* 21: 215–230.
- Larson, B. 2011. *The metaphoric web: Environmental metaphors and sustainability*. New Haven: Yale University Press.
- Lifset, R. 2004. Probing metabolism. *Journal of Industrial Ecology* 8: 1–3.
- Likens, G.E. 1992. *The ecosystem approach: Its use and abuse*, 166. Ed. O. Kinne. Oldendorf: Ecology Institute.
- Marcogliese, D.J. 2005. Parasites of the superorganism: Are they indicators of ecosystem health? *International Journal for Parasitology* 35: 705–716.
- Newcombe, K., J.D. Kalma, and A.R. Aston. 1978. The metabolism of a city: The case of Hong Kong. *Ambio* 7: 3–15.
- Newman, P.W.G. 1999. Sustainability and cities: Extending the metabolism model. *Landscape and Urban Planning* 44: 219–226.
- Odum, E.P. 1969. The strategy of ecosystem development. *Science* 164: 262–270.
- Odum, E.P., and G.W. Barrett. 2005. *Fundamentals of ecology*, 598. Belmont, CA: Thomson Brooks/Cole.
- Patten, B.C., and E.P. Odum. 1981. The cybernetic nature of ecosystems. *The American Naturalist* 118: 886–895.

- Pickett, S.T.A., W.R.J. Burch, S.E. Dalton, T.W. Foresman, J.M. Grove, and R.A. Rowntree. 1997. A conceptual framework for the study of human ecosystems in urban areas. *Urban Ecosystems* 1: 185–199.
- Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, C.H. Nilon, R.V. Pouyat, W.C. Zipperer, and R. Costanza. 2001. Urban ecological systems: Linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas. *Annual Review of Ecology and Systematics* 32: 127–157.
- Pickett, S.T.A., M.L. Cadenasso, and J.M. Grove. 2004. Resilient cities: Meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. *Landscape and Urban Planning* 69: 369–384.
- Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, P.M. Groffman, L.E. Band, C.G. Boone, W.R. Burch, C.S.B. Grimmond, et al. 2008. Beyond urban legends: An emerging framework of urban ecology, as illustrated by the Baltimore Ecosystem Study. *BioScience* 58: 139–150.
- Pickett, S.T.A., J. Kolasa, and C.G. Jones. 1994. *Ecological understanding*, 206. New York: Academic Press.
- Pouyat, R.V., P.M. Groffman, I. Yesilonis, and L. Hernandez. 2002. Soil carbon pools and fluxes in urban ecosystems. *Environmental Pollution* 116: S107–S118.
- Redman, C.L. 1999. Human dimensions of ecosystem studies. *Ecosystems* 2: 296–298.
- Ruth, M. 1993. *Integrating economics, ecology and thermodynamics*, 251. Dordrecht: Kluwer Academic Publishers.
- Sahely, H.R., S. Dudding, and C.A. Kennedy. 2003. Estimating the urban metabolism of Canadian cities: Greater Toronto Area case study. *Canadian Journal of Civil Engineering* 30: 468–483.
- Swyngedouw, E. 2006. Metabolic urbanization: The making of cyborg cities. In *In the nature of cities: Urban political ecology and the politics of urban metabolism*, ed. N. Heynen, M. Kaika, and E. Swyngedouw, 21–40. London: Routledge.
- Tansley, A.G. 1935. The use and abuse of vegetational concepts and terms. *Ecology* 16: 284–307.
- UNU-IAS Urban Ecosystems Management Group. 2004. Cities as drivers of sustainable development. United Nations University-Institute of Advanced Studies, Barcelona, Spain, 7.
- Warren-Rhodes, K., and A. Koenig. 2001. Escalating trends in the urban metabolism of Hong Kong: 1971–1997. *Ambio* 30: 429–438.
- Wolman, A. 1965. The metabolism of cities. *Scientific American* 213: 179–190.

AUTHOR BIOGRAPHY

Nancy Golubiewski's (✉) research encompasses land-change science; urban ecology, landscape ecology, and terrestrial ecosystem ecology; carbon accounting; and ecosystem services. She holds a PhD from University of Colorado-Boulder in ecology, specializing in urban ecology and remote sensing. She serves on the Scientific Steering Committee of the Global Land Project, the New Zealand IGBP (Global Change) Expert Panel of the Royal Society of New Zealand, and the Editorial Advisory Board for the Encyclopedia of Earth.
Address: Ashhurst, New Zealand.
e-mail: GolubiewskiN@gmail.com