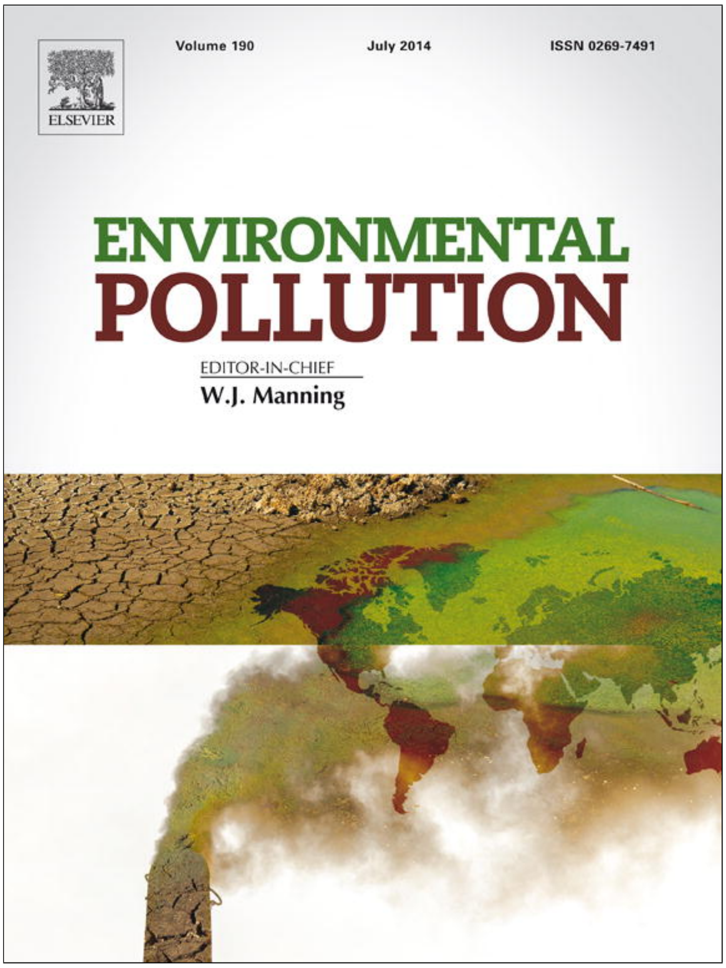
Volume 190
July 2014
ISSN 0269-7491
ELSEVIER
ENVIRONMENTAL
POLLUTION
EDITOR-IN-CHIEF
W.J. Manning

Environmental Pollution 190 (2014) 139–149

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Review

Urban ecosystem modeling and global change: Potential for rational urban management and emissions mitigation

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ARTICLE INFO

Article history:
Received 7 January 2014
Received in revised form
24 March 2014
Accepted 25 March 2014
Available online 18 April 2014

Keywords:
Urban ecosystem modeling
Urbanization
Global change
Emissions mitigation

ABSTRACT

Urbanization is a strong and extensive driver that causes environmental pollution and climate change from local to global scale. Modeling cities as ecosystems has been initiated by a wide range of scientists as a key to addressing challenging problems concomitant with urbanization. In this paper, 'urban ecosystem modeling (UEM)' is defined in an inter-disciplinary context to acquire a broad perception of urban ecological properties and their interactions with global change. Furthermore, state-of-the-art models of urban ecosystems are reviewed, categorized as top-down models (including materials/energy-oriented models and structure-oriented models), bottom-up models (including land use-oriented models and infrastructure-oriented models), or hybrid models thereof. Based on the review of UEM studies, a future framework for explicit UEM is proposed based the integration of UEM approaches of different scales, guiding more rational urban management and efficient emissions mitigation.

1. Introduction

Human activities, through extensive industrialization and land use change, play an increasingly salient part in global environment change (Shukla et al., 1990; Vitousek et al., 1986, 1997). A variety of process and distribution technologies were devised and applied to daily transportation and production, allowing the shipping of materials and the transmitting of energy to a far distance within an unimaginably short time (Fischer-Kowalski and Hüttler, 1998; Wright, 1990). This trend has accelerated in the 21st century, thanks to our endeavors of promoting information technology and lowering the cost for cross-region transportation. Saying out of reflection rather than out of arrogance, human activity drives planetary processes overriding the established balances and feedbacks within other species (Piao et al., 2009; Sushinsky et al., 2013).

Given that one half of the population now resides in urban areas, urban settlements contribute a greater anthropogenic environmental impact than rural colonies at both local and global scales (United Nations Population Division, 2007; Broto and Bulkeley, 2013). On one hand, the building of cities have made a lot people's lives greener, healthier and more convenient with the advanced facilitates and sophisticated servicers (Glaeser, 2011); on the other hand, the speed of urbanization has a direct influence on pollution within urban areas (e.g., eutrophication, solid wastes) and environmental change global level (e.g., global warming) (Guan et al., 2008; Güneralp and Seto, 2008; Wan et al., 2002). The influence of cities will be even more prominent in the future since the projected urban population and lands in Africa, South America, and part of Asia will experience another major boost in the following 30 years (Angel et al., 2011; Seto et al., 2011, 2012). In addition, the sizes of global cities have been growing unprecedentedly, producing over 20 colossal cities called 'megacities' (population>10 million, by convention) in the 2010s, which is prodigious given the fact that only two existed in 1950s (Taubenboeck et al., 2012; United Nations Population Division, 2006).

An ecosystem is generally defined as organism-complex and all the physical factors forming the environment of the biome, which have inherent structure, processes and ways of functioning (Tansley, 1935). The recognition of cities as ecosystems has approached a consensus after a wide and heated debate among ecologists and urban scientists over the last decades (Felson and Pickett, 2005; McPherson et al., 1997; Pickett and Grove, 2009). Urban ecosystems are characterized with dynamic boundaries and high dependence on their fringe environments. They are some of

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http://dx.doi.org/10.1016/j.envpol.2014.03.032
0269-7491/

the most profoundly-altered ecosystems on the planet that are organized by diverse human–environment processes and patterns (Collins et al., 2000). Analogous to other natural parallels, urban ecosystems have their own:

- Structures: distribution of organismal (including human) population, landscape patches and channels, soils and geologic materials transportation, and local atmospheric and hydrologic dispersal pattern (Anas et al., 1998; Hawley, 1950; Jenerette et al., 2006).
- Processes: communication among social institutions, political and cultural activities, organismal behavior, biogeochemical cycles, and the evolved ecological and economic processes in the built environment (Grimm et al., 2008; Groffman et al., 2002).
- Functions: primary production, ecosystem respiration, nutrient transformation, information transfer, resources consumption of different ecological components, and ecosystems services (Machlis et al., 1997; Pickett et al., 1997, 2009).

Herein, urban ecosystem modeling (UEM) is defined as the modeling of a city as a whole system using concepts and methodologies from ecology constituting the interactive socio-ecological components they encapsulate. Over the last five decades, much progress has been made in UEM by landscape ecologists, human ecologists and sociologists, who have a shared ambition of measuring anthropogenic impacts from a local to a global scale (Alberti, 1999; Neil and Wu, 2006; Pickett et al., 2004, 2011). Operational models in UEM have been designed to portray the dynamics of the diverse components forming urban ecosystems, including abiotic and biotic factors connected by energy, material, and information fluxes (Alberti et al., 2003; Pickett and Cadenasso 2006; Chen and Chen, 2011, 2012). There are two mutually related ways to look at UEM for its contribution to science and planning in a global change context. On one hand, the adoption of ecological and biological knowledge into UEM provides a solid theoretical basis for urban system planning and management. On this basis, urban scientists and managers are now able to address the tradeoffs between designing the environmental amenities of cities for people and reducing environmental impacts of urban regions (Deelstra, 1998; Moffatt and Kohler, 2008). On the other, the imperatives of urban ecosystems revealed by UEM have the potential to be generalized as common rules for broader ecological investigation, constituting an open frontier for ecological research (Pickett et al., 2005). Many geographic studies of cities offer valuable insights to ecologists for observing human–environment interactions, which is important since ecologists have come to realize that very few ecosystems are totally devoid of human influence (McDonnell and Pickett, 1993; Grimm et al., 2008).

The goal of this paper is to offer a critical review of the current state of practices in UEM and answer three questions. First, how can UEM address human–environment interactions under global change? For this, opinions and ideas proposed by scientists in different disciplines should be jointly discussed. Second, what approaches are the most commonly used to model urban ecosystems? Addressing this question requires a careful investigation of the current literature focused on system-oriented UEM. Finally, is it possible to address urban dynamics and its interactions with global change in an explicit and holistic way in the future? We argue that the integration of different types of models will be of great importance for future urban assessment and management framework.

The paper is presented as follows. We begin by presenting current perspectives of different disciplines on urban ecosystems and UEM under global change (Section 2). Further, we conduct a review of UEM approaches in Section 3, and highlight key features of top-down, bottom-up and hybrid models of urban ecosystems, such as model functions and applications, data requirements, model outputs and connections with global environmental change. Based on the review, we propose a future framework that integrated UEM studies can employ (Section 4).

2. UEM in an interdisciplinary context

An urban ecosystem is an energy-intensive ecosystem with the essence of extensive human activities (Odum and Odum, 1980; Pickett et al., 1997). The expansion of urban settlements causes a wide range of wicked problems that a single discipline cannot easily address, such as resources exploitation, nutrient cycle alteration, renewable energy resource depletion, habitat fragmentation, urban wildlife loss, wetlands degradation, surface run off generation, heat island creation, eutrophication, and global warming (Xiang, 2013). Fundamentally, this is mainly because a city is not as balanced as most ‘human-free’ ecosystems—there is a huge, linear flow of resource absorption from the environment to human society. Conversely, the feedback control of ecological consequences to social policy is relatively weak. Urban ecosystems are appropriate model systems for examining the coupled social–biophysical processes, which requires the power of interdisciplinary intellect (Collins et al., 2000). Given that, UEM can be very instructive when incorporating the interdisciplinary insight of human–environment interactions into sustainable urban management (Alberti et al., 2003; Pickett et al., 2011).

In fact, there is ongoing interdisciplinary discussion worldwide on the UEM and its connection to other urban issues. A number of international conferences and workshops held in the past few years were themed with UEM, some of which are listed in Table 1. While more global academic activities are bringing different ideas together, it is important to scrutinize different sets of opinions on the implementation of UEM of scientists from various disciplines.

2.1. Human ecology

Urban settlements are not distinct areas of specialization for human ecologists, but rather a close-up experimental field of applying a human ecological frame of knowledge. From a human ecology point of view, human communities can be explained via orthodox ecology imperatives and expanding the applicative boundary (Adams, 1935; Rebele, 1994). Urban ecosystems reflect

Table 1
Recent international conferences and workshops themed with UEM.

Time	Conference/Workshop	Theme
September, 2011	18th Biennial ISEM Conference	Ecological modeling for global change and coupled human and natural systems
October, 2012	International Workshop on Frontiers in Urban Ecology and Planning	Linking east and west scholars to advance ecological knowledge, planning and management of urban ecosystems
March, 2013	International Workshop on Ecological Modelling and ISEM-Pacific Annual Meeting	Low carbon cities and ecological modeling
May, 2013	International Workshop on Integrated Modelling of Urban Ecosystems	Ecological integration to meet the challenge of fast urbanization

some characteristic structure and processes of complex and self-organizing systems (Openshaw, 1998; Turner, 1989). The important attributes of urban ecosystems such as economic activities, societal division of labor, and resource use are parallel to the population distribution, community structure, and system of self-organization frequently analyzed in natural ecosystems. Urban communities and urban ecosystem modeling (UEM) have long been of interest to human ecologists in several aspects (Wilson, 1984; Pickett and Grove, 2009): (a) incorporation of the role of humans as part of the organismal complex for system-wide urban dynamics evaluation; (b) use of urban units (company, school, social organization) as interdependent organizational forms to analyze the producing and consuming activities of populations; (c) construction of theoretical foundations to account for human derived structures, actions, and interactions in urban areas comprising cities, suburbs, and exurbs; (d) identification of the internal and external driving forces that give rise to, sustain, and transform the urban phenomena over time. There is increasing evidence proving the validity of using UEM in examining urban phenomena (Bodini et al., 2012; Chen and Chen, 2012; Feng et al., 2013; Ngo and Pataki, 2008). What can ecologists and urban scholars learn from each other? An increasing number of studies suggest that a city can be better evaluated when it is treated as a whole ecosystem and when researchers adopt theories and methods from ecology; conversely, the study of human-dominated ecosystems has been integrated into ecology itself and enhances the development of the broader ecology study (Collins et al., 2000; Grimm et al., 2000, 2008; Pickett and Grove, 2009). For example, the concept of ecological footprint reveals the impact of cities based on natural capital—a concept that can also be applied to natural ecosystems to inspect their dominance of resources on other connected ecosystems.

2.2. Landscape ecology

Landscape-oriented ecology could be the first consistent endeavor to analyze the anthropogenic effects of urban spatial patterns (e.g., patch and channel composition) on ecological processes (e.g., biogeochemical fluxes) (Alberti and Waddell, 2000; Turner and Gardner, 1991). What concerns landscape ecologists most are coupled human–ecological processes and their connection with the changing spatial representation of the land. These processes include temperature fluctuation, ecological evolution, transport and residential development, invasive species diffusion, wildlife migration, and urban pollutant distribution–all of which are vital references for policy makers to interpret the relation of urban environmental change with human activities. How does landscape ecology work in UEM? First, the urban spatial structure can be described as a cumulative and aggregate order that involves a large number of intelligent and adaptive agents, which help illuminate the impact of local interactions within urban dynamics on the regional and global composition of the whole metropolitan area (Batty and Xie, 1994; Couclelis, 1985). Furthermore, it is useful for disentangling the complex socio-economic and biophysical driving forces that influence land use change patterns (Wu and Levin, 1997; Verburg et al., 2004). Finally, landscape ecology-based UEM has direct linkages to policy-making by combining simulations of landscape dynamics and optimization under a series of realistic scenarios of urban design (Li et al., 2009; Li, 2011). In contemporary landscape ecology, the coupling of landscape and economic analyses with ecological modeling has been given an increasingly high priority in UEM. For example, this coupling could happen in a mutual way—outputs of the economic analysis and land use change analysis (e.g., forest management, land use structure) are used as inputs in the ecological model; in turn, outputs of the ecological model (e.g., habitats condition) are used as inputs of economic cost-benefit calculations (McClean, 1995; Verburg et al., 2004).

2.3. Industrial ecology

Industrial ecologists focus their study on materials and energy flows in producing and consuming activities, the effects of these flows on the natural environment, and the influences of economic, political, and social factors on the transformation processes of resources (White, 1994; Wernick and Ausubel, 1995). As cities grow, the flow of energy and materials through them grows, which is attributed to the increasingly intensive socioeconomic activities of transforming and transferring food, goods, energy, and services (Ayres and Ayres, 2002; Decker et al., 2003; Graedel and Allenby, 1995). Most studies exhibit increasing per capita metabolism in cities with respect to water, energy, and materials, while others show increasing efficiency for energy and water use over time (Baccini and Brunner, 1991; Kennedy et al., 2007, 2011). Wolman's paper published in 1965 is generally considered as one of the pioneering articles on the metabolism of cities, in which he quantified the metabolism of a hypothetical U.S. city in response to deteriorating air and water quality in urban areas (Wolman, 1965). Many attempts have been made by industrial ecologists since then to track the impact of major cities worldwide emphasizing resource and waste flows (e.g., Barles, 2009; Haberl, 2001; Warren-Rhodes and Koenig, 2001). Urban metabolism generally accounts for all of the biophysical and socioeconomic processes that occur in cities that result in growth, production of energy, and elimination of wastes (Baccini and Brunner, 1991; Kennedy et al., 2007). Recently, systems ecology models (e.g., ecological network analysis) have been introduced to UEM to examine the structure and functioning of urban ecosystems underpinning their industrial and biophysical processes, and these models have attracted great attention by its track of environmental emission pathways and inter-sector relationships (Bodini et al., 2012; Chen and Chen, 2012; Zhang et al., 2009b; Zhang, 2013). Although there are critiques from rigorous ecology perspectives that the concept of the metabolism of a city is parallel to individual organisms rather than ecosystems (Golubiewski, 2012; Swyngedouw, 2006), urban metabolic studies have specific advantages in UEM by addressing the changing trends and sectorial interactions associated with resource consumption and waste generation of expanding urban areas (Chen and Chen, 2012; Wang et al., 2011; Warren-Rhodes and Koenig, 2001).

2.4. Social & political ecology

Social ecology and political ecology have been proposed since the 1970s to study the social and political drivers of environmental problems such as habitat degradation and biodiversity loss (Catton and Dunlap, 1980; Foster, 1999). They are hybrid fields at the interface of ecology, urban politics and geography, often conceptualizing the city as a result of diverse socio-natural interactions. Social ecologists give a process-oriented account of metabolism that emphasizes the interplay of local, regional, and global socio-natures in constituting any specific city or urban space (Keil, 2005; Heynen et al., 2006). One of the most contributive insights for UEM derived from social ecology and political ecology is the treatment of natural resources as a rare public capital and an essential component of urban ecosystems rather than as a fuel in urban society's engine. The key transition from urban political views to political ecology views dominates the UEM within both subdisciplines: the city is constitutively social and natural from the bottom to the top, and urban nature is just as political as urban society (Keil and Julie, 2006; Wachsmuth, 2012). There are a plenty

Table 2
Integration and overlap of different disciplines in UEM.

	Human ecology	Landscape ecology	Industrial ecology	Social & political ecology
Human ecology	Ecosystem phenomena and rules in cities; Urban rules for generic ecosystems[a]	Human residence and population migration; Landscape ecological network[b]	Energy and available energy comparison in urban and other ecosystems	Ecological principles of human life and decisions
Landscape ecology	/	Spatial urban structure and patterns; 3-D regulatory city; Land use management	Spatial material/energy diagraph; Impact of land use change on urban metabolism	Social force on landscape change; Balanced decision making on land use planning
Industrial ecology	/	/	Biophysical processes; Material/energy production and consumption	Social drivers of changing metabolism in cities
Social & Political ecology	/	/	/	Social and political drivers of urban phenomena; Social solutions to environmental problems
Consideration of Global change in UEM	Interaction between humans and other urban species; Response of anthroposphere to global change[c]	Identification of carbon source and carbon sink; Impact of land use change on global change	Effect of human activities on global nutrient cycling; Relation of industrial metabolism with global change	Interaction of economic/social organization and political decisions with problems of global change

[a] Goals for integration within the discipline.
[b] Goals for integration between the two disciplines.
[c] Consideration of global change in modeling.

of examples where natural scientists and sociologists can learn from each other, especially in the field of human-dominated systems like urban ecosystems. In fact, the term "urban ecology" was first coined by sociologists who sought to use ecological theory to describe diverse urban behaviors (Collins et al., 2000). But there are still some gaps between social/political ecology and other research realms concerning the natural aspects in expanding urban areas where additional communication is needed in future (Swyngedouw, 1996; Heynen et al., 2006). Urban ecosystems are very unlike other forms of ecosystems in the huge influence of culture, social constraints and opportunities on ecosystem succession. Urban ecologists should seek out a better way to interact with social scientists in order to model urban dynamics more explicitly, and therefore design sustainable cities based on a more comprehensive consideration.

2.5. Disciplines overlap

Though identified and discussed individually, all of these disciplines actually have overlapping parts with each other to different extents. Concrete common research subjects and overlap degree of different disciplines in UEM are illustrated in Table 2, as is the consideration of global change study within these disciplines. They all transformed and applied orthodox ecology theory to urban studies in a way that urban phenomena and dynamics can be described and explained. In the table, both the integration of knowledge within the discipline and the overlap between disciplines are described based on the above introduction of each discipline. For example, within human ecology, ecological explanations of phenomena in cities and urban rules for generic ecosystems are two directions to be integrated in the same discipline (Park, 1952; Descola and Pálsson, 2013); in terms of two different disciplines, human ecology and landscape ecology, the issues of human residence and population migration can be modeled using the same logic, and the human ecologist can also use the landscape ecological networks to simulate human behaviors and decisions (Turner, 1989; Opdam et al., 2006). Some are obviously more closely related with each other, such as human ecology and industrial ecology—scientists of both disciplines use energy/material flow intensity as a comparable measurement for human-dominated ecosystem and other ecosystems alike. In others like social & political ecology and industrial ecology, disparate approaches are employed and little interaction between the two disciplines has been made. In such cases, huge areas of cooperation and communication are left to be explored in future UEM studies. One more thing in common is that all these disciplines have specific concerns on global change issues, either from biophysical or from socioeconomic perspectives. For example, human ecology contributes to the modeling of interaction between humans and other urban species in a changing environment and the response of human activities to global change (Vitousek, 1994; Niemelä, 1999).

3. State-of-the-art models for UEM

Many urban ecosystem models are available today that address various issues in the process of sustainable development. A literature investigation of SCI-indexed journals was conducted to count the existing studies of ecological modeling of urban systems (Fig. 1). The results indicate that UEM in general has been a rapidly growing field at least over the last decades, as is the specific study of system-based modeling of urban ecosystems. Many scholars highlight UEM in their research in the last decade, a time when society is experiencing an expansion of urban areas and a boost in urban population globally. Moreover, there is a trend of using more modeling techniques in various urban studies since the percentage of UEM in urban ecosystem studies has increased since the 1990s. This may reflect that the great merit of using eco-models has been increasingly appreciated in solving urban ecosystem problems concomitant with urbanization. As suggested by the proportion of global change consideration in UEM literature, global environmental change has been increasingly highlighted by UEM studies. This is mainly due to the globalization of production chains as well as the resultant environmental problems over the last two decades.

The existing models used in UEM, though sharing the same assumption of treating cities as ecosystems, are highly diverse in terms of inherent rationale and model structure. It is difficult to simply classify those models according to their content or purpose since they address different aspects or components of the urban ecosystem. Alternatively, we divide our discussion of UEM into three different but related modeling perspectives—top-down models, bottom-up models, and hybrid types thereof are investigated in turn hereafter.

3.1. Top-down models

Most of the top-down models used in UEM have the same categories of raw data as national and regional studies, and share other characteristics of system-oriented models. They concern economic

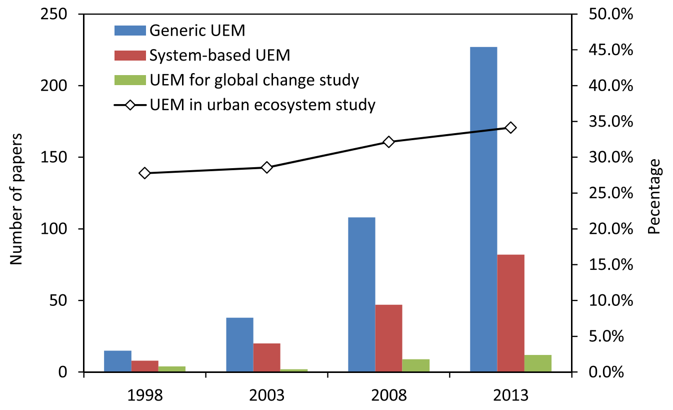

Fig. 1. The growth trend of UEM studies. Notes: Generic UEM: papers returned by searching "model" and "urban ecosystem" plus "ecosystem model" and "city". System-based UEM: papers returned by limiting the search result of generic UEM with the keyword "system". UEM for global change study: literature returned by limiting the search result of generic UEM with "global change" or "environmental change"; UEM in urban ecosystem study: articles' number of Generic UEM divided by papers taking "urban ecosystem" as keyword.

and biophysical processes such as industrial production, resource consumption, and carbon emissions, which are mostly decomposed into sector or industry level for quantitative comparisons. Basically, these top-down models focus on (a) materials/energy flow or (b) system structure.

Material flow analysis (MFA) is one of the earliest approaches to model the metabolism of cities that is capable of quantifying material exchange relation between man and nature (Ayres and Kneese, 1969). There have been a number of applications of MFA in global cities to model the metabolic intensity and its relation to urbanization (e.g., Hanya and Ambe, 1976; Nilsson, 1995; Douglas et al., 2002; Hendriks et al., 2000). Two types of substance flow are mainly focused in MFA-based UEM: flows of small volume but high environmental impact (heavy metal, pesticide, etc.), and flows of large volume but low environmental impact (carbon, water, sand, etc.). Some of the early ecosystem ecologists concerned with urban ecosystems categorized ecosystems based on their energy intensity. They suggested that energy use can be a common basis of measurement for comparing human-dominated ecosystems with those free from human disturbance (Odum and Odum, 1980; Odum, 1997). Over the last few decades a deluge of city-targeted energy models have been developed as key tools in assessing sustainable urban design and related policies and technologies (e.g., Akisawa and Kaya, 1998; Lozano et al., 2009; Mancarella and Chicco, 2009; Zhang and Huang, 2007). Other models use available energy (concerning both quality and quantity of energy) to indicate resource consumption and configuration. Embodied energy (emergy) analysis (Odum, 1983), has been applied to assess energy hierarchy, resource use efficiency and health status of urban ecosystems (Huang, 1998; Huang and Chen, 2005; Su et al., 2009). It received some criticism for its oversimplification of transforming processes and second-law inconsistency during the technical process (Månsson and McGlade, 1993; Sciubba, 2010). But from the ideological perspective, emergy still has its unique merit in comparing complex systems for the work hidden in the memory of biophysical processes (Chen et al., 2014; Geng et al., 2013; Jiang et al., 2009; Zhang et al., 2008, 2009a). Exergy and extended exergy accounting—products of the second law of thermodynamics—have also been employed in modeling large complex systems such as urban ecosystems to assess their environmental impact, welfare and potential to be sustainable (Jiang and Chen, 2011; Sciubba et al., 2008; Liu et al., 2011). Another innovative concept coined by Rees (1992)—ecological footprint (EF)—translates the impact of a city into the area (in hectares) of productive lands it relies upon. EF accounts for the resources and all of the energy and matter consumed by the city that eventually passes through to the environment. Recent progress in EF has enabled using carbon footprint (Jenerette and Larsen, 2006) and water footprint (Feng et al., 2011; Sovacool and Brown, 2010) to describe the environmental loads of cities. Ecosystem services valuation, an economically-mediated way of measuring human impact on nature capital, has been widely used for the evaluation of a wide range of ecosystems since the 1990s (Costanza et al., 1997). Ecosystem services of global cities are increasingly threatened due to a lack of proper valuation of natural resources in management decisions (Liu and Costanza, 2010; MEA, 2005). Therefore, multiple approaches to urban ecosystem services have been initiated recently (Hubacek and Kronenberg, 2013), which not only concern the services generated within the urban area (Bolund and Hunhammar, 1999), but also the benefits human populations derive from ecosystems (Manes et al., 2012).

Besides concerns over the magnitudes and intensities of resource and energy flows, an understanding of the interactive human–nature processes is critical for an explicit UEM. A number of system dynamics models have been developed to compute energy consumption and carbon emissions of the urban ecosystem as a whole as well as of its different sectors (Abou-Abdo et al., 2011; Chen et al., 2013; Feng et al., 2013; Hadley and Short, 2001; Kunsch and Springael, 2008; Li and Chen, 2013; Li et al., 2013, 2014; Yuan et al., 2008; Zhang et al., 2008). A system dynamics model is most appreciated for its ability to predict future performance of the system based on the causality of interactions among its social and natural components. Alternatively, ecological network models that track the direct/indirect ecological flows in ecosystems concern system structure and function based on a steady-state assumption. Systems ecologists argue that ecological network models can be useful to inspect coupled systems where anthropogenic disturbance has to be considered (Fath, 2004; Schramski et al., 2006). Recent progress of network models in UEM has addressed the mutual interactions and control relationships between urban sectors and system-wide properties of the city (such as eco-structure, metabolic density, and synergism) (Chen and Chen, 2012; Zhang et al., 2010). Hybrid models that integrate exergy, emergy and network analysis bridge the gap of material/energy-focused and structure-focused modeling techniques (Bristow and Kennedy, 2013; Dai et al., 2012; Liu et al., 2010; Giampietro et al., 2009; Zhang et al., 2009b).

3.2. Bottom-up models

Landscape changes are among the biggest anthropogenic drivers that impact the environment. A better understanding of urban dynamics entails linking micro-level land use simulation with macro-level biophysical processes evaluation. The bottom-up models reviewed in this study do not cover all the related models falling into this realm; instead, models focusing on (a) land use and (b) infrastructure in urban areas were selected due to their dominance in supporting contemporary urban design and planning.

Various spatially explicit simulation tools have been applied to model various landscapes and biophysical processes in urban areas (Turner, 1989; Alberti and Waddell, 2000). The various simulation tools are interrelated in intricate ways. Alberti (1999) classifies and compares these models according to the approach they use to predict spatial activities or their responses of model design questions. We highlight the major classes of operational models discussed in the literature that are relevant here: Gravity-based models, market-based models, agent-based models, and cellular automata. The gravity-based model (McFadden, 1973) is based on the hypothesis that residences gravitate toward employment locations and addresses scale and distance impacts of cities. In this manner, the interactions weaken in relation to the distance as with the gravitational force. Scholars developed gravity-based models to evaluate transportation planning, employment activities, inter-city telecommunication intensity, etc. (Krings et al., 2009), and recently radiation model has also been used to predict mobility patterns (Simini et al., 2012). Market-based models are designed to simulate the impact of the residential land market on urban location (Alberti, 1999). For example, the UrbanSim model is based on the interactions of individual choices and the actions taken by households, businesses, developers, and governments, in which the behavior of these decision-making units interface through the land market (Waddell, 2000).

The agent-based model (ABM) was applied to urban ecosystems by landscape ecologists in the early 1970s (which was originally developed in forest and fisheries models), and it has been used for urban modeling and planning only in the last decade (Portugali, 2000). The 'agents' for UEM represent humans, economic and ecological components, and the physical environment. Recent progress on modeling ecological patchiness, traffic flows, and economic structures integrates various sources of information, allowing description of space and spatial interactions in cities (Benenson, 2004). Cellular automata (CA) was proposed in the 1990s to model and visualize complex spatially distributed processes (Takeyama and Couclelis, 1997). CA consists of cells arranged in a regular grid that change state following specific transition rules (Batty and Xie, 1994). There have been studies integrating GIS and fuzzy set approach into CA-based UEM to predict regional patterns of urbanization (Batty et al., 1999; Liu and Phinn, 2003).

Different from land use models, infrastructure-oriented models do not directly address the interactions of human behaviors with local environmental change; instead, they usually start from artificial construction such as buildings, facilities, and products (Keirstead et al., 2012). Two key steps dominate the implementation of most infrastructure-oriented models: (a) identification of infrastructure attributes; (b) evaluation of infrastructure impacts on the economy and environment (Johansson, 2007). In infrastructure-oriented UEM, some scholars consider the direct effects of infrastructures on economy at macro region or country-wide scale (Bergman and Sun, 1996), while others evaluate the indirect environmental impact based on inventories of material, energy, and environmental flows and cycles (Chester et al., 2012; Davis et al., 2010; Rozos and Makropoulos, 2013). The infrastructure models have been interfaced with emerging theories and techniques such as new growth theory (Romer, 1990), economic geography (Krugman, 1991), agglomeration economics (Fujita and Thisse, 2002), GIS (Jensen and Cowen, 1999), and life cycle assessment (Chen and Chen, 2013a,b; Chester et al., 2012). A range of objects of infrastructure have been considered in UEM, including communication, transportation, drainage, energy and water supply network, Climate Change etc. (Davis et al., 2010; Hatt et al., 2004; Johansson, 2007; Lakshmanan and Anderson, 2007).

3.3. Hybrid models

It is interesting that most practices of urban planning are carried out from the top-down, while the overwhelming dynamics of the city arise from the bottom-up (Christian, 2012). Currently, there are various endeavors trying to combine top-down and bottom-up approaches in urban models. Often both spatially dynamic data and sectorial data are needed for such models.

Daniell et al. (2005) developed a multi-agent model termed 'Assessment of Urban Sustainability Through Integrated Modelling and Exploration (AUSTIME)', which consists of six modules: CO_2, Water, Ecosystem Health, Economic, Social, and Waste. The model carefully links sustainability indicators with landscape planning and policy priorities for adaptive urban development. de Almeida et al. (2009) presented an integrated approach called 'integrated transportation and energy activity-based model (iTEAM)', comprising interrelated approaches that are bottom-up (activity-based micro-simulation agent mode adapted from Waddell et al. (2003)) and top-down (material flow accounting that adapted from Niza et al. (2009)). iTEAM is a compacted tool focused on urban transportation and energy system with the goal of enhancing sustainability of urban ecosystems. The implementation of iTEAM requires a wide range of data such as household socioeconomic characteristics, residence attributes, household equipment, and mobility.

Besides the multi-agent based UEM, other hybrid modeling tools combine urban metabolic flows (e.g., total materials, energy, carbon, and emergy) with spatially explicit indicators or visualization techniques. Chrysoulakis et al. (2013) present the 'BRIDGE' project to link decisions to the nature of the urban landscape and outcomes (pollution, carbon fluxes, etc.). The hybrid model links measurements of physical flows with high spatial resolution numerical models to address sustainability indicators, and to provide visualization of the outcomes of future development alternatives in spatial maps. Huang et al. (2001, 2007) connect energetic principles with spatial hierarchical models of natural, agricultural and urban subsystems, and simulated the energy use and urban sprawl of Taipei's urban ecosystem. Churkina (2008) synthesizes a conceptual framework linking socioeconomic drivers with vertical and horizontal carbon fluxes based on his review of urban carbon cycle models. Mellino et al. (2013) developed a sustainability-oriented approach that integrates emergy and GIS allowing for the description of the spatial distribution of environmental value in support of urban planning policies.

3.4. Models comparison

In Table 3, we summarize the major models reviewed in this paper, including top-down models (materials/energy-oriented models and structure-oriented models), and bottom-up models (land use-oriented models and infrastructure-oriented models), and integrated models thereof. The main data requirements, model outputs and the connection with global change are given for each operational model on a comparative basis. Although these models have obvious differences in simulation and interpretation, they overlap with each other to some extent in the data collection and output generation process. Integrated models for UEM usually not only combine top-down and bottom-up approaches within the unified framework, but also bridge the gap of diverse input data and output indicators. In this case, more communication between models will save a lot of duplicative work before simulation and facilitate a more explicit understanding of the changing urban environment.

Cities are considered major contributors to global warming due to the GHG emissions produced in their "industrial breath" (or metabolism). Therefore, these modes are more or less connected to the assessment of global environmental change, though not all of them have been directly used for this purpose. The different ability (or potential) of addressing specific aspects of global change also implies the advantage of theoretical fusions and joint application of UEM techniques.

4. Explicit UEM under global change: future framework

Human beings are qualitatively unlike other organisms, and cities are the most energy/resource-intensive form of human

Table 3
Comparison of current models for UEM and their connections with global change.

Operational model	Data requirements	Model outputs	Connection with global change	References
Materials/energy-oriented models (Top down)				
MFA	Flows of goods Flows of wastes Flow of substances (C, N, etc.) Resource consumption	Resource use intensity Material balance Material/water ratio Metabolic intensity	Biogeochemical cycle of nutrients	Nilsson, 1995; Douglas et al., 2002; Hendriks et al., 2000
Energy	Direct energy flows (fossils fuel, solar power, wind power, biofuels, etc.) Indirect energy flows (Construction materials, equipment, facilities, products)	Energy intensity Input/output energy ratio Indirect/direct energy ratio System energy efficiency Energy hierarchy	Energy consumption and carbon emissions	Odum, 1997; Akisawa and Kaya, 1998; Lozano et al., 2009
Emergy	Renewable resources input Non-renewable resources input Economic input (goods, services, etc.)	System energy transformity Specific emergy Environmental load Sustainability	Resource renewability and environmental impact	Huang, 1998; Huang and Chen, 2005; Su et al., 2009
Exergy, Extended exergy	Local nonrenewable resources, resource consumption, waste, export of good and service Sectorial materials flow	Degree of exploitation and economic efficiency Environmental impacts and welfare	Resource efficiency and environmental impact	Jiang and Chen, 2011; Sciubba et al., 2008; Liu et al., 2011
Ecological footprint (EF)	Energy, food, or forest products production and consumption	Ecologically productive land Urban ecological deficit Productive area/carbon emissions/ water required	Human footprint and ecological capability	Rees, 1992; Jenerette and Larsen, 2006; Sovacool and Brown, 2010
Ecosystem services	Natural resource list; Environmental quality; Biomass and biodiversity; Average global value of ecosystem services	Economic value of specific services; Urban change and human welfare; Cost of losing natural capital	Ecosystem well-being; changing environmental balance	Costanza et al., 1997; Bolund and Hunhammar, 1999; Manes et al., 2012
Structure-oriented models (Top down)				
System dynamics	Population Resource consumption Inter-sector materials/energy flow Initial stock of resources, energy or substances	Sectorial relationships Energy consumption Carbon emissions Predictive system growth	Diverse dynamics and causality of local to global change	Feng et al., 2013; Hadley and Short, 2001; Kunsch and Springael, 2008
Ecological network analysis	Energy/materials input and output of urban compartments (sectors)	Total system throughput Cycling index Mutualism Ecological and industrial structure	Processes and functions of nutrient cycles	Chen and Chen, 2012; Zhang et al., 2010
Exergy-network	Data required for both exergy and network analysis	Resource efficiency System structure Environmental impact	Energy/materials storage in sectors	Bristow and Kennedy, 2013; Liu et al., 2010
Land use-oriented models (Bottom up)				
Gravity model	Population Employment activities Housing condition Land use scenarios	Communication intensity Transportation planning Landscape structure	Transportation and land use structure and simulation	Krings et al., 2009; McFadden, 1973
Market-based model	Household inventory Income, population State and local policy	Impact of the residential land market on urban location	Social drivers of urban environmental change	Alberti and Waddell, 2000; Waddell, 2000
Agent-based model	Flows of assets, including jobs, information, and population Social attitudes and relations	Urban segregation Personal choice to residential dynamics Residential reaction to the physical environment	Residential activities in the changing environment	Benenson, 2004; Portugali, 2000
Cellular Automata	Spatial distribution of population and species Land use scenarios	Patterns of land use and movement; urban expansion and sprawl process	Ecological and climatic impacts of urban development	Takeyama and Couclelis, 1997; Batty and Xie, 1994
Infrastructure-oriented models (Bottom up)				
in situ infrastructure model	Raw materials of infrastructures like communication, transportation, drainage, energy and water supply network, etc.	Economic cost-benefit of infrastructure planning; Transportation efficiency; Communication efficiency	Local impact of artificial infrastructures	Keirstead et al., 2012; Bergman and Sun, 1996
Life-cycle infrastructure model	Both raw materials and costs in construction process of infrastructures	Energy input–output Environmental impacts Net effect of infrastructures	Global chain effect of artificial infrastructures	Chester et al., 2012; Rozos and Makropoulos, 2013
Integrated models (Bottom up and Top down)				
AUSTIME	Natural capitals, financial statistics, human and infrastructure, flow of energy and resources	Effects of human behaviors on natural habitat and physical environment, spatial and temporal landscape dynamics	Change of human activities and natural habitat	Daniell et al., 2005
iTEAM	Land-use scenarios, transportation, social interactions, and inter-agent energy flows	Impact of human activities on urban transport, land-use structure, resource consumption	Effect of transportation Land-use scenarios	de Almeida et al., 2009

(*continued on next page*)

Table 3 (*continued*)

Operational model	Data requirements	Model outputs	Connection with global change	References
BRIDGE	EO GIS graphical data, surface characteristics, precipitation and PM10 concentration, housing and sectorial data	Heat fluxes, GHG emissions, socioeconomic status, air quality, sustainability	Spatial distribution of resources consumption and GHG emissions	Chrysoulakis et al., 2013
Spatial energy model	Direct energy storages and flows Indirect energy storages and flows Distributions among natural, agricultural and urban area	Spatial hierarchy, relationship between self-organization and energy hierarchy	Spatial distribution of energy consumption and intensity	Huang et al., 2001, 2007
Spatial carbon model	Driving forces of impact, Vertical fluxes of carbon, Horizontal fluxes of carbon	Urban metabolism and urbanization effect on carbon cycle	Spatial dynamics of carbon matter	Churkina, 2008
Emergy-GIS	Solar insolation, heat flow, wind–kinetic energy, precipitation, land use GIS data	Environmental value of lands (renewable empower density), spatial distribution of ecosystem services	Environmental impact and the changing sustainability	Mellino et al., 2013

settings on earth (Adams, 1935). Urban ecosystems face a lot of challenges accompanied with urbanization, owing to the dramatic environmental changes from local to global scale (Buhaug and Urdal, 2013; Pataki et al., 2006). The idea of expanding the application of orthodox ecological science to urban ecosystem modeling (comparing cities with other natural ecosystems on the same basis), and the other—developing an independent realm of modeling urban processes (strong linkage with social science and landscape planning, evading the contradiction of ecology with sociology) has its own major merits and enthusiasts. Varieties of modeling works were separated by these two fundamental ideas. What physicists believe is that one can never obtain an independent model of a system once he includes himself in that system (Hawking and Mlodinow, 2010). The interaction of observation can result in deviation from its original status. But can we obtain an explicit (not physically explicit but decision-making explicit) understanding of urban ecosystems with enough detail to guide sustainable development?

Review of the existing models used in UEM provides some insight to approach the answer to this. Scholars from different disciplines have distinct opinions as to how to model human and environmental properties in an urban ecosystem, especially when

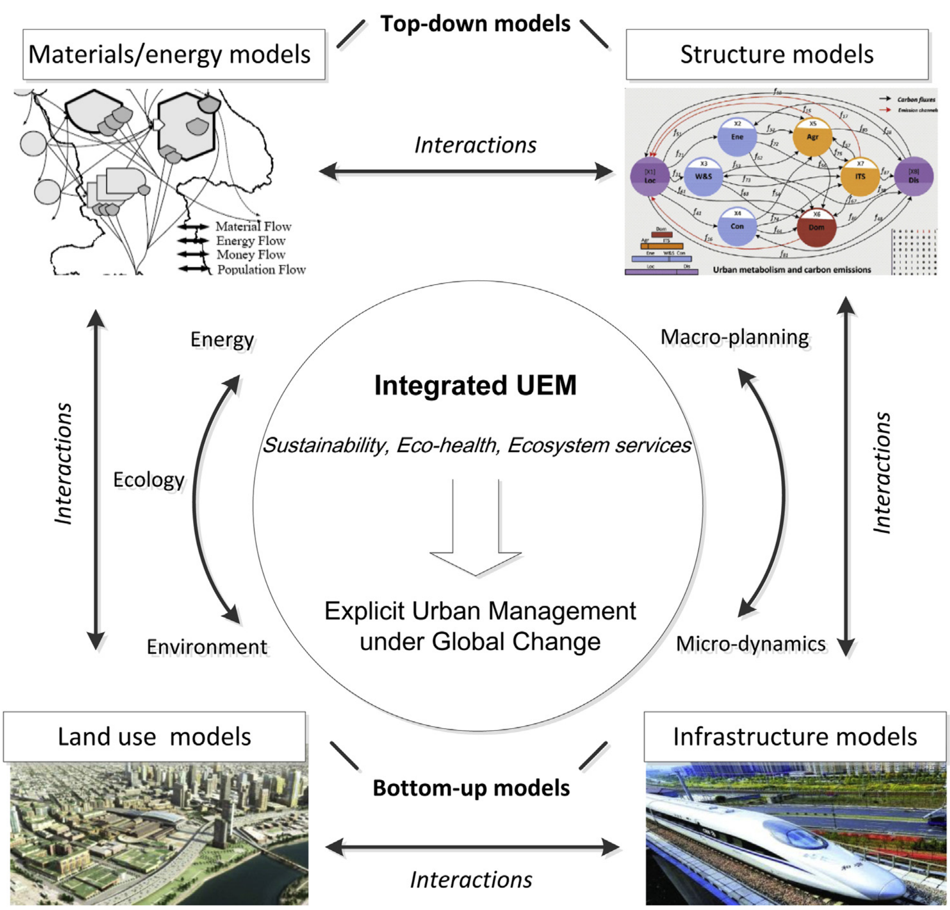

Fig. 2. Integrated framework for future UEM in a global change context.

the ecosystem is experiencing local and global change simultaneously (Sassen and Dotan, 2011). But what they have in common is the consistent focus on human–nature interaction processes, or more specifically, anthropogenic impact on natural environment and resources, and feedback of ecological consequence to human decisions. These factors are most important in developing operational models to address the socioeconomic behaviors and biophysical processes under global change. Therefore, the current models for UEM are not exclusive from each other; they are somewhat overlapped with considerable similarity of data collection and output description. Different types of models, stated or not stated, are explicitly formulated in their own ways. But due to the extremely high complexity of urban ecosystems, it is unrealistic to aim for a complete and high-resolution picture of system dynamics and mechanism by any individual model alone. Instead, it would be more prudent to emphasize that model results can be best used when they are integrated in system-based UEM.

Based on these insights, we propose a conceptual framework for future development and fusion of UEM studies (Fig. 2). It lays special consideration into holistic indicators such as sustainability, eco-health and ecosystem services based on the modeling of urban ecological properties, as has been proven very important in addressing global environmental change (Boyko et al., 2012; Sassen and Dotan, 2011). With these assessment and management goals, this framework highlights the integration of UEM at multiple levels, including:

- Integration of operational models. Two types of inter-model integration are required for an explicit UEM: integration within top-down models and within bottom-up models (horizontal integration), and integration of top-down models with bottom-up models (vertical integration). There are already practices of vertical integration of models, some of which have specific connections to global change evaluation. For example, combining exergy with network modeling can reveal urban resource consumption and eco-structure, in which the impact of global environmental change on resource use intensity and structure can be clearly illustrated. What is more challenging is the vertical integration of material/energy and structure models with landscape and infrastructure models. This requires intense interaction of simulation processes and data acquisition processes, which is still relatively weak in supporting the modeling of urban ecological properties and their response to global change.
- Integration of micro-dynamics and macro-planning. Decision support systems applied today do not capture micro-scale dynamics fully and make them fruitful for urban development practice. The communication between urban spatial-temporal dynamics and urban policy making should be enhanced by better understanding the feedback of ecological consequence to human health and welfare. In pursuit of a more rational urban management, interpretation of explicit UEM under global change can be achieved by multiple indicators, including sustainability, eco-health, and ecosystem services. Though the framework is focused on urban system and aims at city-based management, but it is able to address some of the global change challenges by bridging energy and emissions model in UEM with climate change.
- Integration of energy, ecology and environment. Growing interests have led us to integrate the main disciplines (i.e., energy, ecology and environmental issues) as our development strategy in order to adapt our future to the irreversible local and global changes inherent in human civilization. It has become evident that the complexity of urban development problems requires the integration of multi-disciplinary metaphysics and approaches to enhance and deepen the understanding of the role of urban ecosystems in global environmental change. A new and integrated perspective shared by professionals and policy-makers from different disciplines is necessary to be dedicated to managing urban ecosystems.

Acknowledgments

This work was supported by the Major Research plan of the National Natural Science Foundation of China (No. 91325302), Fund for Creative Research Groups of the National Natural Science Foundation of China (No. 51121003), National Natural Science Foundation of China (No. 41271543), and Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 20130003110027).

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