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Review

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

Shaoqing Chen [a], Bin Chen [a,*], Brian D. Fath [b,c]

[a] State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China
[b] Department of Biological Sciences, Towson University, Towson, MD 21252, USA
[c] Advanced Systems Analysis, International Institute for Applied Systems Analysis, Laxenburg, Austria

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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

* Corresponding author.
E-mail address: chenb@bnu.edu.cn (B. Chen).

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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