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A hierarchical patch mosaic ecosystem model for urban landscapes: Model development and evaluation

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ABSTRACT

Urbanization effects on ecosystem functions are both important and complex, characterized by scale multiplicity, spatial heterogeneity, and intensive human disturbances. Integrating the hierarchical structure of urban landscape pattern with ecosystem processes through simulation modeling can facilitate our understanding of human–environment interactions in urban environment. Current ecosystem models often focus on plant physiological and biogeochemical processes in homogeneous land covers, incapable of addressing the structural complexity in urban landscapes with multiple anthropogenic drivers across a range of spatial scales. Here we present the Hierarchical Patch Mosaic-Urban Ecosystem Model (HPM-UEM), a multi-scaled model that explicitly treats spatial pattern and hierarchical structure of urban landscape by incorporating both top-down controls and bottom-up mechanisms in urban environment. By addressing six hierarchical levels from individual plant to the urbanized region, HPM-UEM provides a "hierarchical ladder" to scale up local ecosystem functions across the nested urban land hierarchies (i.e., land cover, land use, landscape, and the urbanized region), and facilitate linking ecosystem processes and socioeconomic drivers. By organizing human influences in a spatially nested hierarchical patch mosaic structure, HPM-UEM models the complex spatiotemporal pattern of multiple environmental constraints on urban ecosystem functions. The model was evaluated based on extensive datasets developed by the Long-Term Ecological Research (LTER) network, especially the Central Arizona-Phoenix (CAP) LTER. Model testing results showed that HPM-UEM predicted both C fluxes and spatial pattern of C stocks with reasonable accuracy. HPM-UEM enabled us to assess spatial patterns and multiple-scaled dynamics of C cycle of the urban landscape, revealing the distinct productivities and C densities of different urban land types across different spatial scales. Sensitivity analyses indicated that future environmental changes and landscape modifications could have strong and complex effects on urban ecosystem functions. By matching ecological processes, anthropogenic environmental controls, and land and socioeconomic dynamics based on hierarchical levels, HPM-UEM could be coupled to multiple-scaled urban land-use models, climate models, and socioeconomic models to gain a comprehensive understanding of urban biogeochemical cycles.

1. Introduction

Humans have transformed about one-third to one-half of the earth's land surface, substantially altering the global biogeochemical cycle (Vitousek et al., 1997). Of different forms of land transformation, urbanization is arguably the most profound and complex, and has dominated land-use changes since the mid-20th century. In the United States, for example, urban and developed areas increased from 3.9% in 1982 to 5.2% in 1997 and were projected to reach 9.2% in 2025 (Alig et al., 2004). Globally, urbanized land is expected to increase by about one million km^2 over the next 25 years (McDonald, 2008). Numerous studies have indicated that urbanization has profound impacts on the productivity and C balance of terrestrial ecosystems from regional to continental scales (Imhoff et al., 2004; Pataki et al., 2006; Schaldach and Alcamo, 2007; Churkina, 2008; Svirejeva-Hopkins et al., 2004; Buyantuyev and Wu, 2009). Zhang et al. (2012) estimated that urban and developed land accounts for about 6.7–7.6% of total ecosystem C storage within the southern United States (US), larger than the pool size of shrubland.

Using urban vegetation to offset fossil C emissions has been proposed as a strategy to mitigate some of the negative impacts

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of urbanization (McPherson 1998; Nowak, 2006; Young, 2010; Zhao et al., 2010). Such projects require multi-disciplinary cooperation between ecologists, urban geologists, social scientists, and policy makers. However, urban ecologists frequently find communication between disciplines difficult due to the differences in terminologies. For example, when ecologists mention land types, they usually mean lands of homogeneous vegetation such as grassland or broadleaf forests. In contrast, when land-use modelers or economists mention land types, they often refer to the usage of the land in relation to certain socioeconomic functions (i.e., land-use), such as residential or commercial areas that consist of both impervious surfaces and green-space. For urban management, the C storage of an urban park is more meaningful to policy makers than the C density of a turfgrass ecosystem. The dilemma reflects the fact that ecologists work on a different research scale from the other groups. While ecologists focus on the ecophysiology of plants and ecological functions of local ecosystems (or land-covers) that are usually small pieces of urban land fragments with relatively homogeneous land surface, social scientists and policy makers are more interested in the socioeconomic functions of the land-uses and landscapes (e.g., towns or agricultural lands) that usually have a larger spatial extent and heterogeneous surface structure. It is, therefore, important to develop a scaling tool to extrapolate the ecosystem functions (e.g., the net primary productivity, or NPP) on the land-cover level to land-use or even landscape scales. Such scaling is possible because urban land use is composed of multiple land covers (e.g., a residential area consists of impervious surfaces, lawns, and yard trees), forming a nested structure.

It has been suggested that the urban land complexity takes the form of hierarchy, whereby a complex system consists of interrelated subsystems that are in turn composed of their own subsystems, and so on, until the level of elementary or "primitive" components is reached (descriptions of the Hierarchy Theory are found in O'Neill et al. (1986) and Wu (1999)). In this two-leveled hierarchy, land cover is the elementary level. According to Wu and David (2002), there are two other hierarchical levels above the land-use scale: the landscape level and region level. Landscape is composed of multiple land-use patches in which spatial patterns emerge, and characterized by the dominant land-use types (e.g., urban, rural, agricultural, and natural landscapes). Region is a mixture of landscapes, and characterized by its socioeconomic background (e.g., a North American metropolitan region vs. an East Asian metropolitan region), as well as its biogeophysical background, such as climate, geomorphology, hydrology, soils, and vegetation at the regional scale (e.g., a desert metropolitan region vs. an agricultural grassland region). The land use → landscape → region hierarchy (→ indicates the scaling up direction) of urban land structure reflects the hierarchical structure of human society (i.e., neighborhood/district → town/city → metropolitan region/economic zone), and has already been incorporated in hierarchical socioeconomic and land-use models (Veldkamp and Fresco, 1996; Moreira et al., 2009). Adding the land-cover/local ecosystem level to the urban land hierarchy could help us to link ecological processes to the complex urban land structure (including patterns of the environmental constraints) and the underlying socioeconomic dynamics (see the Appendix Fig. A1). By modeling the bottom-up mechanisms and top-down constraints in the urban hierarchy (O'Neill et al., 1986), ecosystem functions (e.g., NPP) can be scaled up from the land-cover level all the way to regional level along the "hierarchical scaling ladder" (Wu, 1999; Jenerette, 2004), assessing ecosystem services by various land types to support urban ecosystem management.

The hierarchical urban ecosystem model is also required for addressing the multiple anthropogenic and environmental drivers that work on different scales. Urban ecosystem functions have been dramatically affected from local to global scales by human management (Martin and Stabler, 2004) and anthropogenic environmental changes in climate (Arnfield, 2003) and atmosphere (Lohse et al., 2008). The impacts of global climate change (Chen et al., 2012), urban-induced environmental changes (Shen et al., 2008; Trusilova and Churkina, 2008), and urban land-use management (Milesi et al., 2005) have been individually investigated in separate modeling studies, however, no study has considered all of these three types of environmental controls that act on different scales. On the regional scale, climate and atmospheric changes caused by anthropogenic greenhouse gas emissions determine the background environmental conditions in urban ecosystems. On the landscape level, urban-induced environmental changes such as urban heat islands (UHI) and CO_2 dome effects (Idso, 2001; Arnfield, 2003) could modify the environmental variables. On the land-use scale, intensive management (e.g., irrigation and landscaping) and introduction of exotic species could further alter the microclimate, and directly modify the structure and biogeochemical cycles of local ecosystems (Pouyat and Carreiro, 2003; Jenerette et al., 2007). Correctly modeling the hierarchical structure of anthropogenic controls is not only important for revealing the complex spatial patterns of human disturbances and their effects on ecosystem functions (Grimm et al., 2008a), but also helpful for linking anthropogenic controls to socioeconomic processes on their corresponding scales (see the Appendix Fig. A1).

In addition to the urban land structure, the hierarchy of the ecological organization (i.e., individual plant → population → local ecosystem) was also inadequately addressed in current urban models (e.g., Nowak and Crane, 2000). The individual plant and population levels, together with the related ecological processes such as population dynamics, were generally overlooked. Without considering population dynamics, vegetation competition for energy and nutrients cannot be modeled. Former studies had to assume that a single vegetation type occupied each land cover. In contrast, George et al. (2009) and Ziska et al.'s (2004) studies in Baltimore, MD, indicated that long-term, urban-induced environmental changes could trigger community succession that altered ecosystem functions such as NPP, highlighting the importance of considering population dynamics in urban areas. Without information of plant structure, urban vegetation management, such as tree pruning, cannot be modeled, and important ecological services such as the effect of tree shade on home energy usage (Nowak and Crane, 2000) cannot be estimated. Furthermore, information about crown size and canopy coverage is important for modeling energy partition in ecosystem, especially for open canopies commonly found in urban forests. Without such information, most models used the two-stream energy partition scheme that assumes a homogeneous canopy with 100% land coverage (Sellers, 1985), which could result in up to 40% overestimation of the leaf-absorbed solar radiation when applied to open canopies (Yang et al., 2001). Therefore, the ecosystem hierarchical levels, such as the plant population and the individual plant levels should be explicitly addressed in urban ecosystem modeling.

In general, urbanization alters biotic and abiotic ecosystem properties from local to continental scales (Grimm et al., 2008a), and urban ecosystems are affected by various anthropogenic and environmental factors across multiple scales (Grimm et al., 2008b). A hierarchical ecosystem model can help deal with urban ecosystem complexities, and conduct cross-scaled studies to gain a complete picture of urban biogeochemical cycles (Grimm et al., 2008a). Based on the conceptual model of Hierarchical Patch Dynamics (Wu, 1999; Wu and David, 2002; Wu et al., 2003), this study developed a Hierarchical Patch Mosaic–Urban Ecosystem Model (HPM-UEM) that includes six nested hierarchical levels: individual plant → population → land-cover (or local ecosystem) → land-use → landscape → region. The biophysical and ecophysiological processes at and below the local ecosystem scale