Multi-factor controls on terrestrial carbon dynamics in urbanised areas

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Abstract

As urban land cover and populations continue rapidly increasing across the globe, much concern has been raised that urbanization may alter terrestrial carbon dynamics. Urbanization involves complex changes in land structure and multiple environmental factors. Relative contribution of these and their interactive effects need be quantified to better understand urbanization effects on regional carbon (C) dynamics as well as assess the effectiveness of C sequestration policies focusing on urban green space development. This study developed a comprehensive analysis framework for the factors (and their interactions) that control urbanization effect on ecosystem C dynamics, and proposed a factorial analysis scheme to analyze their relative contributions. In total fifteen factors belonging to five categories were identified. Some of them, like the interactive effects between global changes and urban land conversion, have not been studied before. Guided by the factorial analysis scheme, 24 number experiments were designed to systematically isolate and quantify the relative contribution of individual factors. A case study was conducted in the southern United States (SUS) to test this newly developed factorial analysis scheme. We found the impact of land conversion was far larger than the other factors. Urban managements and interactive effects among major environmental controls create important C sink to compensate the land conversion effect. The mechanisms underlying the complex interactive effects were analyzed. Our findings provide valuable information for regional C management in the urbanised areas of SUS: (1) it is important to preserve pre-urban C pools rather than to rely on the C sink in urban ecosystem to compensate for the lost C during land conversion. (2) In forested area, it is recommendable to improve landscape design (by arrange green spaces close to the city center) to maximize the urbanization-induced effect on C sequestration; while in the arid shrubland regions, urban managements will be a more effective way for C sequestration. (3) Lawn managements could create strong C sink even when the fossil fuel C cost are taken into account. (4) Protecting urban forests from disturbances such as logging and wildfire could be an effective way to enhance urban C sink. In general, the proposed factorial analysis scheme provides a useful tool for quantifying the complex mechanisms controlling C dynamics, and defining best development practices in urbanised areas.

Keywords: Urbanization, Urban ecosystems, Land use change, Carbon cycle, Global Change, Dynamic Land Ecosystem Model (DLEM)

1. Introduction

Urbanization, the aggregation of population in cities and transformation of rural areas into urban/developed land-use, became a dominant demographic trend and important land transformation process in recent decades (Seto *et al.*, 2010; Pickett *et al.*, 2011). At present about 3-5% of global land area has been converted to urban and developed land-use (hereafter refer to as urban) (Svirejeva-Hopkins & Schellnhuber, 2008; Seto *et al.*, 2010), 13-17% of which were intensively developed (Schneider *et al.*, 2010). Urban areas in the United States increased about 130% between 1960 and 2000 (www.census.gov, last accessed in Jul. 2012). Global urban areas could increase by about one million km^2 over the next 25 years (McDonald, 2008). The spatial prominence of urban areas and fast urban land conversion rate is reason enough to study its environmental impacts (Zipperer and Pickett 2012). A major finding of urban ecological research in the past decade is that urban ecosystems play an important role in both local and regional biogeochemical cycles (Imhoff *et al.*, 2000; Pataki *et al.*, 2003; Grimm *et al.*, 2008), esp. urban ecosystems account for a significant portion of terrestrial carbon (C) storage (Nowak & Crane, 2002; Pataki *et al.*, 2006; Pouyat *et al.*, 2006; Churkina *et al.*, 2010; Davies *et al.*, 2011; Hutyra *et al.*, 2011; Edmondson *et al.*, 2012). 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 (SUS), larger than the pool size of shrubland. The potential for C sequestration in urban vegetation (McPherson *et al.*, 1997) and soil (Pouyat *et al.*, 2008) has drawn attention from both ecologists and decision makers (Poudyal *et al.*, 2010). Municipal interest in climate change mitigation through C offset trading has increased as many cities have established substantial programs, such as tree planting, to increase ecological services of urban ecosystems (Nowak, 2006; Tratalos *et al.*, 2007; Young, 2010). A management strategy for urban and peri-urban land, as suggested by the Intergovernmental Panel on Climate Change (IPCC, 2001), including tree planting, improved waste management and wood production could lead to a C sink of 0.3 t C ha^{-1} a^{-1}. Escobedo et al. (2010) indicated that urban forest management can create moderate carbon sink in the southeastern US.

However, the ecological consequence of urbanization is highly complex (Pickett *et al.*, 2011), not only because of the strong spatial heterogeneity of urban ecosystems, which is composed by land cover types with distinct biogeochemical characteristics (Cannell *et al.*, 1999; Alberti, 2005; Buyantuyev *et al.*, 2010), but also because urbanization usually results in significant changes in many interacting environmental factors that affects ecosystem C processes, such as land conversion from rural to urban land-use (Schaldach & Alcamo, 2007), shifts in disturbance and management regimes (Kissling *et al.*, 2009; Fissore *et al.*, 2012), and urban-induced climate and atmospheric changes (Koerner & Klopatek, 2002; Fenn *et al.*, 2003; Kuttler, 2011). Furthermore, the legacy effect of pre-urban land-use changes (Ramalho & Hobbs, 2012) and influences from global climate changes (McCarthy *et al.*, 2010) could also modify ecosystem's responses to the urbanization-induced environmental changes. Analyzing the impacts of these changes and their interactive effects will help in our understanding of how regional C cycles are affected by urbanization, quantifying the impacts of various environmental stresses, and identifying the major factors that control C dynamics of developed areas. Such knowledge can be valuable for policy makers and managers to predict the long-term ecological consequences of urbanization, to elucidate where management efforts should focus, and to formulate meaningful guidelines and tailor strategies for urban C managements.

Despite its importance and complexity, urbanization is an often-missing component in global change studies (Kaye *et al.*, 2005; Pouyat *et al.*, 2006). There are several remote sensing analyses that addressed urbanization effect on net primary productivity (NPP) (Imhoff *et al.*, 2000; Milesi *et al.*, 2003; Lu *et al.*, 2010). With an empirical inventory approach, Cannell *et al.* (1999) roughly estimated the effects of urbanization on the C budget of the United Kingdom. Only a few modeling studies have analyzed the responses of regional C dynamics to the environmental changes induced by urbanization. Many studies suggested that urban land conversion could have strong negative impact on regional to global C storage (Schaldach & Alcamo, 2007; Svirejeva-Hopkins & Schellnhuber, 2008; Zhang *et al.*, 2008; Eigenbrod *et al.*, 2011). Trusilova and Churkina (2008) compared the impacts of different urban-induced environmental changes on the C cycle in Europe, and found strong C sequestration due to urbanization-induced atmospheric changes. Milesi *et al.* (2005) assessed effects of different management practices on the C storage of US urban lawn. Zhang *et al.* (2012) found that pre-urbanization vegetation type and time since land conversion were closely related to the extent of urbanization effects on C dynamics of

Southern US during the last six decades. Despite these efforts, a comprehensive study that investigates the dominant environmental changes and addresses their relative importance on regional C dynamics is still not available, although it has been repeatedly suggested that due to the complex interactions among multiple involving factors, the ecological consequences of urbanization could not be fully understood without a full set of controlling drivers and their interactions being addressed (Hutyra *et al.*, 2011; Pickett *et al.*, 2011; Ramalho & Hobbs, 2012).

In this study, we first comprehensively analyzed the factors that may control the urbanization effect on ecosystem C dynamic (Fig. 1), and proposed a numeric experimental scheme, i.e. scenarios design, to conduct factorial analysis on the effects of different factors in section 2. Then as a case study of the newly developed analysis scheme, the dynamic land ecosystem model (DLEM, Tian et al. 2011a) was applied to quantify the urbanization effect on the C dynamics of the SUS from 1945-2007, and to analyze the relative contributions from each environmental factors and their interactive effects (Zhang *et al.*, 2012). SUS was selected as the study area because it was identified as the region with the most rapid urbanization in the US, where about one-third of the developed area has been added in the last 15 years of the 20th century (Alig *et al.*, 2004). Our study only considered the C dynamics of ecosystem (i.e. vegetation and soil) in urban. Fossil fuel emissions unrelated to urban managements were out of the scope of this study (Townsend-Small & Czimczik, 2010; Bartlett & James, 2011).

2. Factors controlling urbanization effects

To study the effects of urbanization on regional C balance, Zhang et al. (2012) compared the model simulation results of the urbanization scenario (or the "business as usual scenario") against the results from a non-urbanization scenario, in which urbanization process was controlled and all lands remained in pre-urban land types. They found the urbanization from 1945-2007 resulted in a regional C loss of 0.21 Pg C in the SUS. The study, like others (McCarthy *et al.*, 2010), also indicated that urbanization is not a simple C release process, but involves complex changes in land structure and multiple environment factors, whose effects should not be treated independently. Whenever an ecosystem component is modified by one environmental stress, the ecosystem's responses to other factors could also be altered due to the non-linear interactions among the coupled ecosystem components and processes (Wu, 1999). For example, elevated CO_2 in urban areas could be particularly important in relieving water stress induced by urban heat island effect (Groffman *et al.*, 2006). Therefore, it is important to consider all the major environmental factors and their interactive effects on C processes when studying the urbanization effects on regional C balance.

In Fig. 1, we generalize the factors that may control the urbanization effects (UBNZ; descriptions for the abbreviations are found in Fig. 1): (1) Urban vegetation is intensively managed. Irrigation, fertilization, and weed/disease controls improve lawn productivity (Milesi *et al.*, 2005). Remnant ecosystems in urban areas are generally protected from intensive disturbances such as agricultural soil tillage, wild fire, and commercial logging (Raciti *et al.*, 2011). All these urban managements (UBMG) could result in high C density in urban ecosystems as observed in former studies (Nowak & Crane, 2002; Hutyra *et al.*, 2011; Edmondson *et al.*, 2012). (2) Urbanization-induced environmental changes (UIEC), such as urban heat island (UHI), elevated CO_2 (UCO2) and N deposition (UNDP), and reduced solar radiation due to aerosol pollutions (UDIM) could affect plant growth, succession and soil respiration in urban (Lovett et al. 2000, Awal et al. 2010, Zipperer 2011). According to Shen et al. (2008), the interactive effects among these UIEC factors (IT_UIEC) should not be ignored. (3) Urban land conversion (UBNC) alters the landscape structure, where pre-urban land-covers are replaced by impervious surfaces and artificial green spaces such as urban lawns. During the process, vegetation biomass is removed, soils are disturbed, and large amount of C are released from the ecosystem (Schaldach & Alcamo, 2007; Zhang *et al.*, 2008). (4) Global changes (GLBC) in climate (CLM), land use (LUC), and atmosphere (e.g., CO_2, N deposition (NDP), and O_3) have different effects on different vegetation/land-cover types. In this study, LUC only refers to pre-urban land-use change. Because UBNC alters the vegetation/land-cover type, it also indirectly affects ecosystem's responses to global changes. For example, the legacy effects of pre-urban land-use history could explain the spatial pattern and temporal dynamic of ecosystem C pools in urban and developed areas (Golubiewski, 2006; Jenerette *et al.*, 2006). Therefore, the interactive effects between GLBC and UBNZ (GLBC-UBNC) should not be ignored when investigating urbanization effects. Furthermore, the interactive effects among global changes

(IT_GLBC) could have important ecological impacts (McMurtrie *et al.*, 2008). (5) Finally, the interactive effects among the above four major type of urban controls (IT_OTHER in Fig. 1) should not be overlooked (Wu, 1999).

Numeric experiments and factorial analyses can be conducted to quantify the effects of each of the above factors on carbon balance. For this purpose, a model scenario scheme is presented in Table 1. Based on these scenario outputs, factorial analyses can be conducted to isolate the effect of individual factor and their interactive effects. According to Fig. 1, we have

$$\text{UBNZ} = \text{UBNC} + \text{UBMG} + \text{UIEC} + \text{GLB-UBNC} + \text{IT\_OTHER} = S_{\text{UBNZ}} - S_{\text{GLBC}}$$

$$\Rightarrow \text{IT\_OTHER} = (S_{\text{UBNZ}} - S_{\text{GLBC}}) - (\text{UBNC} + \text{UBMG} + \text{UIEC} + \text{GLB-UBNC}) \quad (1)$$

Where S_{UBNZ} is the urbanization scenario (or the “business as usual scenario”), and S_{GLBC} is the control scenario, in which no urbanization takes place (Table 1). The difference indicates the overall urbanization effect on C balance (Zhang et al., 2012). UBNC is estimated with the S_{UBNC} scenario, in which only urban land conversion occurs.

$$\left.\begin{aligned} \text{UBMG} &= \text{LWN} + \text{UFM} \\ \text{LWN} &= S_{\text{LWN\&UBNC}} - S_{\text{UBNC}} \\ \text{UFM} &= S_{\text{UFM\&UBNC}} - S_{\text{UBNC}} \end{aligned}\right\} \quad (2)$$

$S_{\text{LWN\&UBNC}}$ and $S_{\text{UFM\&UBNC}}$ simulate the C balance in managed grass (lawn) and urban forests in (converted) urban areas, respectively. It should be noted that it is impossible to simulate urban land management without also simulate the urban land conversion. Their results are compared against the UBNC to isolate the effects of lawn (LWN) and urban forest (UFM) management.

$$UIEC = UHI + UCO2 + UNDP + UDIM + IT\_UIEC = S_{UIEC\&UBNC} - S_{UBNC}$$

$$\Rightarrow \; IT\_UIEC = (S_{UIEC\&UBNC} - S_{UBNC}) - (UHI + UCO2 + UNDP + UDIM) \qquad (3)$$

$S_{UIEC\&UBNC}$ simulates the combination effects of multiple urban induced environmental changes and urban land conversion. We cannot simulate urban induced environmental changes without also simulating urban land conversion (land use change). Therefore, the effects of UHI, UCO2, UNDP, and UDIM are calculated similarly to the LWN and UFM:

$$\left.\begin{aligned} UHI &= S_{UHI\&UBNC} - S_{UBNC} \\ UCO2 &= S_{UCO2\&UBNC} - S_{UBNC} \\ UNDP &= S_{UNDP\&UBNC} - S_{UBNC} \\ UDIM &= S_{UDIM\&UBNC} - S_{UBNC} \end{aligned}\right\} \qquad (4)$$

Finally, the interactive effects between global changes and urban land conversion can be derived as:

$$GLB\text{-}UBNC = LUC\text{-}UBNC + NDP\text{-}UBNC + O3\text{-}UBNC + CO2\text{-}UBNC + CLM\text{-}UBNC + IT\_GLBC = S_{GLBC\&UBNC} - (S_{GLBC} + S_{UBNC})$$

⇨ $IT\_GLBC = S_{GLBC\&UBNC} - (S_{GLBC} + S_{UBNC}) - (LUC\text{-}UBNC + NDP\text{-}UBNC + O3\text{-}UBNC + CO2\text{-}UBNC + CLM\text{-}UBNC)$ (5)

Where S_{GLBC} simulates the global change effects; and $S_{GLBC\&UBNC}$ simulates the combined effects of global change and urban land conversion. The difference between the result from the combined scenario and the sum of the GLBC and UBNC scenarios, i.e. S_{GLBC} and S_{UBNC}, shows the interactive effects between the two factors. Similarly,

$$LUC\text{-}UBNC = S_{LUC\&UBNC} - (S_{LUC} + S_{UBNC}) \quad (6)$$

$$NDP\text{-}UBNC = S_{NDP\ \&UBNC} - (S_{NDP} + S_{UBNC}) \quad (7)$$

$$O3\text{-}UBNC = S_{O3\&UBNC} - (S_{O3} + S_{UBNC}) \quad (8)$$

$$CO2\text{-}UBNC = S_{CO2\&UBNC} - (S_{CO2} + S_{UBNC}) \quad (9)$$

$$CLM\text{-}UBNC = S_{CLM\ \&UBNC} - (S_{CLM} + S_{UBNC}) \quad (10)$$

Detailed information about scenario design can be found in Table 1. Based on the work reported by Zhang et al. (2012), we conducted two additional scenarios to simulate urban C storage under extreme conditions: S_{CMAX}, S_{CMIN}, to assess the uncertainties related to model parameters. For S_{CMAX}, parameters were selected to maximize C sequestration capacity of urban ecosystem, while for S_{CMIN}, parameters were selected to provide a conservative estimation.

3. Materials and methods in the case study

The DLEM is a process-based model that integrates the biophysical, biogeochemical, and hydrological processes to simulate impacts of environmental changes on water, C, and N cycles (see Fig. S1a in the supplementary material). The model has been parameterized and validated against intensively studied natural sites, and has been applied in multiple regional C dynamic studies (Tian *et al.*, 2011ab, 2012). Zhang et al. (2012) have developed an urbanization module for DLEM to assess the impacts of urbanization on long-term C dynamics in the SUS. Their study, however, only focused on the overall effects of urbanization without investigating the relative contribution from individual factor. In this current study, by conducting factorial analysis, we examined the relative contribution of different environmental controls and their interactive effects on regional C dynamics during urbanization. Here, we briefly introduce the study area, model structure, and the development of model inputs including the background global-change datasets (Supplementary Table S1) as well as the parameters for human-induced changes in urban. More detailed descriptions are found in Zhang *et al.* (2012).

3.1. Study area

Because an ecological understanding of urban effect must include the suburban areas and settled villages as well as city cores (Pickett *et al.*, 2011), the "urban" areas refer to all the urban and developed lands in the SUS in this study. This study focuses on the 1.2×10^5 km^2 urban lands in the SUS (red areas in Fig. S2 in the supplementary material). Following Zhang et al. (2012), this study focuses on the impacts of urbanization from 1945-2007 on regional net carbon exchange (NCE). NCE quantifies the C balance (with positive value indicating C sequestration) of the ecosystems in response to environmental change in a certain period (Tian et al., 2003, 2011).

3.2. Model description

Urban landscapes are composed by two major land functional types – urban impervious surface (UIS), and urban vegetation. Stearns (1971) identified three urban vegetation types - ruderal, residual, and managed. For simplification, ruderal and residual are merged into the dominant/potential local vegetation type in urban (UVG), and the managed vegetation is represented by urban lawn (ULW), an important characteristic of urban land-use conversion with respect to the C cycle (Kaye *et al.*, 2005; Golubiewski, 2006). Therefore, an urban landscape is treated as a mosaic of UIS, UVG, and ULW in DLEM. The development of UIS and ULW land typically includes the clearing of existing vegetation, massive movements of soil. DLEM not only models the disturbances on vegetation and soil during land clearing, but also tracks the fate of removed biomasses following the study of Houghton (1999) and Nowak and Crane (2002). Converting agricultural land to UVG will result in cropland abandonment and regeneration of potential vegetation (Dwyer et al. 2000). Otherwise, UVG conversion will not directly disturb pre-urban ecosystem. The disturbance regimes in UVG land, however, change after urbanization in DLEM. Urban forest and other residual ecosystems are protected from wildfire and commercial logging (Campbell *et al.*, 2007; Defosse *et al.*, 2011), disturbances that are responsible for the low biomass density in the SUS forest (Birdsey 1992). Taking the disturbances' effect into account, the overall turnover rate of rural forest (Tian et al., 2012) is about 10% higher than that of urban forest, whose annual mortality was set to 2.2% to 3.5% according to Nowak (1986, 1994).

3.3. Model inputs

In model simulation, the background climate, atmosphere, and land use drivers were modified by urbanization-induced environmental changes, the values of which were estimated based on literature reviews (Table 2). The background environmental drivers provide global change information because they are transient datasets that changed annually or daily from 1945 to 2007. To control a certain global change driver, we fixed its value to the year 1945. For example, in the climate only scenario (S_{CLM} in Table 1), only climate data changed from 1945-2007, the values of other drivers (CO2, N deposition, O_3, and land use) were fixed to the value of 1945. If a certain urbanization-induced environmental change factor is considered in the simulation, the corresponding background value will be modified by its parameter from the Table 2.

3.3.1. The background climate, atmosphere, and land use dataset

We reconstructed an 8 km resolution daily climate dataset of the entire SUS from 1895 to 2005 (Fig. 2a,b,c) by integrating the daily climate pattern of the North American Regional Reanalysis (NARR; 32 km resolution) dataset (Mesinger et al., 2006) into the monthly PRISM (Parameter-elevation Regressions on Independent Slopes Model; 4 km resolution; 1895-present) climate data (Daly et al., 2008;

prism.oregonstate.edu/). A detailed description of the method is found in Zhang (2008). PRISM is a knowledge-based system to interpolate climate elements under the assumption that for a localized region, elevation is the most important factor in the distribution of temperature and precipitation. To make predictions, PRISM dynamically calculates a linear climate–elevation relationship for each DEM grid cell using a moving-window, a procedure that smooth out signals of urbanization-induced climate changes (Daly et al., 2008). Like most reanalysis data, the surface temperatures of NARR were estimated from the atmospheric values by regional climate modeling, thus were not sensitive to changes in land surface (Kanamitsu et al., 2002). Therefore, the reanalysis datasets were used to provide information of background climate change in former UHI studies (Si *et al.*, 2012). The climate change data from 1895-2005 reconstructed based on the PRISM and NARR datasets were used to address the background global climate change (Fig. 1; GLBC-CLM) in this study.

Ozone AOT40 data (Fig. 2d) were retrieved from a global dataset developed by Felzer et al. (2005). EDGAR-HYDE 1.3 nitrogen emission data (Van Aardenne et al., 2001) were used to interpolate three maps from Dentener (2006) to generate a time-varying annual nitrogen deposition dataset (Fig. 2e). Both data sources had coarse spatial resolutions (0.5°-1°), and were downscaled to 8×8 km^2 using bilinear interpolation. Due to their coarse resolutions and because the atmospheric models that were used to generate these datasets did not consider the local urbanization effects (Felzer et al., 2005; Dentener, 2006), the AOT40 and nitrogen deposition datasets represented the background global atmospheric changes in this study. The background global annual CO_2 concentration was obtained from the National Oceanic and Atmospheric Administration (NOAA) (www.esrl.noaa.gov).

To simulate the land-use changes, DLEM requires annual urban and cropland maps (1 represents urban or croplands; 0 for natural vegetation). Distribution maps for cropland and urban/developed lands from 1895 to 2007 (Fig. 2f) were reconstructed by combining the contemporary land-use map that was derived from NLCD2001 (Homer et al., 2007) with historical census dataset for cropland, urban, and population (Waisanen and Bliss, 2002). A detailed description can be found in Zhang et al. (2012).

Sources of other inputs including the base maps (potential vegetation, soil properties, and topographic characteristics, etc.) and cropland management (irrigation and fertilization) datasets can be found in the Supplementary Table S1. Detailed description of the data development methodologies are found in Zhang (2008).

3.3.2. Urban-induced environmental changes

DLEM further models the effect of urban-induced environmental changes (i.e. UHI, aerosol pollutions, and increased CO_2 and N deposition) on urban ecosystem, which (except for the aerosol pollutions) generally enhance the growth and biomass accumulation rate of urban vegetation (Ziska *et al.*, 2004). Based on literature review, we estimated the parameters controlling urban-induced environmental changes (Table 2). To evaluate the effects of parameterization uncertainties on the model simulations, we designed two additional scenarios to simulate urban C storage under extreme conditions: UBNZ_Cmin and UBNZ_Cmax (Table 1). Parameters of UBNZ_Cmin were set so that carbon sequestration were minimized while carbon loss was maximized during urbanization; UBNZ_Cmax was the contrary (Table 2).

(1) The urban heat island effect

DLEM estimates the elevated temperature in urban (i.e. UHI, unit: °C) with the regression model developed by Karl et al. (1988):

$$\mathrm{UHI} = \alpha \times (p)^{0.45} \tag{11}$$

where α is a regression coefficient that varies with seasons and size of urban population (p). Based on the climate records from 1219 stations in the US, Karl et al. (1988) determined the values of α for the maximum, minimum, and average temperature for each season in three different urban sizes ($p < 10000$; $p \in [10000,100000]$; $p > 10000$). To develop 8-km resolution urban population dataset from 1945-2007, county-level urban population data developed by Goldewijk (2005) was divided by the area of urban/developed land to calculate the mean urban population density of each county. Then, the urban population map for each year was developed by multiplying the area of each urban region/patch in the NLCD 2001 land-use map with the urban population density of the local county.

(2) The elevated atmospheric CO2 concentration in urban/developed lands

Rural-urban CO_2 gradient is highly variable depending on time, location, wind direction, and distance from traffic, etc. (Idso et al., 1998, 2001, 2002; Vogt et al. 2006). The reported daily urban-rural CO_2 gradient ranged from 5 ppmv (Berry and Colls, 1990) to 66 ppmv (George et al., 2007). However, the daytime CO_2 gradient that determines the CO_2 fertilization effect on urban ecosystem is usually much smaller than the daily average due to solar-induced convective mixing (Idso et al., 2002) and the C uptake by plants (Kordowski & Kuttler, 2010). Day et al. (2002) reported that the daytime CO_2 concentration of the vegetated area in the center of Phoenix, AZ was only 8 ppmv higher than the background value. According to the measurements by Clark-Thorne and Yapp (2003), the daytime CO_2 concentration of urban interior was averagely 5-7 ppmv higher than the rural CO_2 in Dallas, TX. Angeles Garcia *et al.* (2012) found the daytime suburban CO_2 concentrations were 6-16 ppmv higher than rural levels in Northern Spain Based on these and other reports (Berry and Colls, 1990; (Li *et al.*, 2010; Rice & Bostrom, 2011), we assumed that the atmospheric CO_2 concentration of an urban vegetated area is 10 ppmv higher than the background value.

(3) Urbanization-induced air pollution

Urban atmospheres have higher concentrations of nitrogen and aerosols than the rural region (Lovett et al., 2000; Azimi et al., 2005). In general, urban boundary layer pollutants are believed to reduce solar irradiance by 0-10% in North American Cities

(Oke, 1979, 1982; Peterson and Stoffel, 1980; Estournel et al., 1983). DLEM assumed that aerosol pollutions reduce the urban solar radiation by 5%. Urban air pollution generates high concentrations of both ozone precursors and ozone scavengers. Gregg et al. (2003) found the detrimental effects of tropospheric ozone were lower in urban than in suburban. Due to the uncertainties in urban ozone (Trusilova and Churkina, 2008), we did not consider the urbanization-induced ozone change in this study. Like atmospheric CO_2, the temporal and spatial patterns of urban nitrogen deposition are highly variable. Previous studies indicate that the daytime atmospheric NO_2 concentration of urban and developed land usually ranges from 0.03 to 0.06 ppmv, an order higher than the value measured in rural ecosystem (Hanson et al. 1989). In this study, we used the mean value of 0.045 ppmv as the elevated urban NO_2 concentration.

It should be noted that these UIEC were not static but changed through time. In this study, we assumed that the rise of CO_2 and air pollutants in urban areas were positive correlated to the historical per capita fossil fuel emissions:

$$\mathrm{PL_i} = \mathrm{PL_{mean}} \times \mathrm{f\_EMS_i} \quad (12)$$

where PL_i is the urbanization-induced atmospheric change (i.e., elevated NO_2, CO_2, and aerosol) in year *i*; PL_{mean} refers to the mean urbanization-induced air pollution according to recent (since 1980) studies (parameters in Table 2); f_EMS_i is the normalized fossil fuel emission factor for year *i*:

$$\mathrm{f\_EMS_i} = \frac{\mathrm{EMS_i}}{\mathrm{EMS_{1980\_2000}}} \quad (13)$$

where EMS_i is the per capita annual fossil fuel emission of US in year *i*; EMS_{1980_2000} denotes the mean value between 1980 and 2000. To calculate the annual per capita fossil fuel emissions, we obtained the annual national fossil fuel emission data compiled by Marland et al. (2008) and the historical US population data from the US Census Bureau (http://www.census.gov/population/www/popclockus.html).

3.3.3. Urban managements

(1) Lawn managements

Urban lawns are irrigated, fertilized, and clipped. In DLEM, urban lawns are irrigated whenever the soil water content is lower than 50% of the field capacity. Since many of the US lawns are irrigated excessively (Milesi et al., 2005), we may underestimated the water use in irrigation. This uncertainty in irrigated water did not significantly affect the predicted C dynamics in urban lawn.

Based on the values provided by several reports in the literature, e.g., 8 - 9 g N m^{-2} yr^{-1} (Rockwell, 1929), 5 - 10 g N m^{-2} yr^{-1} (Thompson, 1961), 10 g N m^{-2} yr^{-1} (Qian et al., 2003), 2.4 - 15 g N m^{-2} yr^{-1} (Osmond and Hardy, 2004), 9 g N m^{-2} yr^{-1} (Law et al., 2004), and 9.7 g N m^{-2} yr^{-1} (Zhou et al., 2008), DLEM assumes that 10 g N m^{-2} yr^{-1} will be the N fertilization rate for the professionally managed lawns. This value is close to the 10.9 g N m^{-2} yr^{-1} fertilization rate for the managed lawns in US as estimated by Zirkle et al. (2011). In reality, however, the rates of N fertilization to lawns varied significantly from household to household in the US (Augustin, 2007). The professionally managed lawn only account for half of the US lawn area (Grounds

Maintenance, 1996). Only half of the home lawns are fertilized in a given year (Augustin, 2007). Only 25% of the fertilized home lawns are professionally managed. The remaining 75% are managed by the home owners with fertilization rates ranging from 4 - 9 g N m^{-2} yr^{-1}. Combining all these information, we deduced that the annual N fertilization rates to US lawns vary from 6.4 g N m^{-2} yr^{-1} (when 4 g N m^{-2} yr^{-1} is applied by home owners) to 7.3 g N m^{-2} yr^{-1} (when 9 g N m^{-2} yr^{-1} is applied by home owners). In the simulation, DLEM used the average value of 6.8 g N m^{-2} yr^{-1} for the urban lawn.

Urban lawns are usually clipped every 0.5 to 2 weeks in the US (Milesi et al., 2005; Kaye et al., 2005). In this study, we assumed an averaged mowing cycle of 10 days in SUS. This estimation agrees with a 900-person survey in Illinois, which reported an average mowing rate of 30 per year (Zirkle et al., 2011). Following Milesi et al. (2005), a lawn will only be mowed if its leaf area index exceeds the threshold value of 1.5. After mowing, 20% of the vegetation biomass will be removed. The belowground biomass will enter the soil litter pool, while the aboveground portion will enter the product pool and decay in one year. All clipped biomass will enter the product pool and decay in one year.

(2) Mortality and management of urban forest

We assumed that urban trees were protected from commercial logging, and thus could grow very old. Large uncertainties exist in the mortality rate of urban trees. Field measurements revealed that street trees could have various mortality rates depending on their size - 2.1% to 3.0% for trees whose DBH < 77 cm; and 5.4% for larger trees (Nowak, 1986). Nowak (1994) assumed an annual mortality rate of 2.6% in their urban forest modeling study. In DLEM, the annual background mortality rate of urban trees ranged from 2.2% to 3.5%, positively correlated with tree size (Nowak, 1986). Following Sitch et al. (2003), the background mortality is modified by light competition at the stand level. In DLEM, forest die back will take place to maintain the foliage-projected coverage under 95%. Urban forests have relatively open canopy compared to rural forests, providing it an advantage to suppress light competition and support bigger trees. DLEM calculates the foliage-projected coverage of urban forest based on the total land area of the urban to simulate the open canopy effect.

Like lawns, urban forests may be managed, such as pruning and litter raking. It was found that intensive pruning might reduce the biomass of urban trees by as much as 25% (Nowak, 1994; Nowak et al., 2002; Escobedo et al., 2010). Unlike lawn, however, intensively managed trees, such as street trees that account for about 62% of the managed urban forest in the US (Kielbaso, 2008), only contribute to a small fraction (e.g., 2-4% in Oakland, CA and Chicago) of urban forests (Dwyer et al., 2000). Furthermore, a national survey revealed that more than 60% of US cities do not have urban forest management programs (Kielbaso, 2008). Even if all cities in the SUS have forest management program, and 10% of urban forest is street tree that accounts for 50% of the managed forest, managed tree will only account for 20% of urban forest. Under this assumption, about 20% × 25% = 5% of the forest biomass was removed by pruning (Nowak, 1994; Nowak et al., 2002) (Table 2).

In some managed urban forests, a fraction of the litter (such as the litter from the pruned trees) will be removed and disposed of in a landfill. Nowak et al. (2002) assumed that only 3.7% of the removed carbon would be released during the first 5 years, and the remaining would be permanently locked up in a landfill. Accordingly, DLEM simulated the process of litter removal by allocating 1.85%, 1.85%, and 96.3% of the removed litter to 1-, 10-, 100-yr product pools that have turnover rates of 1 year, 10 years, and 100 years, respectively. No information about the patterns of litter management is currently available for the urban/developed land in the SUS. Since the fraction of intensively manage urban forest is quite low (Dwyer et al., 2000), we assumed that only 10% of litter will be removed and disposed in a landfill (Table 2).

4. Case study results

The temporal pattern of carbon dynamic during urbanization was controlled by the UBNC, which was estimated to result in about 0.37 Pg C loss from 1945-2007 (Fig. 3). In contrast, the urban managements (i.e. UBMG) and UIEC enhanced C storage by about 0.12 Pg and 0.03 Pg, respectively. Factorial analysis based on numeric experiments indicated the interactive effects between global changes and urban land conversion has negative effect on C storage, causing the study area to lose about 0.02 Pg C from 1945-2007. The complex interactive effects (i.e. IT_OTHER) among the four major types of environmental changes, urban land conversion, urban managements, UIEC, and GLBC-UBNC, resulted in C sequestration of 0.04 Pg, comparable to the effects of UIEC and GLBC-UBNC.

The effects of UEIC, urban managements, and GLBC-UBNC can be further broken down to reflect the effect of individual factors (Fig. 1). From 1945-2007, urban lawn management (i.e. LWN) enhanced C storage by 489.9 g m^{-2} (the SUS subgroup in Table 3) or 63.6 Tg in the SUS (Fig. 1), having the strongest C sequestration effect among all factors. Urban forest managements (i.e. UFM), including direct management (Table 2) and indirect effects from altered disturbance regimes (e.g., protection from commercial logging and wildfire), also resulted in large C sequestration of 396.3 g m^{-2} or 51.5 Tg. Other factors that have significant positive effects on C sequestration included the increased N deposition (248.9 g m^{-2} and 32.3 Tg in the SUS) and CO_2 (220.5 g m^{-2} and 28.6 Tg in the SUS) in urban. In comparison, UHI and interactive effects among UIEC factors caused 15.6 Tg (120.3 g m^{-2}) and 16.0 Tg (123.2 g m^{-2}) C loss from the SUS, respectively. The interactive effect between UBNC and global change factors were smaller than other controls. While its interactions with global O_3 and climate change may enhance C sequestration, interactions between UBNC and other global changes (pre-urban land-use change, atmospheric CO_2 and N deposition change, and the interactive effects among the global change factors) caused C loss (Fig. 1).

Because the juxtaposition of land use and ecotypes strongly influences regional patterns of urban ecosystem functions (Nowak et al., 1996), we further analyze the impacts of urbanization on ecosystem C density based on the dominant/potential local vegetation type (i.e. UVG; Table 3). The results indicated that urbanization had strong negative effect on C density (-2084 g m^{-2}) in forest area, only slight negative effect on

C density (-95 g m^{-2}) in grasslands, and positive effect on C density (390 g m^{-2}) in shrubland/desert (Table 3). The C sequestration effects of UIEC and forest managements were strongest in forest area, followed by grassland and shrubland/desert areas. The interactive effects between global change and urban land conversion had negative effect (-276 g m^{-2}) on C density in forest area and positive effect (168 g m^{-2}) on C density in grassland area. Because of the large forest area in the SUS and because of the relatively strong responses of forest C dynamics to land conversion and urban induced changes, forest area determined the pattern of regional C dynamics in response to urbanization from 1945-2007(Fig. 1; Table 3).

5. Discussion

5.1. Importance of the ability to quantify the relative contributions from multiple controls on urban C dynamics

Nowhere is ecological complexity more apparent than in urban areas (Kaye *et al.*, 2006). The aggregated effects of urbanization on land–atmosphere exchange processes remains highly uncertain despite decades of study on components of the problem (Pickett et al., 2011). Only considering certain aspects of urbanization, former studies drew contradictory conclusions about urbanization effect. Those focusing on urban land conversion concluded that urbanization have negative effects on ecosystem productivity and C storage (e.g., Imphoff et al., 2000; Schaldach and Alcamo, 2007; Zhang et al., 2008). Those focusing on urbanization-induced environmental changes found positive effects on carbon sequestration from the elevated CO_2, N deposition, and prolonged growth season in urban (e.g., Trusilova and Churkina, 2008). Other studies emphasized on the effects of urban managements on promoting C sequestration in urban ecosystem (e.g., Qian et al., 2010; Milesi et al., 2005). Still others suggested that the interactive effects among different factors should not be overlooked (e.g., Shen et al., 2008). So, which factor is more important?

To answer this question, we first identified 15 factors that may affect ecosystem carbon dynamics during urbanization and organized them into five major categories under an urban analysis framework that shows the relationship among the factors (section 2, Fig. 1). Although it may not include all factors, the framework provides the most comprehensive analysis on the dominant factors so far. Among the five major categories in the Fig. 1, GLBC-UBNC (i.e., the interactive effect between global changes and urban land conversion) and IT_OTHER (i.e., the overall interactive effects among urban land conversion, urban management, UIEC, and GLBC-UBNC) are newly identified controls that have never been addressed before. Our case study in the SUS showed the IT_OTHER even had a larger impact on C dynamics than the UIEC. Furthermore, we proposed that the high carbon density of urban forest could be explained by a new mechanism – the low turnover rate of trees due to the suppressed disturbances (flooding, wild fire, pest, commercial logging, etc.) in urban (see the following discussion in the section 5.3). Considering their potentially important effects, field observations and experiments should be setup to evaluate the importance of these newly identified factors. Other factors, such as the urban land conversion, urban managements, and urbanization-induced environmental changes have been individually analyzed in former studies (Milesi et al., 2005; Schaldach and Alcamo, 2007; Trusilova and Churkina, 2008), but their effects on urban ecosystem carbon dynamics have never been compared before this study.

Then, we designed 24 numeric experiments, based on the result of which a factorial analysis scheme was developed to systematically isolate and quantify the relative contribution of individual factors (section 2; Table 1). This is an important contribution to urban and global change researches. Global urban area is large and increasing rapidly. Urbanization effects on C cycle and climate have become the focus of global change research (Grimm et al., 2008). Reforestation projects have been initiated in many cities for C sequestration and climate regulation (Young, 2010). Of particular importance to climate-change policy and carbon management is the ability to quantify the relative contributions of multiple environmental factors to net carbon source and sink behavior (Heimann and Reichstein, 2008). Our study, for the first time, provides the ability to quantify the relative contribution of the dominant factors (Fig. 1) to C dynamics in urbanized areas. Guided by this factorial analysis scheme, our case study in the SUS found that the urban land conversion, urban managements, and overall interactive effects among major factors (IT_OTHER in Fig 1) were the first, second, and third most important controls on the ecosystem carbon dynamics from 1945-2007 (Fig 1). The impact of land conversion was far larger than the other factors. Our findings also show the big potential of carbon sequestration by improving urban managements as well as the large uncertainties related to the complex interactive effects among multiple environmental changes (see section 5.2 in the Discussion). Although the findings in our case study only reflect the urban carbon dynamics in the SUS from 1945-2007, our framework of urban environmental controls and the factorial analysis scheme can be applied in other regions.

5.2. Complex interactive effects among factors

One of the major uncertainties in urban C dynamic is from the interactive effects among environmental factors, which could have strong ecological impacts, sometimes even determined the direction of the overall ecosystem C balance (Shen et al., 2008; Tian et al., 2011b). However, many former urban studies overlooked the interactive effects and assumed the effects of multiple factors to be additive (e.g., Zirkle et al., 2011). Our case study found the overall interactive effects of the major control factors could increase C sequestration in the SUS by about 39.9 Tg, larger than the effect of urbanization-induced environmental changes (29 Tg) (Fig. 1). This C sink mainly located in the forested areas, which in average gained 411 gC m^{-2} due to the overall interactive effects of urbanization from 1945-2007 (Table 3). Compared to the pre-urban forests, urban trees in general had higher biomass and productivity, because they were protected (by human managements) from disturbances (such as commercial logging) that caused the high turnover rates and low biomass of the rural forest in SUS (Birdsey 1992). Our simulations shows that these larger trees are more responsive to urbanization-induced environmental changes and can fix more C, a phenomenon confirmed by recent observations from Escobedo et al. (2010) and Stephenson et al. (2014). The underlying mechanism is related to the relatively large total leaf area of big trees. According to the Pipe model (Shinozaki et al., 1964) that controls Photosynthate allocation in woody plant, total tree leaf mass increases as the square of trunk diameter. A typical tree that experiences a tenfold increase in diameter will therefore undergo a roughly 100-fold increase in total leaf mass. Larger leaf mass means the tree has higher growth potential if not limited by water and nutrient availability. Therefore, bigger trees are more sensitive to elevated CO_2 and N deposition in urban. In rural forest stand, the high C sequestration rate of large, old trees could be offset by intensified mortality related to light competition. The urban forest, however, has relatively open canopy, and are able to support large trees (see section 3.3.3). Therefore, when a rural forest became a remnant forest in urban, its trees could grow bigger, faster, and were more sensitive to the increased urban CO_2 and N deposition because of the urban management effect that suppressed disturbances (commercial logging) and light competition.

We also found strong interactive effect (-16 Tg) among the UIEC factors (UHI, CO_2 dome, and elevated N deposition), comparable to the negative effects of UHI (-15.6 Tg) (Fig. 1). Unlike Trusilova and Churkina (2008), who found the UIEC interactive effect increased C sequestration in Europe, we found it suppress the urban C sink in the SUS (Fig. 1). This is mainly because the two regions experienced different urbanization-induced climate changes. In our simulation, urbanization will increase local surface temperature in the SUS, but Trusilova and Churkina (2008)'s data indicated significant reduction of temperature by 0.73-1.26 °C followed the urbanization in Europe. We found the UHI effect increased potential evapotranspiration and exacerbated the water stress in the warm temperate ecosystems of the urban areas in the SUS. Like Shen et al. (2008), our simulation indicated that increase water stress suppressed elevated CO_2 and N deposition effects on ecosystem C sequestration. Trusilova and Churkina (2008)'s data, in contrast, indicated reduced temperature and increased precipitation in urbanised areas in Europe, both climate changes improved water availability and magnified elevated CO_2 and N deposition effects.

Shen *et al.* (2008) suggested that the effect of urbanization-induced changes are difficult to predict due to the influenced from other factors such as global climate change. Guided by the factorial analysis scheme developed in this study, for the first time, we found a way to separate the global change effects (i.e. GLBC) from the urban land conversion (i.e. UBNC) and quantify their interactions (i.e. GLBC-UBNC) (Fig. 1). We found GLBC-UBNC had negative effects on regional C storage (-24 Tg), almost offset the C sink induced by UEIC (29 Tg) (Fig. 1). Such an important mechanism, however, had been overlooked in former studies. The interaction between UBNC and different global change factors had different effects on C dynamics. In general, GLBC-UBNC would have negative impact on C storage if the global change factor enhances ecosystem C sequestration. This is because the lands converted to impervious surface are no more responsive to global change. For example, elevated CO_2 and N deposition in atmosphere stimulate C sequestration. After a pre-urban ecosystem is converted to impervious surface, the related C sinks (in response to CO_2 fertilization) disappear. Therefore, the interactive effects between urban land conversion and changes in global CO_2 and N deposition seem to have negative effect on C sequestration (Fig. 1).

5.3. Implications for urban management

Many cities and regional governments are taking significant steps to reduce and offset their carbon emission and increase ecological services of urban ecosystems (Nowak, 2006; Tratalos *et al.*, 2007; Young, 2010). Our findings provide valuable information for regional C management in the urbanised areas of SUS: First, we found the C loss caused by urban land conversion dominated the carbon sink induced by all other factors from 1945-2007 in the SUS (Fig. 1). This finding highlights the importance to preserve pre-urban C pools during land development, probably by reducing soil disturbances or reserving large areas of remnant green space, rather than relying on the carbon sink in urban ecosystems to compensate for the C loss during land conversion. Escobedo et al. (2010) suggested that preserving large trees had a larger C benefit than planting young trees in the urbanised areas of the SUS. This is especially important for the forested regions, which when converted to urban could release nine times more C than the shrubland (Table 3). Our analysis shows about 77% of urban and developed areas in the SUS were converted from forest, becoming a primary threat to the C sequestration in the forested area of the SUS (Wear, 2002).

Second, our study, as well as others (Ziska *et al.*, 2004; Trusilova & Churkina, 2008), indicated the urban-induced environmental changes possibly promote NPP and C sequestration in urban ecosystems. Because these UIEC factors generally have a “dome” pattern that peaks at the city center and gradually levels off along urban-rural gradient (Idso et al., 1998), it is advisable to arrange green spaces close to the city center to maximize their C sequestration capacity. The distinct responses from different vegetation types to urbanization should also be taken into consideration. Shen et al. (2008) suggested grass to be more sensitive to urban CO_2 dome effect than desert shrub. We found the carbon sink effect of UEIC decreased, while the carbon sink effect of lawn managements increased, in the sequence of forest, grass, and shrub areas (Table 3). Therefore, in the forested areas, it is recommendable to improve landscape design (such as arrange green spaces close to the city center) to maximize the UIEC effect; while in the arid shrubland areas, the focus should be put on improving urban managements to enhance C sequestration.

Third, our study indicates managements could create strong C sinks in urban vegetation (115.1 Tg C from 1945-2007 in SUS, about 55% of which was induced by lawn managements). Grasslands receiving fertilizer produced 7% to 298% more dry biomass than unfertilized grassland (Zirkle et al., 2011). Qian *et al.* (2010) observed that irrigation increased SOC of turfgrass, which could sequester 32-78 g C m^{-2} a^{-1}. Zirkle et al. (2011) estimated that N fertilization and irrigate together could increase the SOC of US home lawn (or the so-called "Do It Yourself lawn") by 78.5-79.5 gC m^{-2} a^{-1}. However, high CO_2 uptake in lawns is not without a "carbon cost" from fossil fuel CO_2 emitted during maintenance (Townsend-Small and Czimczik, 2010). In a literature review on US lawn managements, Zirkle et al. (2011) estimated the mean hidden carbon cost of N fertilizer, pesticide, and irrigation to be about 10.1-20.4 gC m^{-2} a^{-1}, 0.4-2.6 gC m^{-2} a^{-1}, and 0.1-0.3 gC m^{-2} a^{-1}, respectively for home lawn. In total, lawn maintenance could result in about 23.6-43.9 gC m^{-2} a^{-1} fossil fuel carbon emission, equaling to 30%-56% of the carbon sink (~79 gC m^{-2} a^{-1}) induced by N fertilization and irrigation (Zirkle et al., 2011). This translates to about 25.7-47.8 Tg hidden carbon cost in lawn maintenance in the SUS from 1945-2007. In another word, about 40%-75% of the 63.6 Tg C sink induced by lawn management was offsetting by the related hidden carbon cost. Previous also studies indicated that if carbon-based maintenance is performed, urban forest will eventually become a C source (Nowak et al., 2002), or weak sink (Escobedo et al., 2010). Unlike lawn, however, intensively managed trees only account for a small fraction of the urban forest in US. A national survey revealed that less than 40% of US cities have urban forest managements programs, and 62% of the managed urban forest is street tree (Kielbaso, 2008). Considering the fact that street tree usually contribute to a small very fraction (e.g., 2-4% in Oakland, CA and Chicago, IL) of urban forests (Dwyer et al., 2000), hidden carbon cost from urban tree maintenance should be relatively small at regional scale. Furthermore, there is substantial scope in reducing management-related CO_2 emission, because different equipment and maintenance techniques may have distinct carbon emission rate (Reid et al., 2010). For example, walk-behind lawnmower produces far less carbon emission than the riding mowers. It was estimated that half of the lawnmowers used by US homeowner belong to riding mower (Quigley, 2001), which has far larger C emission than walk-behind mower (Zirkle et al., 2011). By improving the efficiency of riding mowers or choosing to use the walk-behind mower, the maintenance carbon emission of urban vegetation could be significantly reduced.

Another possibility is to collect and utilize the 164 Tg dry biomass of lawn clippings and pruned tree twigs/limbs produced annually in the managed urban ecosystem in US for bioenergy production (Springer, 2012). Finally, well-managed urban vegetation can also indirectly reduce the C emission with its shading and cooling effects (Akbari et al., 1992; Taha et al., 1996). These factors and processes will be considered and integrated in the DLEM in our future urban studies.

Fourth, we found that altered disturbance regime might explain the observed C sink in urban forest. Urban forest was reported to have higher C density and growth rate than the average rural forest (Nowak and Crane, 2002; Golubiewski, 2006). This phenomenon was attributed to urbanization-induced environmental changes (Pouyat et al., 2007) and reduced light competition in urban forest due to its open canopy (Nowak, 1994). We propose another possible mechanism – the altered disturbance regime after urbanization may enhance C sink in urban forest. Most city trees are protected from frequent tillage, wildfire, and commercial logging, leading to suppressed soil disturbances and increased tree age (lower mortality and higher biomass) (Hutyra et al. 2011). In comparison, the influence of more intensive management of plantations and natural forests resulted in a mosaic of different age classes and an averaged low biomass density (Birdsey 1992). The risk of C emission through catastrophic wildfire burning is also considerably reduced by shifted fire regime (Guilden et al. 1990; Pickett et al. 2011) or fire control/management in urban areas (Campbell et al. 2007, Defosse et al. 2011). Based on a literature review (see section 3.2 and 3.3.3), we estimated that the overall turnover rate (considering both the mortality rate and the disturbance effect) of rural forest is about 10% higher than that of urban forest (assuming zero disturbance from fire or commercial logging in urban) in SUS. Our simulation showed the effect of management and altered disturbance regimes together resulted in a C sink of 51.5 Tg in the SUS urban forest. Because direct management such as pruning negatively affected C storage, the C sink can be attributed to the altered disturbance regime; a potentially important mechanism that should be further investigated in future study.

5.4. Uncertainties

Modeled C balance is essentially a result of the interactions among model assumptions, empirical and mechanistic relationships, and model parameterization. Urban ecosystem modelling is especially difficult and bound to large uncertainties (Churkina, 2008). Urbanization has complex effects on local climate, atmosphere, and disturbance regimes. Urban environment conditions and land management vary from place to place and from time to time (Alberti, 2005). Because the ecophysical and socioeconomic mechanisms underlying these urban-induced environmental changes are largely unclear (Pouyat et al., 2007; Pickett et al., 2011), we have to rely on an empirical parameterization approach to address the multiple controls on urban C dynamics in this study. As described in section 3.3, based on extensive literature review and academic reasoning, we derived the model parameters to approximate the average urban-induced environmental changes in the study region (Table 2). To evaluate the effects of parameterization uncertainties on the simulation results, we designed two additional scenarios to simulate urban C storage under extreme conditions: UBNZ_Cmin and UBNZ_Cmax (Table 1). The simulation results indicated that uncertainties related to parameterization of urban-induced environmental changes amounted to -2% to 3% of the urban-induced C dynamics (Fig. 3).

Previously, we validated the DLEM simulated C and water fluxes, nitrogen cycle, and soil processes and trace gas emission against intensively studied ecological research sites (Tian et al., 2011a,b). Because urbanization does not change genetic characteristics of plants or fundamental mechanisms of ecological processes (Niemela, 1999), former validation results indicated that DLEM can correctly simulate ecosystem's responses to multiple environmental stresses in urbanised areas. To evaluate DLEM performance for simulating C processes in urban ecosystems, we further compared model predictions with 16 field observations (including VEGC, SOC, and NPP) from 12 studies that were located in or close to the SUS (Table 4). For those studies with sample variance, all of our model predictions fall in the range of one standard error.

6. Conclusion

Urbanization involves complex changes in land structure and multiple environment factors, whose effects should not be treated independently. As urban land cover and human population continue to increase across the globe rapidly, it is important to investigate the individual effects of and complex interactions among multiple factors on the ecosystem structure and processes in urbanised lands. Our case study revealed how the C dynamics in the 1.2×10^5 km^2 urbanised areas of the SUS were influenced by multiple environmental factors from 1945-2007, but the numeric experimental design and the factorial analysis schemes proposed in this study could be applied in other regions. Such efforts as the one reported not only improves our understanding of the complex effects of urbanization on regional C dynamics, but also provides a quantitative approach for assessing the effectiveness of policies and defines best development practices.

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Table 1 Scenario design for numeric experiments and factorial analysis

Description	Scenarios	Factors											
		Urban land conversion	Global environmental changes					Urbanization induced environmental changes				Urban managements & disturbance regimes	
			Climate	CO_2	Nitrogen deposition	Ozone exposure	Pre-urban LUC	Urban heat island	Elevated urban CO_2	Elevated urban N deposition	Aerosol dimming effect	Urban lawn management	Urban forest management
All combined	S_{UBNZ}	√	√	√	√	√	√	√	√	√	√	√	√
	$S_{UBNZ\_Cmin}^{*}$	√	√	√	√	√	√	√	√	√	√	√	√
	$S_{UBNZ\_Cmax}^{*}$	√	√	√	√	√	√	√	√	√	√	√	√
Control (global changes only)	S_{GLBC}	-	√	√	√	√	√	-	-	-	-	-	-
	S_{CLM}	-	√	-	-	-	-	-	-	-	-	-	-
	S_{CO2}	-	-	√	-	-	-	-	-	-	-	-	-
	S_{NDP}	-	-	-	√	-	-	-	-	-	-	-	-
	S_{O3}	-	-	-	-	√	-	-	-	-	-	-	-
	S_{LUC}	-	-	-	-	-	√	-	-	-	-	-	-
Urban land conversion only	S_{UBNC}	√	-	-	-	-	-	-	-	-	-	-	-
Global changes with urban land conversion	$S_{GLBC\&UBNC}$	√	√	√	√	√	√	-	-	-	-	-	-
	$S_{CLM\&UBNC}$	√	√	-	-	-	-	-	-	-	-	-	-
	$S_{CO2\&UBNC}$	√	-	√	-	-	-	-	-	-	-	-	-
	$S_{NDP\&UBNC}$	√	-	-	√	-	-	-	-	-	-	-	-
	$S_{O3\&UBNC}$	√	-	-	-	√	-	-	-	-	-	-	-
	$S_{LUC\&UBNC}$	√	-	-	-	-	√	-	-	-	-	-	-
Urbanization induced environmental changes	$S_{UIEC\&UBNC}$	√	-	-	-	-	-	√	√	√	√	-	-
	$S_{UHI\&UBNC}$	√	-	-	-	-	-	√	-	-	-	-	-
	$S_{UCO2\&UBNC}$	√	-	-	-	-	-	-	√	-	-	-	-
	$S_{UNDP\&UBNC}$	√	-	-	-	-	-	-	-	√	-	-	-
	$S_{UDIM\&UBNC}$	√	-	-	-	-	-	-	-	-	√	-	-
Urban managements	$S_{UBMG\&UBNC}$	√	-	-	-	-	-	-	-	-	-	√	√
	$S_{LWN\&UBNC}$	√	-	-	-	-	-	-	-	-	-	√	-
	$S_{UFM\&UBNC}$	√	-	-	-	-	-	-	-	-	-	-	√

Note: “√” means changes in the environmental factor were considered, while “-” means the factor was unchanged in the simulation.

* Following Zhang et al. (2012), UBNZ_Cmin and UBNZ_Cmax were designed to examine the effect of uncertainties in model parameter on the estimated urbanization effects. Parameters of UBNZ_Cmin were set so that carbon sequestration were minimized while carbon loss was maximized during urbanization; UBNZ_Cmax was the contrary (Table 2).

Table 2 The parameters of urban managements and urban-induced environmental changes

Scenarios*	Lawn Managements				Urban Forest Managements		Urbanization Induced Environmental Changes		
	Irrigation (Y/N)	Litter remove (Y/N)	Clipping interval (days)	Nitrogen fertilization (gN $m^{-2}a^{-1}$)	% of biomass pruned	% of litter removed to land fill	Elevated CO_2 (ppmv)	Reduced solar radiation due to aerosol (%)	Elevated NO_2 (ppmv)
S_{UBNZ_Cmin}	Y	Y	5	6.4	10%	25%	5	-10%	0.03
S_{UBNZ}	Y	Y	10	6.8	5%	10%	10	-5%	0.045
S_{UBNZ_Cmax}	Y	N	15	7.3	0%	0%	20	0%	0.06

* S_{UBNZ} represented the normal condition (i.e. "business as usual" scenario). S_{UBNZ_Cmin} scenario provided a conservative estimation of the urban carbon storage, while the S_{UBNZ_Cmax} scenario simulated the maximum carbon storage of urban/developed area.

Table 3, Contributions of multiple environmental controls to urbanization effect (UBNZ) on carbon (C) dynamic of the Forest (including needleleaf, broadleaf, mixture, and wetland forests), Grass (including C3 and C4 grasslands, and grassy wetland), and arid shrubs (including shrubland and desert) ecosystems in the Southern United States (SUS) from 1945-2007. Unit: g C m^{-2}

			Forested area	Grassland area	Shrubland area	southern US
Urbanization effect (UBNZ)	Urban land conversion (UBNC)		-2655	-1078	-303	-2845
	Interactive effects between urban land conversion and global changes (GLBC-UBNC)	UBNC interact with climate change	43	33	21	39
		UBNC interact with global CO_2 change	-89	-25	-28	-73
		UBNC interact with N deposition change	-86	-19	-10	-69
		UBNC interact with global O3 change	70	28	27	58
		UBNC interact with pre-urban land-use change	-96	12	41	-68
		Interactive effects among the global change factors	-117	141	-68	-71
	Overall effect of GLBC-UBNC		-276	168	-18	-183
	Urbanization-induced environmental changes (UIEC)	Urban heat island effect	-136	-98	-33	-120
		Urban CO_2 dome effect	252	155	88	221
		Effect from elevated N deposition in urban	270	245	92	249
		Interactive effects among the UIEC	-130	-131	-64	-123
	Overall effect of UIEC		256	171	82	226
	Urban managements (UBMG)	Urban lawn management	455	639	694	490
		Urban forest management	525			396
	Overall effect of UBMG		980	639	694	886
	Overall interactive effects among UBNC, UIEC, UBMG, and GLBC-UBNC (IT_Other)		411	4	-6.7	307
	Overall effect of UBNZ		-2084	-95	390	-1609

Table 4 Comparison of model predictions against observed carbon pools and fluxes of urban ecosystems

City	Lon/Lat (dd)	PFT*	Age	NPP (g C/m^2/yr) + SE@		VEGC (kg C/m^2) + SE@		SOC1m (kg C/m^2) + SE@		Sources of Observations
				Observation	Prediction	Observation	Prediction	Observation	Prediction	
Atlanta, GA	-84.4/33.65	CF	NA			9.7± 0.7	9.3			Nowak & Crane, 2002
Baltimore, MD	-76.6/39.28	BF	NA			10.0±1.3	11.2	12.1±1.8	11.0	Nowak & Crane, 2002; Pouyat et al., 2008
Baltimore, MD	-76.6/39.28	Lawn	> 50					12.2±1.1	11.9	Pouyat et al., 2008
Baltimore, MD	-76.6/39.28	Lawn	30					10.7	9.6	Pouyat et al., 2008
Baltimore, MD	-76.6/39.28	Lawn	20					8.1	8.9	Pouyat et al., 2008
Boston, MA	-71.03/42.37	BF	NA			9.1±1.1	9.9			Nowak & Crane, 2002
Fort Collins, CO[&]	-105.1/40.6	Lawn	> 60					13.1	13.5	Kaye et al., 2005
Front Range,CO[#]	-105/40	Lawn	NA	762±92	731	1.55 ±0.16	1.59	11.6	12.0	Golubiewski, 2006
Miami-Dade, FL	-80.20/25.77	BF	NA			7.47	6.83			Escobedo et al., 2010
Philadelphia, PA[$]	-75.17/39.95	BF	NA			9.0±0.9	10.3			Nowak & Crane, 2002
Syracuse, NY[$]	-76.12/43.12	BF	NA			9.4±1.0	9.7			Nowak & Crane ,2002
Washington DC	-76.5/30.88	Lawn	NA	737	715	1.49	1.54			Falk, 1976

*Plant functional type (PFT): CF denotes Coniferous forest; BF denotes deciduous forests

@ NPP: net primary productivity; VEGC: vegetation carbon; SOC1m: soil organic carbon (0-1 m). Table 1 values (root NPP:NPP, root C:VEGC365, C:Biomass) were used to convert the above-ground NPP and biomass to total NPP and VEGC. By assuming that 53% of SOC of grassland in the upper 30 cm (Jobbagy and Jackson, 2000), we calculated the SOC of lawns to 1 m for those studies only measuring top 30 cm.

#Intensively managed sites. 23 samples. Two tailed Student's t-test indicated differences between model predictions and observations were not significant (90% level).

& Intensively managed lawn: annual N fertilization rate = 11 gN/m^2/yr; clipped litter left on site.

$ The species composition of the northern forest is not same to that of the southern forest. Before conducting simulations in NY and PA, we estimated/calibrated the physiological parameters of the BF functional type against the intensively studied Harvard Forest LTER site. For other cities and the regional simulations in the SUS, we used the parameters which were developed based on the studies in the Duke Forest.

Figure captions

Fig. 1, The urbanization effects (UBNZ) on regional carbon dynamics are controlled by four major types of environmental changes, including (1) urban land conversion (UBNC) during which rural land-use type is converted to urban and developed land-use composed by impervious surfaces, managed urban lawn, and other urban vegetation (e.g., urban forest); (2) urban management (UBMG) including lawn management (LWN) such as irrigation and fertilization, and urban forest management such as protection from logging and fire disturbances; (3) urbanization induced environmental changes (UIEC) including effects of urban heat island (UHI), elevated CO_2 (UCO_2) and N deposition (UNDP), reduced solar radiation due to air pollution (UDIM), and interactions among these UIEC factors (IT_UIEC), and (4) the interactive effects between UBNC and multiple global environmental changes (GLBC-UBNC) including changes in climate (CLM-UBNC), CO_2 (CO_2-UBNC), N deposition (NDP-UBNC), ozone exposure (O_3-UBNC), pre-urban land-use change history (LUC-UBNC) such as cropland conversion and abandonment, and the interactions among all GLBC-UBNC factors. IT_OTHER represents the overall interactive effects among the four major controls (i.e. UBNC, UBMG, UIEC, and GLBC-UBNC). The numbers in the figure show the carbon flux in response to each factor from 1945-2007 in the southern United States. Unit: TgC.

Fig. 2. Temporal patterns of major global change factors in the study region from 1945-2007. (a) annual precipitation; (b) temperature; (c) relative humidity; (d) ambient ozone exposure; AOT40 is the accumulated dose over a threshold of 40 ppb during daylight hours in a month (Felzer et al., 2004); (e) annual nitrogen deposition rate; (f) Landuse changes. The dynamic of Pre-urban cropland showed the net balance between cropland conversion and cropland abandonment in the control scenario (i.e., S_{GLBC}, assuming no urbanization has taken place since 1945). In reality (i.e. in the S_{UBNZ}) all lands have been converted into urban.

Fig. 3, Cumulative effects of urbanization (UBNZ) to the carbon dynamic of the Southern United States from 1945-2007 and the contributions of multiple environmental drivers. UBNC is the effect of urban land conversion; GLBC-UBNC is the interactive effect between global environmental changes (GLBC, including changes in climate, CO_2, N deposition, ozone, and landuse) and UBNC; UBMG is the management effect on the carbon dynamic of urban vegetation (such as lawn and urban forest); UIEC is the effects due to urbanization induced environmental changes (such as urban heat island, CO2 dome effect, and elevated N deposition in urban); the overall interactive effects among UBNC, GLBC-UBNC, UBMG, and UIEC is represented by IT_OTHER. Following, Zhang et al. (2012), $UBNZ_{Cmin}$ and $UBNZ_{Cmax}$ represent the minimum and maximum urbanization effects, respectively, as influenced by uncertainties in model parameterization (Table 2).