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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 significantly alter terrestrial carbon dynamics that affects atmospheric CO_2 concentration and climate. 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 C dynamics as well as assess the effectiveness of C sequestration policies focusing on urban green space development. In this study, we analyzed the factors that may control the urbanization effect on ecosystem C dynamics, and proposed a numeric experimental scheme, i.e. scenarios design, to conduct factorial analysis on the effects of different factors. Then as a case study, a dynamic land ecosystem model (DLEM) was applied to quantify the urbanization effect on the C dynamics of the Southern US (SUS) from 1945–2007, and to analyze the relative contributions from each environmental factor and their interactive effects. We found the effect of urban land conversion dominated the C dynamics in the SUS, resulting in about 0.37 Pg C lost from 1945–2007. However, urban ecosystem management and urban-induced environmental changes enhanced C sequestration by 0.12 Pg and 0.03 Pg, respectively. Their C sequestration effects, which amounted to 40 % of the magnitude of land conversion effect, partially compensated for the C loss during urbanization. Numeric experiments and factorial analyses indicated complex interactive effects among different factors and between various land covers and environmental controls, findings need to be further confirmed by field studies. The proposed numeric experimental scheme provides a quantitative approach for understanding the complex mechanisms controlling C dynamics, and defining best development practices in urbanised areas.

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). The proportion of urban population exceeds 50 % currently and is projected to exceed 60 % in the next two decades (United Nations Population Fund, 2007). 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 and Schellnhuber, 2008; Seto et al., 2010), 13–17 % of which were intensively developed (Schneider et al., 2010). Urban areas in the US increased about 130 % between 1960 and 2000 (www.census.gov, last accessed in July 2012). Global urban areas could increase by about one million km^2 over the next 25 yr (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 and 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 US (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 $\mathrm{t\,C\,ha^{-1}\,a^{-1}}$. Escobedo et al. (2010) indicated that urban forest management was moderately effective at offsetting annual CO_2 emissions relative to other reduction strategies 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 and Alcamo, 2007), shifts in disturbance and management regimes (Kissling et al., 2009; Fissore et al., 2012), and urban-induced climate and atmospheric changes (Koerner and Klopatek, 2002; Fenn et al., 2003; Kuttler, 2011). Furthermore, the legacy effect of pre-urban land-use changes (Ramalho and 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 effects (UBNZ) 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 UK. 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 and Alcamo, 2007; Svirejeva-Hopkins and 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 (UBNZ) effects on C dynamics of Southern US during the last six decades. Despite these efforts, a comprehensive study that investigates all the 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 and Hobbs, 2012).

In this study, we first comprehensively analyzed the factors that may control the UBNZ 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. Then as a case study, a dynamic land ecosystem model (DLEM, Tian et al., 2011a) was applied to quantify the UBNZ 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 yr of the 20th century (Alig et al., 2004).

DLEM is a process-based ecosystem model that consider the effects of multiple environmental stresses on biogeochemical cycles including the C, water, and nitrogen

(N) processes (Tian et al., 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. Our study only considered the C dynamics of ecosystem (i.e. vegetation and soil) in urban. Carbon fluxes related to resource importation and consumption by urban dwellers are beyond the scope of this study, because like many others (Svirejeva-Hopkins and Schellnhuber, 2006; Pouyat et al., 2007; Satterthwaite et al., 2010), we believe these impacts should be weighed against the effect of alternative settlement patterns on a per-capita basis – a comparison that requires extensive discussion (Folke et al., 1997; Newman, 2006; Bettencourt and West, 2010). Only the fossil fuel emission related to urban ecosystem managements was discussed (Townsend-Small and Czimczik, 2010; Bartlett and 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 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 and Crane, 2002; Hutyra et al., 2011; Edmondson et al., 2012). (2) Urbanization-induced environmental changes (UIEC), such as UHI, elevated CO_2 (UCO_2) 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, soil are disturbed, and large amount of C are released from the ecosystem (Schaldach and Alcamo, 2007; Zhang et al., 2008). (4) Global change (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. 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

$$\begin{aligned}&\mathrm{UBNZ} = \mathrm{UBNC} + \mathrm{UBMG} + \mathrm{UIEC} + \text{GLB-UBNC} + \mathrm{IT\_OTHER} = S_{\mathrm{UBNZ}} - S_{\mathrm{GLBC}}\\&\rightarrow \mathrm{IT\_OTHER} = (S_{\mathrm{UBNZ}} - S_{\mathrm{GLBC}}) - (\mathrm{UBNC} + \mathrm{UBMG} + \mathrm{UIEC} + \text{GLB-UBNC})\end{aligned} \tag{1}$$

Where S_{UBNZ} is the urbanization scenario (or the "business as usual scenario"), and S_{GLBC} is the control scenario, in which no urbanization take 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.

$$\begin{aligned}&\mathrm{UBMG} = \mathrm{LWN} + \mathrm{UFM}\\&\mathrm{LWN} = S_{\mathrm{LWN\ \&\ UBNC}} - S_{\mathrm{UBNC}}\\&\mathrm{UFM} = S_{\mathrm{UFM\ \&\ UBNC}} - S_{\mathrm{UBNC}}\end{aligned} \tag{2}$$

$S_{\mathrm{LWN\ \&\ UBNC}}$ and $S_{\mathrm{UFM\ \&\ UBNC}}$ 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.

$$\begin{aligned}&\mathrm{UIEC} = \mathrm{UHI} + \mathrm{UCO_2} + \mathrm{UNDP} + \mathrm{UDIM} + \mathrm{IT\_UIEC} = S_{\mathrm{UIEC\ \&\ UBNC}} - S_{\mathrm{UBNC}}\\&\rightarrow \mathrm{IT\_UIEC} = (S_{\mathrm{UIEC\ \&\ UBNC}} - S_{\mathrm{UBNC}}) - (\mathrm{UHI} + \mathrm{UCO_2} + \mathrm{UNDP} + \mathrm{UDIM})\end{aligned} \tag{3}$$

$S_{\mathrm{UIEC\ \&\ UBNC}}$ 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, $\mathrm{UCO_2}$, UNDP, and UDIM are calculated similarly to the LWN and UFM:

$$\begin{aligned}\mathrm{UHI} &= S_{\mathrm{UHI\ \&\ UBNC}} - S_{\mathrm{UBNC}}\\ \mathrm{UCO_2} &= S_{\mathrm{UCO_2\ \&\ UBNC}} - S_{\mathrm{UBNC}}\\ \mathrm{UNDP} &= S_{\mathrm{UNDP\ \&\ UBNC}} - S_{\mathrm{UBNC}}\\ \mathrm{UDIM} &= S_{\mathrm{UDIM\ \&\ UBNC}} - S_{\mathrm{UBNC}}\end{aligned} \tag{4}$$

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

$$\begin{aligned}&\text{GLB-UBNC} = \text{LUC-UBNC} + \text{NDP-UBNC} + \mathrm{O_3}\text{-UBNC} + \mathrm{CO_2}\text{-UBNC}\\ &+ \text{CLM-UBNC} + \text{IT\_GLBC} = S_{\mathrm{GLBC\ \&\ UBNC}} - (S_{\mathrm{GLBC}} + S_{\mathrm{UBNC}})\\ &\rightarrow \text{IT\_GLBC} = S_{\mathrm{GLBC\ \&\ UBNC}} - (S_{\mathrm{GLBC}} + S_{\mathrm{UBNC}}) - (\text{LUC-UBNC} + \text{NDP-UBNC}\\ &+ \mathrm{O_3}\text{-UBNC} + \mathrm{CO_2}\text{-UBNC} + \text{CLM-UBNC})\end{aligned} \tag{5}$$

Where S_{GLBC} simulates the global change effects; and $S_{\mathrm{GLBC\ \&\ UBNC}}$ 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,

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

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

$$\mathrm{O_3}\text{-UBNC} = S_{\mathrm{O_3\ \&\ UBNC}} - (S_{\mathrm{O_3}} + S_{\mathrm{UBNC}}) \tag{8}$$

$$\mathrm{CO_2}\text{-UBNC} = S_{\mathrm{CO_2\ \&\ UBNC}} - (S_{\mathrm{CO_2}} + S_{\mathrm{UBNC}}) \tag{9}$$

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

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

Please refer to Zhang et al. (2012) for the model structure, parameters, study region, and input datasets in this study (also see Supplement Fig. S1, and Supplement Tables S1 and S2). Here, we only briefly introduce the study area (Fig. 2) and model structure. 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 $1.2 \times 10^5\,\mathrm{km}^2$ urban lands in the SUS (red areas in Supplement Fig. S1). 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).

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 mortality rate of rural forest is about 10 % higher than that of urban forest (Tian et al., 2012), whose annual mortality was set to 2.2 % to 3.5 % according to Nowak (1986, 1994) in DLEM. DLEM further models the effect of urban-induced environmental changes (i.e. UHI, UCO_2, UNDP, and UDIM) on urban ecosystem, which (except for the UDIM) generally enhance the growth and biomass accumulation rate of urban vegetation (Ziska et al., 2004). Finally, the intensive managements on urban vegetation, such as fertilization, irrigation, and pruning are modeled. All lawns are intensively managed, but only a small fraction of urban forest (< 20 %) was under management that may remove < 5 % of the forest biomass annually (Dwyer et al., 2000; Kielbaso, 2008; a literature review is found in the Sect. 3 of the supplementary material). In general, all of the factors in Fig. 1 are considered in this study. Based on literature review, Zhang et al. (2012) estimated the parameters controlling urban-induced environmental changes and urban managements (also see the Supplementary Table S2).

4 Results

Except for the annual mean temperature that decreased from 1945–1969 and then increased from 1970–2007, no significant climate trends were found in the SUS from 1945–2007 (Fig. 3a–c), although increased drought intensity was found for many areas in the east while increased precipitation was found in the west (Chen et al., 2012).

The changes in regional atmosphere, i.e. the O_3 exposure and N deposition rates, increased dramatically during the study period (Fig. 3d and e). These changes could have profound impacts on both the pre-urban and urban ecosystems, and influencing the net urbanization effect. Urban/developed land area increased about eight times from $0.13 \times 10^5\,km^2$ in 1945 to $1.2 \times 10^5\,km^2$ in 2007, 77 %, 16 %, and 7 % of which developed in the forested, grassland, and shrub/desert areas, respectively (Fig. 3f). The overall effect was a net C loss of 0.21 Pg C.

The temporal pattern of UBNZ was controlled by the UBNC, which was estimated to result in about 0.37 Pg C loss from 1945–2007 (Fig. 4). In contrast, the 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 (i.e. GLBC-UBNC) 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, UBNC, UBMG, 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, UBMG, and GLBC-UBNC can be further broken down to reflect the effect of individual factors (Fig. 5). From 1945–2007, urban lawn management (i.e. LWN) enhanced C storage by $489.9\,g\,m^{-2}$ (the SUS subgroup in Fig. 6a) or 63.6 Tg in the SUS (Fig. 5), having the strongest C sequestration effect among all factors. Urban forest management (i.e. UFM), including direct management (Table S2 in the supplementary material) 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 UNDP ($248.9\,g\,m^{-2}$ and 32.3 Tg in the SUS) and UCO_2 ($220.5\,g\,m^{-2}$ and 28.6 Tg in the SUS). In comparison, UHI and interactive effects among UIEC factors (i.e. IT_UIEC) 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 global change factors and urban land conversion (i.e. GLBC-UBNC) were smaller than other factors. While O_3-UBNC and CLM-UBNC enhanced C sequestration, other interactions (LUC-UBNC, CO_2-UBNC, NDP-UBNC, and IT_GLBC) caused C loss (Fig. 5).

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 based on the dominant/potential local vegetation type (i.e. UVG; Fig. 6). The results indicated that UBNZ had strong negative effect on C density ($-2084\,\mathrm{g\,m^{-2}}$) in forest area, only slight negative effect on C density ($-95.1\,\mathrm{g\,m^{-2}}$) in grasslands, and positive effect on C density ($389.6\,\mathrm{g\,m^{-2}}$) in shrubland/desert (Fig. 6a). The C sequestration effects of UIEC and UFM were strongest in forest area, followed by grassland and shrubland/desert areas. The interactive effects between global change and urban land conversion (i.e. GLBC-UBNC) had negative effect ($-276.3\,\mathrm{g\,m^{-2}}$) on C density in forest area and positive effect ($168.3\,\mathrm{g\,m^{-2}}$) 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 (Figs. 4 and 5b).

5 Discussion

5.1 Relative contributions from multiple controls on urban-induced C dynamics

Nowhere is ecological complexity more apparent than in urban areas (Kaye et al., 2006). The aggregated effects of urbanization (including changing land cover characteristics, land use patterns, pervious surface fractions, urban heat islands, extended growing seasons, atmospheric pollution, management activities, etc.) on land–atmosphere exchange processes remains highly uncertain despite decades of study on components of the problem (Pouyat et al., 2006; Canadell et al., 2007; Trusilova and Churkina, 2008). Only considering certain aspects of urbanization, former studies drew contradictory conclusions about UBNZ effect: focusing on land conversion, Imhoff et al. (2000) found urbanization reduced ecosystem productivity in the US; Schaldach and Alcamo (2007) estimated the C released by urbanization offset 20 % of the C sequestered by cropland abandonment and afforestation in Central Germany; Zhang et al. (2008) reported urbanization has become the most important C release process in terrestrial ecosystems of three counties in Georgia, US since 2000. Modeling simulations by Shen et al. (2008) and Trusilova and Churkina (2008), however, suggested urban-induced environmental changes (i.e. UIEC) enhanced ecosystem productivity and C sequestration, but the UHI stimulated C emission from the ecosystem, a pattern also revealed by our study (Fig. 5). Nowak and Crane (2002) found urban forests, on a tree cover basis, had about 100 % higher C density and growth rate than the rural forest in US. The difference could be attributed to urban forest management (i.e. UFM) as well as UIEC such as elevated CO_2 (Nowak et al., 2002; Hutyra et al., 2011). Milesi et al. (2005) showed intensive lawn managements (i.e. LWN) could potentially sequestrate 17 $\mathrm{Tg\,C\,a^{-1}}$ into soil in the US.

Results from our case study agree with the findings from all the above studies (Fig. 5). But more importantly, ours is the first attempt to gain a complete picture about UBNZ effect on regional C dynamics and understand the urbanization complexity, by quantifying and comparing the relative impacts from multiple environmental changes that control ecosystem processes, including the interactive effects among these controls. Our case study in the SUS indicate that compared to other factors UBNC had by far the strongest impacts (−2845 $\mathrm{g\,m^{-2}}$) on regional C storage (Fig. 6a). Both UFM and UIEC increased C storage, but UFM had a stronger effect than UIEC (886 $\mathrm{g\,m^{-2}}$ vs. 226 $\mathrm{g\,m^{-2}}$) (Fig. 6a). This result quantitatively confirmed the central principles in urban ecological theory: anthropogenic drivers will dominate natural drivers in the control of ecosystem response variables, and human-caused disturbance is more pronounced during rather than after the land development process (Pouyat et al., 2007; Pickett et al., 2011). It was found that in responses to urbanization, the urban ecosystem's structure (e.g., soil organic carbon, SOC; Pouyat et al., 2006) and function (e.g., NPP; Imhoff et al., 2000) converged on regional and global scales relative to the native systems

(Pouyat et al., 2003), indicating effects from management and anthropogenic environmental change, dominated natural controlling factors (Pickett et al., 2011).

5.2 Complex interactive effects among major controls

Furthermore, we analyzed the interactive effects among different controls by conducting numeric experiments. Like Shen et al. (2008), we found a strong interactive effect among UIEC (i.e. IT_UIEC), comparable to the negative effects from UHI (Fig. 5). The synergetic effect of the four urbanization-induced changes was an increase of the C sequestration in Europe (Trusilova and Churkina, 2008), but our study indicates a negative impact in the SUS (Fig. 5). Shen et al. (2008) suggested that the interactive effect of multiple urbanization-induced changes are difficult to predict due to the influenced from other factors such as global climate change and non-linear responses from different vegetation types in the study region. Therefore, we designed a factorial analysis scheme to separate the effect of global change from the urban land conversion and quantify their interactive effects (i.e. GLBC-UBNC) (Fig. 1). We found GLBC-UBNC had negative effects on regional C storage (−24 Tg), almost offset the C sequestration due to UEIC (29 Tg) (Fig. 5). Such an important mechanism, however, had been overlooked in former urban studies. The interaction between UBNC and different GLBC factors had different effects on C dynamics. In general, GLBC-UBNC would have negative impact on C storage if the GLBC factor enhanced 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, CO_2-UBNC and NPD-UBNC have negative effects on C sequestration (Fig. 5). Because there is no significant climate change in the SUS during the study period (Fig. 3a–c), the effect (i.e. CLM-UBNC) was relatively small. Model simulations, however, predicted dramatic climate change in the 21st century, which will significantly alter the C dynamics in the

SUS (Song et al., 2013). Therefore, the CLM-UBNC effects should not be overlooked when study the C dynamics in urbanised areas.

Unlike other interactions, the interactive effect between LUC-UBNC was negative in forested areas, but positive in desert/shrubland (Fig. 6a). In this study, LUC only refers to pre-urban land-use change. Since the middle of 20th century, SUS has undergone large-scale cropland abandonment, followed by rapid urbanization in many areas (Hart, 1980; Wear, 2002). When an abandoned cropland changed to forest, the land acts as a C sink; but if it changed to desert/shrubland, the C storage decreased because of the low C density in desert. Because it took decades for the C sequestration and C loss to complete, if the land was converted into impervious surface in the middle of the period, the C change processes would stop, showing a negative or positive LUC-UBNC effect depending on the local ecosystem type. Our study indicates that considering pre-urban land-use legacies and time-lagged ecological responses to urbanization places urban-induced C dynamics in the context of its trajectory of change, enhancing the understanding not only of observed patterns, but also the processes and dynamics that generate and maintain them (Ramalho and Hobbs, 2012). Our finding confirms Dwyer et al. (2000)'s statement that land use and urbanization combine to influence the structure and function of the urban ecosystem across the landscape.

5.3 Influence of pre-urban vegetation type

An early study (Zhang et al., 2012) showed significant spatial variation in UBNZ effect on the C dynamics in the SUS, which was related to the distinct responses of various vegetation types to urbanization. For example, Shen et al. (2008)'s analysis indicated grass is more sensitive to UCO_2 than desert shrub. Like the LUC-UBNC as discussed above, we found the effects of UIEC and UBMG factors varied in areas dominated by different vegetation types (Fig. 6). Our analyses show the effects of UEIC decreased, while the effects of lawn managements (i.e. LWN) increased, in the sequence of forest, grass, and shrub areas (Fig. 6a). Turfgrass requires intensive management to sustain high productivity (Townsend-Small and Czimczik, 2010). Indeed, in the absence of irrigation, most species of turf grass would not be able to grow and compete with native vegetation in most of the conterminous US (Milesi et al., 2005). Because desert and arid grassland had less precipitation than forest area, the impact of irrigation was more obvious in these lands. The overall response of an ecosystem to urbanization, however, was dominated by the UBNC effects. According to our results, urban land conversion in forested area released 3416 $\mathrm{g\,C\,m^{-2}}$, about 10 times the C released from a converted desrt/shrubland (303 $\mathrm{g\,C\,m^{-2}}$). Since about 77 % of urban land was developed in forested area, UBNC resulted in large amount of C in the last six decades, becoming a primary threat to the C sequestration in the forested area of the SUS (Wear, 2002).

5.4 Implications for urban ecosystem 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 areass of SUS: first, the strong C loss due to UBNC highlights the importance to preserve pre-urban C pools during land development, probably by reducing soil disturbances, reserving large areas of remnant green space, and transplanting trees. This is especially important in forested areas. Second, our study, as well as others (Ziska et al., 2004; Trusilova and 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. Third, our study indicates managements could create strong C sinks in urban vegetation. The intensively managed urban lawn was found to be highly productive (Golubiewski, 2006; Wu and Bauer, 2012). Studies in northern Colorado found that urban lawns, which occupied about 6 % of the regional land area, accounted for up to 30 % of the regional NPP (Kaye et al., 2005). Qian et al. (2010) observed that irrigation increased SOC input from turfgrass, which could sequester 32–78 $\mathrm{g\,C\,m^{-2}\,a^{-1}}$. Even in intensive buildup area, urban forests were found to have higher growth rates and C densities both in biomass and soil than rural forest (Nowak and Crane, 2002; Pouyat et al., 2009; Hutyra et al., 2011). Although direct and indirect C emission in management of urban vegetation may neutralize its benefit in C sequestration (Townsend-Small and Czimczik, 2010; Bartlett and James, 2011), there's substantial scope in reducing these management-related CO_2 emission (Nowak et al., 2002; Scharenbroch and Lloyd, 2004; Reid et al., 2010; Pickett et al., 2011; Zirkle et al., 2011). Furthermore, utilizing biomass from urban landscapes could significantly contribute to the nation's renewable energy needs. Lawn clippings, fallen leaves and tree limbs are all potential sources of biofuels (Springer, 2012). 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 considerable reduced by shifted fire regime (Guilden et al., 1990; Pickett et al., 2011) or fire control/management in urbanised areas (Campbell et al., 2007; Defosse et al., 2011). Based on a literature review (see Sect. 3 in the Supplement), we estimated that the overall mortality rate (considering disturbance effect) of rural forest is about 10 % higher than that of urban forest. 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 studies.

6 Conclusions

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.

Supplementary material related to this article is available online at http://www.biogeosciences-discuss.net/10/17597/2013/bgd-10-17597-2013-supplement.zip.

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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 and 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_{CO_2}	–	–	√	–	–	–	–	–	–	–	–	–
	S_{NDP}	–	–	–	√	–	–	–	–	–	–	–	–
	S_{O_3}	–	–	–	–	√	–	–	–	–	–	–	–
	S_{LUC}	–	–	–	–	–	√	–	–	–	–	–	–
Urban land conversion only	S_{UBNC}	√	–	–	–	–	–	–	–	–	–	–	–
Global changes with urban land conversion	$S_{\text{GLBC \& UBNC}}$	√	√	√	√	√	√	–	–	–	–	–	–
	$S_{CLM\&UBNC}$	√	√	–	–	–	–	–	–	–	–	–	–
	$S_{\text{CO}_2\text{ \& UBNC}}$	√	–	√	–	–	–	–	–	–	–	–	–
	$S_{NDP\&UBNC}$	√	–	–	√	–	–	–	–	–	–	–	–
	$S_{\text{O}_3\text{ \& UBNC}}$	√	–	–	–	√	–	–	–	–	–	–	–
	$S_{\text{LUC \& UBNC}}$	√	–	–	–	–	√	–	–	–	–	–	–
Urbanization induced environmental changes	$S_{\text{UIEC \& UBNC}}$	√	–	–	–	–	–	√	√	√	√	–	–
	$S_{\text{UHI \& UBNC}}$	√	–	–	–	–	–	√	–	–	–	–	–
	$S_{\text{UCO}_2\text{ \& UBNC}}$	√	–	–	–	–	–	–	√	–	–	–	–
	$S_{\text{UNDP \& UBNC}}$	√	–	–	–	–	–	–	–	√	–	–	–
	$S_{\text{UDIM \& UBNC}}$	√	–	–	–	–	–	–	–	–	√	–	–
Urban managements	$S_{UBMG\&UBNC}$	√	–	–	–	–	–	–	–	–	–	√	√
	$S_{\text{LWN \& UBNC}}$	√	–	–	–	–	–	–	–	–	–	√	–
	$S_{\text{UFM \& UBNC}}$	√	–	–	–	–	–	–	–	–	–	–	√

Note: "√" means changes in the environmental factor were considered, while "–" means the factor was unchanged in the simulation.

[*] Following Zhang et al. (2012), UBNZCmin and UBNZCmax were designed to examine the effect of uncertainties in model parameter on the estimated urbanization effects. Parameters of UBNZCmin were set so that carbon sequestration were minimized while carbon loss was maximized during urbanization; UBNZCmax was the contrary. See Table S2 in the Supplement for detail.

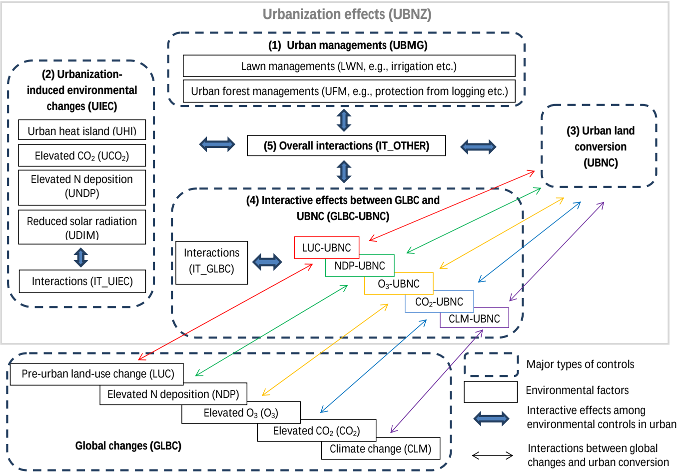

Fig. 1. The urbanization effects (UBNZ) on regional carbon dynamics are controlled by four major types of environmental changes, including (1) urban land conversion (UBNC) during which rural land-use type is converted to urban and developed land-use composed by impervious surfaces, managed urban lawn, 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).

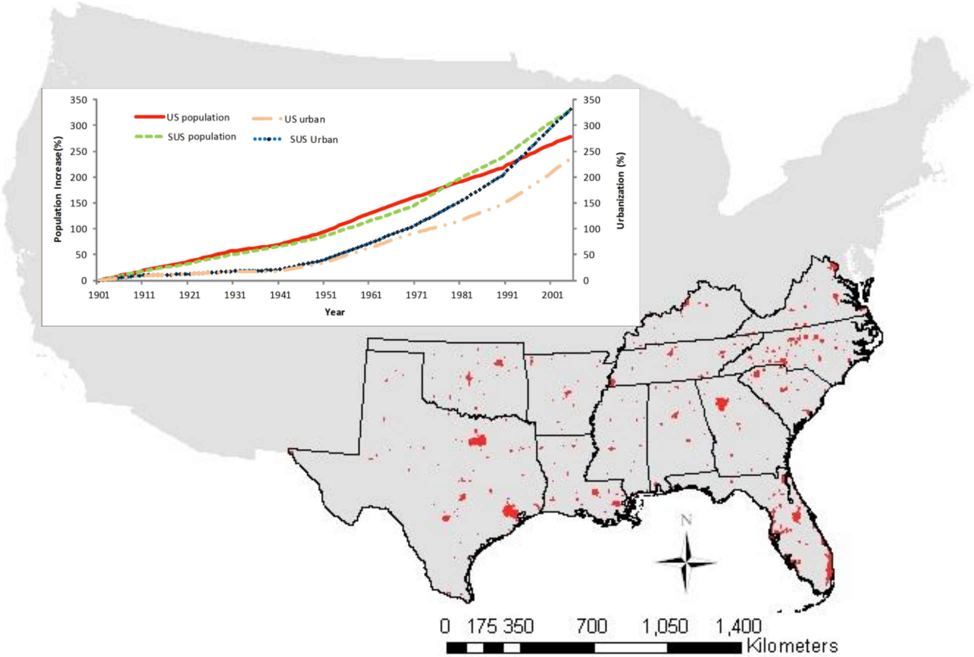

Fig. 2. The boundary of the Southern United States (SUS) and the location of urban/developed lands (in red) in 2001. The urban and developed lands were extracted from the National Land Cover Dataset 2001 (NLCD, 2001; Homer et al., 2007).

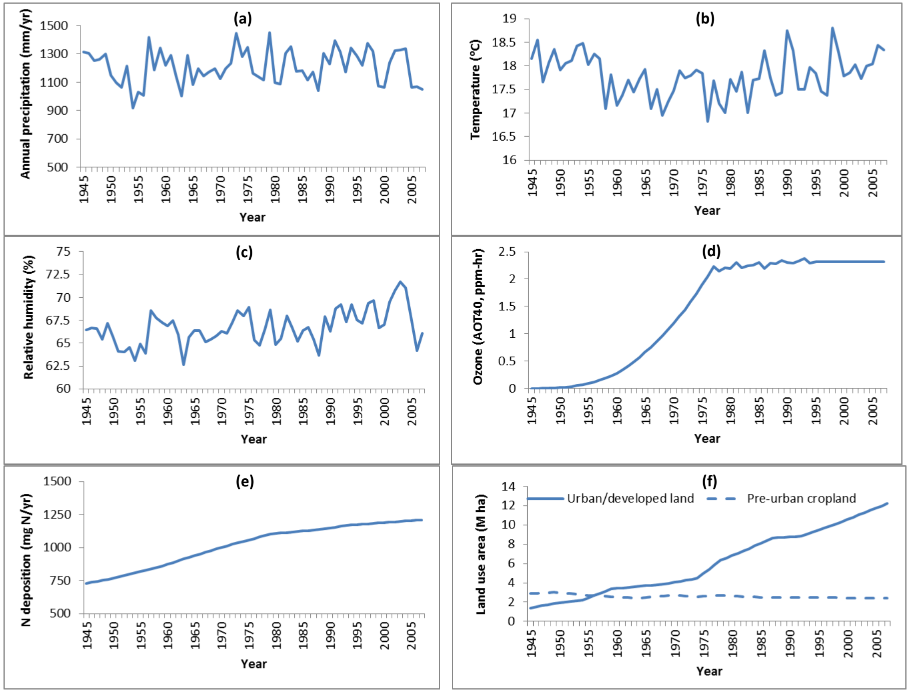

Fig. 3. Temporal patterns of major global change factors in the study region from 1945–2007. **(a)** Annual precipitation; **(b)** temperature; **(c)** relative humidity; **(d)** ambient ozone exposure; AOT40 is the accumulated dose over a threshold of 40 ppb during daylight hours in a month (Felzer 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.

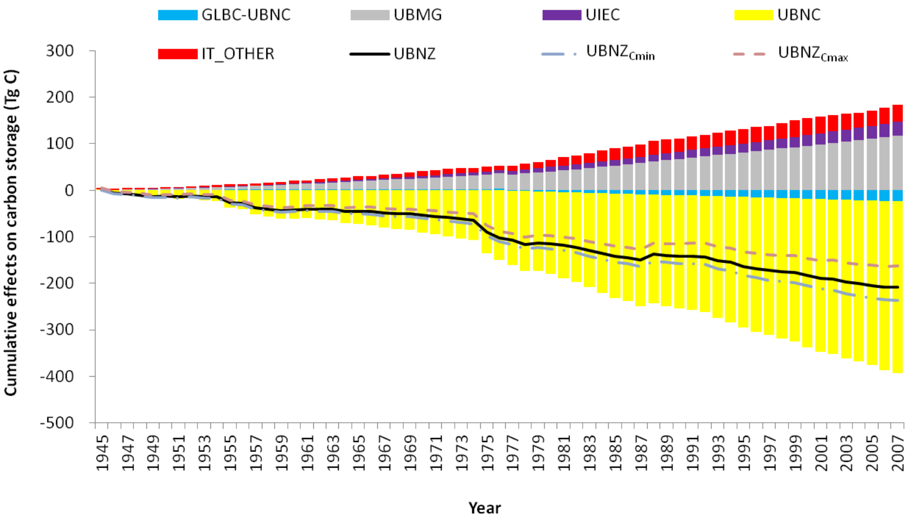

Fig. 4. Cumulative effects of urbanization (UBNZ) to the carbon dynamic of the Southern US from 1945–2007 and the contributions of multiple environmental drivers. UBNC is the effect of urban land conversion; GLBC-UBNC is the interactive effect between global environmental changes (GLBC, including changes 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, CO_2 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), UBNZCmin and UBNZCmax represent the minimum and maximum urbanization effects, respectively, as influenced by uncertainties in model parameterization (Table S2 in the Supplement).

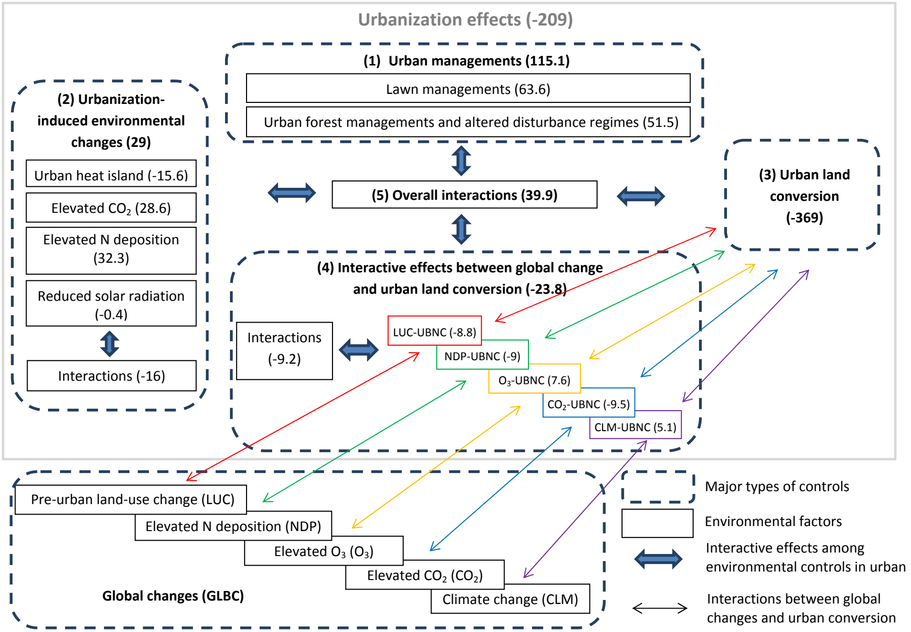

Fig. 5. Effects of different environmental controls on carbon dynamics in urbanised areas in the southern US. Unit: Tg C.

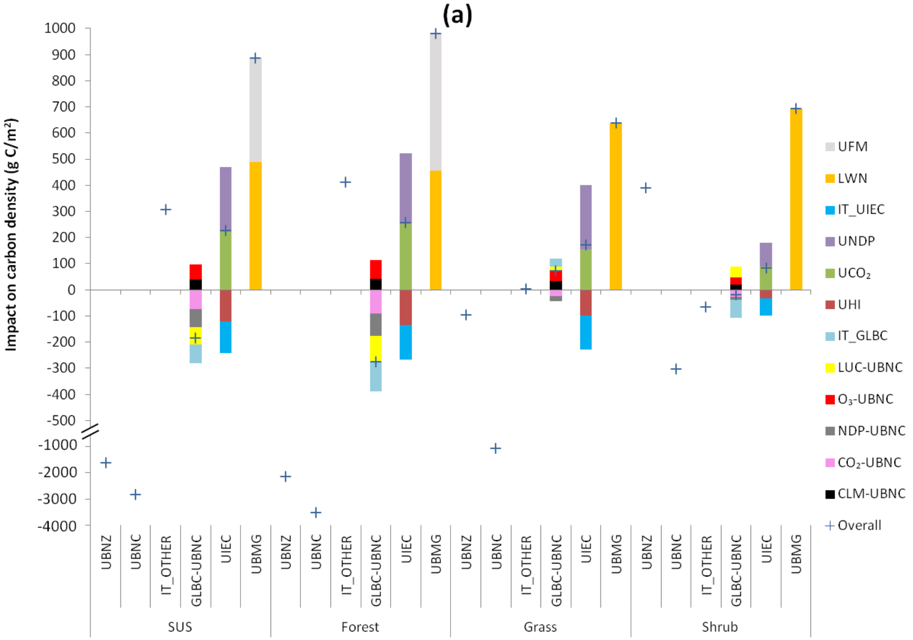

Fig. 6a. Contributions of multiple environmental controls to urbanization effect (UBNZ) on carbon (C) dynamic of the Forest (including needleleaf, broadleaf, mixture, and wetland forests), Grass (including C$_3$ and C$_4$ grasslands, and grassy wetland), and arid shrubs (including shrubland and desert) ecosystems in the Southern US (SUS) from 1945–2007. **(a)** Urbanization effects on carbon density; **(b)** urbanization effects on carbon storage (1 T = 10^{12}). Blue dashes symbolize the overall effect (Overall) for each of the four major environmental controls, including urban land conversion (UBNC) and environmental changes at three different scales: managements of urban vegetation (UBMG) at the landuse scale, urbanization induced environmental changes (UIEC) at the (urban) landscape scale, and the interactions between UBNC and global environmental changes (GLBC-UBNC). Thus, UBNZ = UBNC + UBMG + UIEC + GLBC-UBNC + IT_OTHER, where IT_OTHER represents the interactive effect among UBNC, UBMG, UIEC, and GLBC-UBNC.

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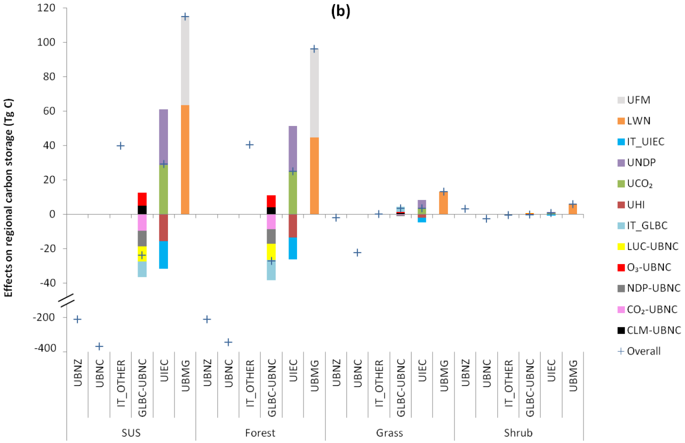

Fig. 6b. At each scale, the overall effects of environmental changes are further determined by multiple factors and their interactions (represented with stacked columns): UBMG = LWN + UFM, where LWN is the effect of lawn managements such as irrigation and fertilization, and UFM is the effect of urban forest managements including protections from logging and wildfire disturbances; UIEC = UHI + UDIM + UCO$_2$ + UNDP + IT_UIEC, where UHI is the effect of urban heat island, UDIM, UCO$_2$, and UNDP are influences from the reduced solar radiation and the elevated CO$_2$ concentration and nitrogen deposition due to air pollution in urban/developed area, respectively, IT_UIEC represents the interactions among these urbanization induced changes; GLBC-UBNC = CLM-UBNC + CO$_2$-UBNC + NDP-UBNC + O$_3$-UBNC + LUC-UBNC + IT_GLBC, where "-UBNC" represents the interactive effects between urban land conversion and different global environmental changes such as climate change (CLM), elevated CO$_2$ (CO$_2$) and N deposition (NDP), increased ozone exposure (O$_3$), and pre-urbanization landuse changes (LUC, including cropland conversion and abandonment). IT_GLBC represents the interactive effects among all these GLBC-UBNC factors. Refer to Fig. 1 for an illustration of the nested relationships of investigated factors, and Table 1 for description of the scenario design.