Biogeosciences Discuss., 10, C9501–C9511, 2014
www.biogeosciences-discuss.net/10/C9501/2014/

Interactive comment on "Multi-factor controls on terrestrial carbon dynamics in urbanised areas" *by* C. Zhang et al.

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Received and published: 19 April 2014

General comment: "(1) The manuscript closely follows Zhang et al. 2012 with the use of the same study domain, temporal period, process model, and analysis of C dynamics to better understand the effects of urbanization on vegetation and soil carbon storage. The map presented in Figure 2 seems identical to the map published in 2012. Distinct from Zhang et al. 2012 the present study conducts a series of sensitivity analyses to better understand what causes the modeled loss of carbon found previously. (2) From my reading of the results and the discussion provided by the authors of major findings (paragraph 2 of discussion) – the results presented are primarily confirmatory of existing literature without clearly identified new insights. Of equal importance the study lacks any validation or comparison with field data. Based on these concerns I consider this manuscript more suitable for a journal such as Ecological Modelling. (3) As a more general concern, using net soil and plant carbon storage as a measure of carbon sequestration potential is misleading. For example the manuscript advocates Milesi et al. (2005), 17 Tg C / yr of sequestration for urban lawns; this number does not include the large amount of emissions associated with the extensive management required. This seems akin to advocating corn ethanol based biofuel because some energy is produced – regardless of the fact that the energy is less than required for production."

Our response: [Note: please find the revised manuscript and tables in the bg-2013-456-supplement.zip file] (1) Although this study and the study of Zhang et al. (2012) used the same model, which was applied to the same region (i.e. the southern United States, SUS), the two studies addressed very different research questions with different analysis approaches. While Zhang et al. (2012) focused on developing (and validating) a process-model to assess the urbanization effects on carbon dynamics of the SUS, this study focused on developing the ability to quantify the relative contributions of multiple environmental factors to net carbon source and sink behavior of the urbanization process. While Zhang et al. (2012) analyzed the spatiotemporal pattern of carbon dynamics in the urbanized area in the SUS, this study comprehensively analyzed the factors that may control the urbanization effect on ecosystem C dynamic (Fig. 1) and then proposed a numeric experimental scheme, i.e. scenarios design, to conduct factorial analysis on the effects of different factors (Table 1). In this regard, the section "2. Factors controlling urbanization effects" that presents an innovative framework to comprehensively analyze the multiple environmental controls from local to global scales on urban ecosystem, is the most important part of this paper. In comparison, the model simulations in the SUS was only a case study that provided an example of the factorial analysis approach proposed in the section 2. It should be noted that the scenarios listed in the Table 1 are NOT sensitivity analyses that usually involve systematically changes of parameter or input values for the purpose of model evaluation (e.g., Zhang et al., 2012), but belong to a carefully designed numeric experimental scheme to isolate and quantify the relative contributions of various environmental controls on ecosystem carbon dynamics during urbanization. The structure of this paper and the objectives of this study have been clearly stated at the end of the Introduction (line 18-24 in page 5, and line 4-7 in page 6). Nevertheless, we recognize that the above-described research objectives and main achievements of this study have not been emphasized adequately in the Abstract and the Conclusions. Although we tried to keep the readers' focus from technical details of model structure and simulation, the reviewer #2 still feels it like a technologically oriented study that is "more suitable for Ecological Modelling". As you will see in the revised manuscript, the Abstract, Conclusion and the Discussion are revised to emphasize the strength and innovative points of this new study. To prevent the readers from mistaking this study as simply another regional simulation follows Zhang et al. (2012), Fig 2 "The boundary of the Southern United States (SUS)" is moved to supplementary material. Furthermore, the subtitle of section 3 is changed from "Materials and methods" to "Materials and methods in the case study" and the subtitle of section 4 is changed from "Results" to "Case study results". In general, unlike Zhang et al. (2012) that focused on a special model and certain study region, this study focused on more general topics of how many environmental factors (including their interactive effects) may control the urbanization effect on ecosystem carbon dynamics, and how to isolate and quantify their relative contributions.

(2) This study has two major contributions to urban ecosystem research: (a) we generalized the factors that may affect ecosystem carbon dynamics during urbanization and organized them in an analysis framework to study their relationship (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 dominant (groups of) factors in the Fig. 1, the interactive effect between global changes and urban land conversion (GLBC-UBNC) and the overall interactive effects among the four environmental changes (IT_OTHER) are newly identified controls that have never been addressed in former studies, according to our literature review. 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 have never been compared to each other before this study. (b) More importantly, we outlined a factorial analysis scheme to isolate and quantify the relative contribution of different factors to the carbon dynamic in urbanized areas. 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 15 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. Furthermore, our findings in the SUS case study provide valuable information for regional C management in the urbanised areas of SUS: (a) 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. (b) 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. (c) Lawn managements could create strong C sink even when the fossil fuel C cost are taken into account. (d) Protecting urban forests from disturbances such as logging and wildfire could be an effective way to enhance urban C sink. We recognize that the importance of the factorial analysis scheme developed in the section 2 as well as the new findings and insights as described above have not been adequately emphasized in the Discussion. In the revised manuscript, we remove the results that simply confirm existing literature to make the Discussion more concise. We emphasize our major contributions (as described above) to urban ecosystem research and the major findings in this study. Furthermore, as requested by both reviewers, the model is validated against field data (as you will find in the last paragraph of the revised Discussion). Previously, we validated the DLEM simulated C and water fluxes, nitrogen cycle, and soil processes and trace gas emission against intensively studied ecological sites (Tian et al., 2011a,b). Because urbanization does not change genetic characteristics of plants or fundamental mechanisms of ecological processes (Niemela, 1999), these former validations indicated that DLEM can correctly simulate ecosystem's responses to multiple environmental stresses in urbanised area. To validate DLEM performance for simulating C processes in urban ecosystems, we 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.

(3) We agree with the reviewer that fossil fuel emission should be considered when assessing the carbon sequestration potential of urban ecosystems. As you will see in the revised manuscript, a new paragraph (the 2nd paragraph) is added to the section "5.4 Implications for urban ecosystem management" of the Discussion to address this issue. The following discussion is cited from the revised manuscript: "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 CO2 uptake in lawns is not without a "carbon cost" from fossil fuel CO2 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 management 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 CO2 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."

Detailed Comments Comment #1: "The large number of abbreviations that are unique to this manuscript creates a challenge for reading. Fewer abbreviations would be helpful."

Our response: As one of our major contribution, we conducted a comprehensive analysis of the factors that may control ecosystem carbon dynamics during urbanization, by trying to include most, if not all, of the dominant factors working at multiple scales. As you can see in the Fig 1, we identified five major categories, 15 individual factors in this study. Some of them e.g., the urban heat island (UHI), are widely discussed effects in urban studies; others, such as the interactive effects between global changes and urban land conversion, have never been addressed before according to our literature review. For simplification and to facilitating discussion, abbreviations were assigned to these factors. We explained the abbreviations in Fig. 1, and provided clear definition and detailed description for each of them in the caption of Fig. 1 as well as in the section 2. Even so, we recognize that the large number of new abbreviations creates a challenge for reading. Therefore, we remove most of the abbreviations from the revised Results and Discussion, only keeping four abbreviations: UHI, UIEC, UBNC, and GLBC-UBNC. UHI and UIEC are kept because they had been widely used elsewhere to refer to urban heat island and urbanization induced environmental changes (e.g., Shen et al., 2008), respectively. UBNC (i.e., effect from urban land conversion) and GLBC-UBNC (i.e., interactive effects between global changes and urban land conversion) are kept because they are frequently mentioned in the context and the descriptions for the two factors are long. Section 2 describes the factorial analysis scheme to isolate and

quantify the relative contributions from individual factors. To make the equations in the section 2 clear and concise, we keep using all abbreviations in this section as well as in the tables and figures.

Comment #2: "Pg 17600 line 3: I disagree that urban areas can provide a meaningful C sink. For this comparison, provide the amount of potential urban vegetation C sink relative to the total urban emissions for a useful comparison."

Our response: We totally agree with the reviewer that urban area is a carbon source if fossil fuel emission is counted in, but we also agree with Escobedo et al. (2010) that urban ecosystems, if managed properly, could provide carbon sink services like the rural ecosystems, especially when considering the relatively high productivity and carbon sequestration capacity of urban ecosystem (McPherson et al., 1997; Pouyat et al., 2008). For example, 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; and the carbon sequestration of the urban trees was 5-fold or more of the equivalent age rural trees in Hangzhou, China (Ji et al., 2011). It may be argued that the area of urban green space is low and the ecosystem carbon sink is too weak to compensate for the fossil fuel carbon emission in individual city. However, the global urban area is increasing rapidly. At present about 3-5% of global land area has been converted to urban and developed land-use (Svirejeva-Hopkins & Schellnhuber, 2008; Seto et al., 2010). Turfgrass is already the largest irrigated crop in US (Milesi et al., 2005). 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. It is widely accepted that urbanization became a dominant demographic trend and important land transformation process in the 21st century (Seto et al., 2010; Pickett et al., 2011). Our study covered the urban and developed areas of the southern United States. At this scale, the total carbon sink in urban ecosystem could be too large to be overlooked. To address the reviewer's concern, we modify this sentence to "Escobedo et al. (2010) indicated that urban forest management can create moderate carbon sink in the southeastern US."

Comment #3: "Pg 17601 line 12: I wouldn't characterize the study as examining "all" the environmental changes associated with urbanization. Perhaps "dominant" would be better? I don't think we have a good idea what all these changes may be."

Our response: Thanks for this comment. We recognize the original expression was inappropriate. We make correction according to the reviewer's comment.

Comment #4: "Pg 17602 line 10-15: This passage is unclear, I don't understand what is meant here."

Our response: Our study focused on the impacts of urbanization on ecosystem carbon dynamics. This passage tries to emphasize that we only consider the ecological processes, and the carbon emission from socioeconomic processes (such as fossil fuel consumption) are not considered in this study. Furthermore, we do not think the urbanization result in higher fossil fuel consumption. Urbanization only aggregates the fossil fuel emission into the urban areas, but may not increase carbon emission rate per capita. To prevent confusion, we replace the original passage with the following sentences: "Our study only considered the C dynamics of ecosystem (i.e. vegetation and soil) in urban. Fossil fuel emissions unrelated to urban ecosystem managements were out of the scope of this study (Townsend-Small & Czimczik, 2010; Bartlett & James, 2011)."

Comment #5: "1st paragraph of results: This paragraph is entirely literature review and doesn't address findings from the research conducted in the manuscript"

Our response: We agree with the reviewer and remove the paragraph in the revised manuscript.

Comment #6: "Pg 17614 line 8-9: Provide some quantitative estimate of renewable fuel potential. I am skeptical about this point"

Our response: We agree that it may not be appropriate to state âĂŤ "utilizing biomass

from urban landscapes could significantly contribute to the nation's renewable energy needs." This sentence is removed. As request by the reviewer, we modified the next sentence to "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)". Please refer to Springer (2012) for details. Comment #7: "Pg 17614 last line: Commonly, urbanization leads to reduced tree longevity. Another sentence is warranted that note this discrepancy and provides some explanation."

Our response: We agree that the word "mortality rate" is misleading. In the revised manuscript, the word "turnover rate" is used instead. To provide further explanation, the sentence is modified into: ". . . 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."

Comment #8: "Figure 5 is almost completely redundant from Figure 1. I don't think both are needed."

Our response: We agree that Fig. 5 is almost completely redundant from Fig. 1. However, we think it is necessary to generalize the dominant factors that were identified in this study with a graphic framework. This is the most comprehensive analysis on the factors that may affect ecosystem carbon dynamics during urbanization, as we know. Therefore, in the revised manuscript, we replace the Fig. 1 with Fig. 5.

Comment #9: "Figure 6a,b are difficult to read with the seemingly random color map of staked bars."

Our response: In the revised manuscript, we used a table (Table 3) to replace the Fig. 6.

Please also note the supplement to this comment:

http://www.biogeosciences-discuss.net/10/C9501/2014/bgd-10-C9501-2014-supplement.zip

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Interactive comment on Biogeosciences Discuss., 10, 17597, 2013.