Effects of land use and cover change on terrestrial carbon stocks in urbanized areas: a study from Changzhou, China

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ARTICLE INFO

Article history:

Received 22 February 2014

Received in revised form

6 July 2014

Accepted 22 July 2014

Available online 2 August 2014

Keywords:

Carbon stocks

Land use and cover change

Soil sealing

Urbanization

ABSTRACT

Land use and cover change is the key factor affecting terrestrial carbon stocks and their dynamics not only in regional ecosystems but also in urbanized areas. Using the typical fast-growing city of Changzhou, China as a case study, this paper explored the relationships between terrestrial carbon stocks and land cover within an urbanized area. The main objectives were to assess variation in biomass and soil carbon stocks across terrestrial land covers with different intensities of urban development, and quantify spatial distribution and dynamic variation of terrestrial carbon stocks in response to urban land use and cover change. On the basis of accurate spatial datasets derived from a series of Landsat TM images during the years 1986 to 2011 and reliable estimates of urban biomass and soil carbon stocks using the InVEST model, our results showed that carbon stocks per unit area in terrestrial land covers decreased with increasing intensity of urban development. Urban land use and cover change and sealing of the soil surface created hotspots for losses in carbon stocks. Total carbon stocks in Changzhou decreased by about 30% during the past 25 years, representing a 1.5% average annual decrease. We suggested potential policy measures to mitigate negative effects of land use and cover change on carbon stocks in urbanized areas.

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1. Introduction

The impacts of urbanization extend over large areas even though the areal percentage of urban land in regional land cover matrices is typically quite small (Wade et al., 2009). Many aspects of environmental change at regional and global scales, including carbon dioxide emissions, have been attributed to urban areas (Flysjo et al., 2012; Seto et al., 2012; Castanheira and Freire, 2013; Hortenhuber et al., 2014). A large body of literature has been published on urbanization and its impact on carbon emissions from industrial energy use, transportation, household consumption, etc (Liu et al., 2011; Sun et al., 2014; Wang and Yang, 2014). Many of these studies have also addressed carbon accounting for anthropogenic components of urban areas such as buildings, landfills and urban road systems using Input-Output analyses, material flows and life cycle assessment (Dhakal, 2010; Guo et al., 2014).

On the other hand, urbanized areas have been found to foster and provide valuable ecosystem services such as carbon stocks in

natural pools that encompass urban biomass and soil (Strobbach and Haase, 2012). Whilst obviously small in relative magnitude compared to carbon emissions from fossil fuels consumption, the size of natural carbon pools nevertheless appears to be substantial (Davies et al., 2011; Liu and Li, 2012). This has been indicated by the results of a recent study from Churkina et al. (2010) showing that urban areas can store as much carbon per unit area as natural ecosystems across the conterminous United States, and more than 80% of this carbon is attributed to urban biomass and soil (i.e., only a small proportion of carbon is stored in anthropogenic pools). Churkina et al. (2010) have also suggested that in the coming decades, more terrestrial carbon stocks will be contained in human settlements, simply because urbanized areas are continuing to expand at an unprecedented rate. However, considering that biomass and soil carbon stocks vary across multiple land covers within urbanized areas, such rapid growth in urban carbon reservoirs driven by land use and cover change is often at the cost of even more severe reduction in carbon stocks from peri-urban and rural areas, which become the main cause of decreased carbon sequestration potential in regional ecosystems (Borjesson and Tufvesson, 2011; Hutyra et al., 2011a; Ponsioen and Blonk, 2012; Zhang et al., 2012). Therefore, land use and cover change can be

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another key factor affecting spatial distribution and dynamic variation of biomass and soil carbon stocks in urbanized areas. However, few studies have addressed this important issue compared to the large volume of literature on anthropogenic carbon pools and emissions from fossil fuels consumption.

Using the typical fast-growing city of Changzhou, China as a case study, this paper explores the relationships between terrestrial carbon stocks and land cover within an urbanized area. The main objectives are to (1) assess variation in biomass and soil carbon stocks across terrestrial land covers with different intensities of urban development, (2) quantify spatial distribution and dynamic variation of terrestrial carbon stocks in response to urban land use and cover change, and (3) discuss some measures for preservation of carbon stocks in urbanized areas.

2. Materials and methods

2.1. Study area

Changzhou is located in southern Jiangsu Province, on the upper Yangtze River Delta ($31^{\circ}09'–32^{\circ}04'N$, $119^{\circ}08'–120^{\circ}12'E$). It is characterized by flat landforms and warm cloudy weather typical of the northern subtropical monsoon climate zone. The cultivated

soils on its periphery are mainly paddy soil, and the major vegetation types are mid-subtropical evergreen and broadleaf forest and northern subtropical mixed stands of deciduous and evergreen forest with dominant species such as masson pine (*Pinus massoniana*), China fir (*Cunninghamia lanceolata*), oaks (*Quercus* spp.) and bamboos (*Phyllostachys* Sieb. et Zucc.). The area of Changzhou has expanded since the mid-1980s, from 187 km² in the 1980s to 1871 km² by the 2000s, which is now comprised of five municipal districts with Tianning, Zhonglou and Qishuyan districts in the urban center, and Xinbei and Wujin districts in peri-urban areas (Fig. 1).

2.2. Classification of land use and land cover

Primary data were derived from a series of Landsat TM images from 1986 to 2011 at a 30 m resolution. Other [supplementary data](#) included a 1:2000 topographic map and administrative maps provided by the Planning and Designing Institute of Changzhou for visual interpretation of land covers. The topographic map was used to differentiate hilly area from flat area in Changzhou. Typical land covers in the study area were classified as forest land (timbered hilly area), green open spaces (vegetated flat area), urban land and water area. We conducted a kappa test using historical land use

Fig. 1. Location of the study area showing (a) Jiangsu Province in eastern China, (b) Changzhou in southern Jiangsu Province, and (c) expansion of urban land in Changzhou from 1986 to 2011.

maps, ground-based reference information and random sampling to test the quality of the classification results. The kappa values averaged 0.82 for the six classified images. All of the values were greater than 0.7, which is the minimal requirement for a satisfactory classification.

2.3. Estimation of terrestrial carbon stocks in different land covers

Carbon stocks in terrestrial land covers were estimated using the InVEST (Integrated Valuation of Environmental Services and Tradeoffs) Carbon Storage and Sequestration model developed by the Natural Capital Project team (Daily et al., 2009; Tallis et al., 2013). For each land cover type, the model requires an estimate of the amount of carbon stored in the four basic carbon pools: aboveground and belowground biomass, litter layer and soil organic matter (Chan et al., 2006; Nelson et al., 2009; Goldstein et al., 2012; Qiu and Turner, 2013). The model then applies these estimates to the land use and land cover map to produce a map of carbon stocks in each grid cell and across the whole study area. The model is also applied to a historical land cover map and the current land cover map to calculate the net change in carbon stocks over time map unit by map unit, assuming that the only changes in carbon stocks are due to changes from one land cover to another (i.e., any grid cell that does not change its land cover will have a sequestration and loss value of 0 over time).

In this study, forest inventory data collected by the Agricultural and Forestry Bureau of Changzhou provided information on the area and distribution of various types of forest in forest land and green open spaces. Biomass carbon stocks per unit area in these types of forest were derived from the results of several local studies (WDC, 2006; Zhao et al., 2010; Cantarello et al., 2011). The estimated biomass carbon stocks in forest land and green open spaces were at some fixed storage level equal to the area-weighted average of reported storage levels of each type of forest within that land cover. A soil map covering the study area was also used (HWSD, 2008), and we summed soil organic carbon for the upper 100 cm in each grid cell and averaged by land cover to estimate soil carbon stocks in forest land and green open spaces.

Urban forest patches such as urban parks and green belts were classified as green open spaces in this study, while the urban land of Changzhou was covered by extensive impervious surfaces, on which biomass carbon stocks were negligible. To assess the impact of extensive impervious surfaces in urban land on soil organic carbon stocks, we incorporated the results of some recent studies from Zhao et al. (2012) and Raciti et al. (2012). According to their results, carbon stocks in soils under urban land averaged about 50% of the values in forest soils at different depths. This was probably

caused by removal of the topsoil during the development process and interrupted accumulation of organic carbon in sealed soils that led to both actual and potential losses in soil carbon stocks. We did not calculate carbon stored in water area, in which the InVEST model produced high uncertainty. As all estimates were drawn from empirical studies, we did not perform accuracy assessment for carbon stocks.

3. Results

3.1. Estimated biomass and soil carbon stocks in different land covers

Average carbon densities in terrestrial land covers were found to decrease with increasing intensity of urban development in the study area: forest land had 78.85 Mg C ha⁻¹, green open spaces had 73.82 Mg C ha⁻¹ and urban land had 25.23 Mg C ha⁻¹ (Table 1). The estimated carbon densities in soil organic matter averaged from 25.23 to 68.91 Mg C ha⁻¹ in different land covers, the greatest of the four basic carbon pools, followed by aboveground (3.18 to 18.87 Mg C ha⁻¹) and belowground biomass (1.42 to 5.88 Mg C ha⁻¹). Carbon stored in litter layer organic matter was the smallest component, only 0.31 to 3.54 Mg C ha⁻¹.

Despite distinct differences in biomass carbon stocks between forest land and green open spaces in the study area, the amount of carbon stored in forest soils was relatively small compared to soil carbon stored in green open spaces (Table 1). This was in part a result of forest structure mainly comprised of young and middle-aged trees, which resulted in restrained accumulation of organic carbon in forest soils. Conversely, irrigated paddy fields, which store a substantial amount of soil organic carbon, covered a large area of green open spaces, making them more abundant in soil carbon stocks than immature forests.

3.2. Effects of land use and cover change on carbon stocks from 1986 to 2011

According to the land use and land cover interpreted from remote sensing images, the urban land of Changzhou expanded rapidly from about 85 km² in 1986 to 800 km² in 2011, while the areal percentage of urban land in terrestrial land covers increased from about 5% to 50% during the same period. The area covered by green open spaces decreased from about 1500 km² (90%) in 1986 to 800 km² (50%) in 2011. This dramatic shift in land covers in the study area led to increased carbon stocks in urban land from 0.21 Tg C to 2.02 Tg C with average annual growth of 9.4%, and decreased carbon stocks in green open spaces from 11.16 Tg C to

Table 1

Biomass and soil carbon stocks (Mg C ha⁻¹) in terrestrial land covers derived from Landsat TM images in Changzhou. Carbon density values have been calculated on a basis of 27 studies undertaken in Changzhou (CZ), southern Jiangsu Province (SJ), Jiangsu Province (J), China (C) and worldwide (W).

Land covers	Aboveground carbon stocks (Mg C ha ⁻¹)			Belowground carbon stocks (Mg C ha ⁻¹)			Litter layer carbon stocks (Mg C ha ⁻¹)			Soil carbon stocks (Mg C ha ⁻¹)			Total carbon stocks (Mg C ha ⁻¹)			References ^a
	$\bar{X}$	$X_{\min}$	$X_{\max}$	$\bar{X}$	$X_{\min}$	$X_{\max}$	$\bar{X}$	$X_{\min}$	$X_{\max}$	$\bar{X}$	$X_{\min}$	$X_{\max}$	$\bar{X}$	$X_{\min}$	$X_{\max}$	
Forest land	18.87	15.08	21.95	5.88	4.70	6.84	3.54	2.50	3.72	50.56	40.02	63.51	78.85	62.30	96.02	1 ^{CZ} , 2 ^{CZ} , 3 ^{CZ} , 4 ^{SJ} , 5 ^{SJ} , 6 ^{SJ} , 7 ^C , 8 ^{SJ} , 9 ^{SJ} , 10 ^{CZ} , 11 ^C , 12 ^{SJ} , 13 ^{SJ} , 14 ^J , 15 ^J , 16 ^J
Green open spaces	3.18	2.84	3.45	1.42	1.32	1.50	0.31	0.22	0.33	68.91	48.30	75.91	73.82	52.68	81.19	1 ^{CZ} , 2 ^{CZ} , 3 ^{CZ} , 7 ^C , 8 ^{SJ} , 9 ^{SJ} , 10 ^{CZ} , 11 ^C , 17 ^{SJ} , 18 ^C , 19 ^C , 20 ^C , 21 ^{CZ} , 22 ^W , 23 ^J , 24 ^J , 25 ^J , 26 ^J
Urban land	0	\	\	0	\	\	0	\	\	25.23	17.59	36.04	25.23	17.59	36.04	10 ^{CZ} , 11 ^C , 12 ^{SJ} , 13 ^{SJ} , 14 ^J , 15 ^J , 16 ^J , 27 ^C

Values are mean ($\bar{X}$), minimum ($X_{\min}$) and maximum ($X_{\max}$). Literatures cited in the table are not listed in the "References" due to limited space and that most of these papers were published in Chinese journals (See Appendix A for Supplementary data).

^a 1. Tang et al., (2005); 2. Tang et al., (2009); 3. Zhang et al., (2011); 4. Wang et al., (2011); 5. Jiang et al. (2002); 6. Wu et al., (2002); 7. Fang et al., (1996); 8. Yang and Jiang (2001a); 9. Yang and Jiang (2001b); 10. HWSD (2008); 11. Zhou et al. (2000); 12. Wang et al., (2009); 13. Yang et al., (2009); 14. Chuai et al. (2011a); 15. Chuai et al. (2011b); 16. Chuai et al. (2012); 17. Lu et al., (2010); 18. Ye and She (2010); 19. Liu et al., (2000); 20. Wang et al., (2010); 21. WDC (2006); 22. Tallis et al. (2013); 23. Yang et al., (2006); 24. Zhang et al., (2011); 25. Chen et al., (2006); 26. Xue et al. (2006); 27. Zhao et al. (2012).

5.97 Tg C, an average annual decrease of 2.5% (Fig. 2a). Carbon stocks contributed by forest land were negligible, owing to the very small percent of area involved. We can infer that distinct differences in the amount of carbon stored per unit area between urban land and green open spaces led to net losses in carbon stocks (Fig. 3). Average estimated carbon densities in Changzhou decreased from 71.31 Mg C ha⁻¹ in 1986 to 49.88 Mg C ha⁻¹ in 2011, and total carbon stocks decreased by about 30% from 11.50 Tg C to 8.09 Tg C. Average annual decrease in carbon densities (1.49 Mg C ha⁻¹ yr⁻¹) and total carbon stocks (0.21 Tg C yr⁻¹) were the greatest during the past decade due to intensified urban land use and cover change.

3.3. Effects of land use and cover change on biomass and soil carbon stocks

Aboveground and belowground biomass carbon stocks decreased by about 45% from 0.78 Tg C to 0.43 Tg C, and soil carbon stocks decreased by about 30% from 10.71 Tg C to 7.66 Tg C during the study period (Fig. 2b). Despite the magnitude of losses in soil carbon stocks (0.04 to 0.22 Tg C yr⁻¹) that well exceeded losses in

biomass carbon stocks (0 to 0.03 Tg C yr⁻¹), average annual decrease in soil carbon stocks was only 0.3 to 2.6% compared to 0.5 to 5.1% annual losses in biomass carbon stocks (Table 2a). Although losses in soil carbon stocks were greater in Changzhou, urban land use and cover change disturbed to a greater extent in biomass carbon stocks.

3.4. Effects of land use and cover change on carbon stocks in the urban center and peri-urban areas

Average estimated carbon densities in the urban center were only 29.41 to 65.59 Mg C ha⁻¹ due to large areas of urban land, smaller than carbon densities (50.35 to 72.89 Mg C ha⁻¹) in peri-urban areas. Total carbon stocks in the urban center were 0.11 to 0.32 Tg C, much smaller than carbon stocks (2.41 to 7.50 Tg C) in peri-urban areas. Average annual decrease in carbon densities was 1.03 to 1.19 Mg C ha⁻¹ yr⁻¹ in the urban center compared to 0.70 to 0.88 Mg C ha⁻¹ yr⁻¹ in peri-urban areas from 1986 to 2011. Losses in total carbon stocks in the urban center were only 0 to 0.01 Tg C yr⁻¹, much smaller than losses in carbon stocks (0.03 to 0.09 Tg C yr⁻¹) from peri-urban areas (Table 2b). Although there

Fig. 2. Estimated carbon stocks from 1986 to 2011 in Changzhou. (a) Carbon stocks (Tg C) in terrestrial land covers. (b) Biomass and soil carbon stocks (Tg C). Both mean, maximum and minimum values of carbon stocks are shown in the figure.

Fig. 3. Maps of losses in carbon stocks (Mg C ha^{-1}) from urban land use and cover change in Changzhou from 1986 to 2011. Red areas and yellow areas show where green open spaces and forest land were replaced by urban land, respectively. Blue areas are transitional areas between land and water.

was an intensified decrease in carbon densities in the urban center, losses in total carbon stocks were much greater from peri-urban areas. Carbon stored in peri-urban areas was much more sensitive to urban land use and cover change than carbon stored in the urban center of Changzhou.

4. Discussion

4.1. Comparing estimated carbon stocks with other studies

Biomass carbon stocks in forest land of Changzhou (averaged $24.75 \text{ Mg C ha}^{-1}$) were comparable to those in the forest land of other cities in southern Jiangsu Province (21.23 to $21.56 \text{ Mg C ha}^{-1}$), indicating that our estimates were reliable and consistent with

already published studies (Zhao et al., 2010). On the other hand, our estimates of biomass carbon stocks were smaller than biomass carbon ($55.37 \text{ Mg C ha}^{-1}$) stored in a natural forest near to the study area (Zhao et al., 2010). This was not only because of forest structure mainly comprised of young and middle-aged trees, which resulted in restrained biomass of a single tree, but also because of reduced tree densities of the whole forest due to human disturbances such as forest harvesting in the study area.

4.2. Comparing losses in carbon stocks from land use and cover change and fossil fuels consumption

Average annual carbon emissions from fossil fuels consumption were calculated from statistical data provided by Changzhou

Table 2

Losses in carbon stocks from 1986 to 2011 in Changzhou. (a) Losses in biomass and soil carbon stocks (10^3 Mg C yr^{-1}). (b) Decrease in carbon densities (Mg C ha^{-1} yr^{-1}) in Tianning, Zhonglou and Qishuyan districts in the urban center, and Xinbei and Wujin districts in peri-urban areas. Values in the parentheses are (a) average annual decrease in carbon stocks (%), and (b) losses in carbon stocks (10^3 Mg C yr^{-1}).

(a)	Aboveground biomass carbon losses	Belowground biomass carbon losses	Litter layer carbon losses	Soil organic carbon losses	
1986–1991	–2.8 (–0.5)	–1.2 (–0.5)	–0.3 (–0.5)	–36.6 (–0.3)	
1991–1996	–7.3 (–1.5)	–3.2 (–1.5)	–0.7 (–1.5)	–112.0 (–1.1)	
1996–2001	–6.1 (–1.4)	–2.7 (–1.4)	–0.6 (–1.3)	–81.7 (–0.8)	
2001–2006	–13.1 (–3.3)	–5.8 (–3.3)	–1.3 (–3.1)	–162.7 (–1.8)	
2006–2011	–16.9 (–5.1)	–7.4 (–5.2)	–1.7 (–5.0)	–217.7 (–2.6)	
1986–2011	–9.2 (–2.4)	–4.1 (–2.4)	–0.9 (–2.3)	–122.1 (–1.3)	
(b)	Tianning district carbon losses	Zhonglou district carbon losses	Qishuyan district carbon losses	Xinbei district carbon losses	Wujin district carbon losses
1986–1991	–1.05 (–4.6)	–0.81 (–4.5)	–0.49 (–3.8)	–0.17 (–10.3)	–0.18 (–38.2)
1991–1996	–0.64 (–3.7)	–0.65 (–4.7)	–0.58 (–2.1)	–0.41 (–44.1)	–0.53 (–73.0)
1996–2001	–0.91 (–5.0)	–0.93 (–6.4)	–0.69 (–1.9)	–0.45 (–15.4)	–0.54 (–62.3)
2001–2006	–1.45 (–7.7)	–2.25 (–15.1)	–1.71 (–4.6)	–1.24 (–37.9)	–1.39 (–117.7)
2006–2011	–1.09 (–6.7)	–1.32 (–9.0)	–2.18 (–7.0)	–1.22 (–47.4)	–1.77 (–173.7)
1986–2011	–1.03 (–5.5)	–1.19 (–7.9)	–1.13 (–3.1)	–0.70 (–26.9)	–0.88 (–93.0)

Statistical Bureau, yielding a total of 73.92 Tg C from 1986 to 2011 with annual rates averaging 0.80 to 6.55 Tg C yr^{-1} . In contrast, losses in carbon stocks from land use and cover change during the same period were 3.41 Tg C, and annual rates were 0.04 to 0.24 Tg C yr^{-1} . Although losses in carbon stocks from land use and cover change amounted to about 4 to 8% of carbon emissions from fossil fuels consumption, this dramatic shift in land covers resulted in a decrease of about 30% in total carbon stocks during the past several decades. It is clear that urban land use and cover change is not only a driving force of urban carbon emissions, but also a key factor affecting carbon dynamics at citywide and regional scales and climate change at a global scale.

4.3. Limitations of the study

The results of monitoring and assessment of Changzhou's carbon dynamics in response to urban land use and cover change depend greatly on accuracy of Landsat image interpretation and reliability of estimation of carbon stocks (Muñoz-Rojas et al., 2011). This approach does not tend to provide with accurate absolute values but it is meaningful in relative terms allowing comparing biomass and soil carbon stocks in different land covers and quantifying losses in carbon stocks from urban land use and cover change. Limitations of the InVEST model used in this research include a simplified urban carbon cycle, the inability to estimate carbon stocks in water area (Tallis et al., 2013) and the resulting unknown carbon dynamics in the transitional areas between land and water (Fig. 3). In future research, it will be necessary to obtain a better description of the pattern of land covers, to obtain more accurate carbon storage values in these land covers during each time period, and to quantify gradient change in terrestrial carbon stocks in response to urban land use and cover change (Alberti and Hutrya, 2009; Hutrya et al., 2011b; Ren et al., 2011).

4.4. Implications of the results

In this study, we used the InVEST model to monitor and assess the effects of urban land use and cover change on spatial and temporal variation in terrestrial carbon stocks in Changzhou based on both accurate spatial datasets and reliable estimates of biomass and soil carbon stocks. We found that urban land use and cover change created hotspots for losses in carbon stocks (Fig. 3). Total carbon stocks in Changzhou decreased by about

30% in the past 25 years, an average annual decrease of 1.5%. As recent growth trends continued, the expansion of urban land markedly decreased areas previously dominated by green open spaces, making urban land use and cover change and losses in carbon stocks an increasingly important component of regional carbon dynamics.

Our results suggest potential policy measures to mitigate losses in carbon stocks from urban land use and cover change for Changzhou and other fast-growing cities in China. Impervious surfaces in existing urbanized areas such as parking lots, public squares and pavements can be replaced by vegetated surfaces (e.g., bricks with gaps between them that allow growth of herbaceous plants with belowground biomass stored in root system) to mitigate negative effects of soil sealing on accumulation of soil organic carbon. Roof gardens on top of buildings provide valuable places for distribution of limited urban green spaces, thereby greatly increasing urban biomass. On the other hand, legislation should be implemented to protect green open spaces and forest land and preserve soil carbon stocks from expansion of urban land in rapidly urbanizing areas. Green belts in these areas not only serve as buffer zones that help to control expansion of urban land, but also serve as the key components capable of storing large amounts of biomass carbon over time.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (No. 71273254, 71033005). The datasets used for estimating biomass and soil carbon stocks were provided by the Renewable Resources and Environmental Science Data Center for West China, Data Sharing Infrastructure of Earth System Science (<http://www.geodata.cn>), and by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (<http://westdc.westgis.ac.cn>). We thank Becky Stewart, a native English speaking scientific editor, for her constructive suggestions for correcting and polishing the manuscript.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jclepro.2014.07.055>.

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