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Effects of Forest Type and Urbanization on Carbon Storage of Urban Forests in Changchun, Northeast China

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Abstract: Rapid urbanization has led to dramatic changes in urban forest structures and functions, and consequently affects carbon (C) storage in cities. In this study, field surveys were combined with high resolution images to investigate the variability of C storage of urban forests in Changchun, Northeast China. The main objectives of this study were to quantify the C storage of urban forests in Changchun City, Northeast China and understand the effects of forest type and urbanization on C storage of urban forests. The results showed that the mean C density and the total C storage of urban forests in Changchun were 4.41 kg/m^2 and 4.74 × 10^8 kg, respectively. There were significant differences in C density among urban forest types. Landscape and relaxation forest (LF) had the highest C density with 5.41 kg/m^2, while production and management forest (PF) had the lowest C density with 1.46 kg/m^2. These differences demonstrate that urban forest type is an important factor needed to be considered when the C storage is accurately estimated. Further findings revealed significant differences in different gradients of urbanization, and the mean C density decreased from the first ring (6.99 kg/m^2) to the fourth ring (2.87 kg/m^2). The total C storage increased from the first ring to the third ring. These results indicate that C storage by urban forests will be significantly changed during the process of urbanization. The results can provide insights for decision-makers and urban planners to better understand the effects of forest type and urbanization on C storage of urban forests in Changchun, and make better management plans for urban forests.

Keywords: urban forest; carbon storage; carbon density; urbanization gradients; climate change

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1 Introduction

With the rapid development of urbanization, urban population has increased greatly in recent decades. It has been estimated that over half of the population in the world now are living in urban areas, and by 2050, 67.2% are expected to be urban dwellers (Davies *et al*., 2011; United Nations, 2012; Zhao *et al*., 2013). Urban areas have become 'the hot spots of global change' (Grimm *et al*., 2008; Strohbach and Haase, 2012). A great amount of carbon (C) emissions can be attributed to urban areas, which are mainly related to burning of fossil fuels, urban land use change and traffic and industrial production (Grimn *et al*., 2008; Satterthwaite, 2008; Kennedy *et al*., 2010; Chuai *et al*., 2013; Zhang *et al*., 2013; Yang *et al*., 2014).

Urban forests act as an important sink for CO_2 by fixing C during photosynthesis and storing C as biomass

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(Nowak and Crane, 2002; Nowak *et al*., 2013). Furthermore, urban forests help to reduce the energy used for cooling and heating, resulting in the reduction of C emissions from power plants (McPherson, 1998). Because of the important roles in mitigating climate change, urban forests are gradually receiving more attention. Since the 1990s, the C storage by urban forests in major US cities has been assessed by Urban Forest Effects (UFORE) model (Nowak, 1993; Nowak and Crane, 2002). In China, the UFORE model was adopted in Beijing to analyze the total C storage by urban forests (Yang *et al*., 2005). Additional studies have also been conducted in cities of several countries by field survey data or other methods, such as Australia (Brack, 2002), Korea (Jo, 2002), British (Davies *et al*., 2011), Germany (Strohbach and Haase, 2012) and China (Zhao *et al*., 2010; Wang *et al*., 2013). However, along with the high resolution images were used and more urban C density measurements were derived, there was a growing echo that urban biological C storage deserve further investigation, as they were more substantial than previously assumed (Davies *et al*., 2011; Hutyra *et al*., 2011; Nowak *et al*., 2013). There is increasing evidence that high resolution images can provide improved accuracy and higher precision for acquiring urban forest cover and calculating C storage (Liu and Li, 2012; Strohbach and Haase, 2012; Pasher *et al*., 2014). Because of the difference in habitat and management of types of urban forests, there might have significant varieties in the calculation of C storage. Previous researches were primarily concentrated on quantifying the C storage of a city, whereas the effects of urban forest type on C storage were not sufficient (Liu and Li, 2012).

China has experienced the highest rate of urban expansion since the 1980s (Seto *et al*., 2011). The urbanization rate increased from 17.9% to 51.3% during the period of 1978–2011, doubled the world average rate (United Nations, 2012). The urban population percentage was 17% in 1987 and reached 50% in 2010 (Ren *et al*., 2011), and it will be higher than the world average in the future (Wu *et al*., 2014). The urban area has increased by 2.31 times over the past two decades (Wang *et al*., 2012, Luo *et al*., 2014). However, the effects of urbanization on the spatial distribution of C storage of urban forests remain poorly understood (Hutyra, 2011; Ren *et al*., 2011). Further studies are urgently needed to clarify the effect of urbanization on C storage by urban forests because of the differences in regional urbanization level (Zhang *et al*., 2008; Dobbs *et al*., 2011; Ren *et al*., 2011; Davies *et al*., 2013). Changchun City in Northeast China is a typical city which has undergone rapid and sprawling urbanization over the past decades. The urban population and urban expansion have accelerated notably in recent decades (Huang *et al*., 2009b; Li *et al*., 2012). Understanding the spatial distribution of C storage of urban forests in Changchun and its relationship with urbanization are critical for planning a low-C and sustainable city. The main objectives of this paper are to: 1) quantify the aboveground C storage and C density of urban forests in Changchun; 2) discuss the differences in C storage and C density among types of urban forests and gradients of urbanization.

2 Materials and Methods

2.1 Study area

Changchun is the capital city of Jilin Province in Northeast China. Its urban population and urban expansion have accelerated notably in recent decades. The main urban area had increased from 117 km^2 to 365 km^2, and the population had increased from 2.20×10^6 to 3.62×10^6 during the period of 1994–2010 (Huang *et al*., 2009a; 2009b; Li *et al*., 2012). The city expanded out mainly in the form of concentric ring roads. The climate is a continental monsoon climate of North Temperate Zone with distinct seasons and rain, wet moderate climate characteristics (Ren *et al*., 2013). The average annual temperature is 4.8℃ and the average annual precipitation is 522–615 mm. The forest land types are mainly composed of coniferous forest and deciduous broad-leaved forest. The study area (43°42′–44°03′N, 125°09′–125°27′E) is primarily within the fifth ring road of Changchun, with an area of 524.06 km^2 (Fig. 1).

2.2 Urban forest classification and forest cover area estimation

Urban forests were classified into five types based on their location, function and management objectives (He, 2004). These five types were: 1) road forest (RF): trees along railroads, highways, boulevards, roads, and streets for protecting, guiding the traffic and improving the environment; 2) attached forest (AF): trees next to buildings in school yards, campuses, hospitals, commercial and business districts, industrial areas and residential areas to offer entertainment space and improve the

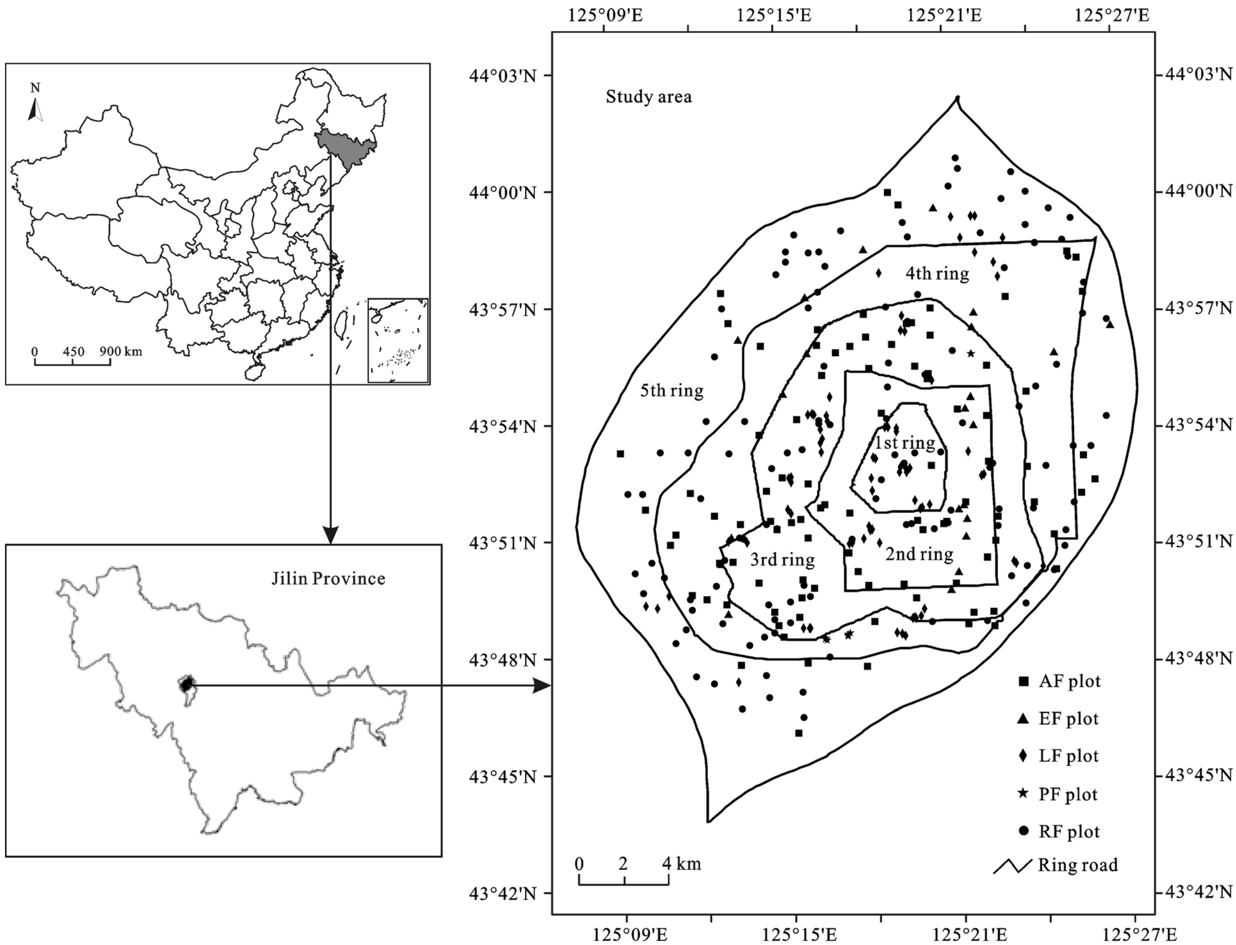

Fig. 1 Location of study area and sampling plots. RF, road forest; AF, attached forest; LF, landscape and relaxation forest; EF, ecological and public welfare forest; PF, production and management forest

quality of living and working environment; 3) landscape and relaxation forest (LF): trees in the public parks, forest parks, historic sites, and scenic areas for landscape and relaxation purposes; 4) ecological and public welfare forest (EF): trees planted as windbreaks, to prevent soil erosions, to prevent from flood, to protect watersheds, and to reduce pollutions or noises; and 5) production and management forest (PF): trees in the nurseries, orchards, plantations, and wood-lands for commercial purposes (He, 2004; Liu and Li, 2012). Urbanization gradients were defined by different ring roads based on the development process of Changchun from the first ring to the fifth ring. Spot-5 data were taken at 10:25 a.m. local time on September 14, 2010 with a spatial resolution of 2.5 m. The data were first re-projected to Transverse Mercator coordinate system and geo-rectified based on 127 control points in ENVI 4.8 (Exelis VIS). Different types of urban forests cover were extracted from the images by manual visual interpretation method and then calculated in ArcGIS 10.0 (ESRI). In addition, the Google Earth images as the assistant image were used to identify the small forest patches.

2.3 Field survey

A stratified random sampling method was adopted to allocate the plot numbers (Nowak *et al.*, 2003). The plot number of each forest type was determined according to its forest coverage (Liu and Li, 2012). Field surveys were conducted from July to October, 2012. Each plot was 400 m^2. The regularly shaped plots were 20 m wide and 20 m long. For the irregularly shaped plots, we adjusted the plot width and length to cover an area of 400 m^2. With a total of 331 plots surveyed, which included 123 plots for RF, 96 plots for AF, 80 plots for LF, 20 plots for EF, and 12 plots for PF (Fig. 1). Meanwhile, more than 10 plots were surveyed for each urban forest type, which met the standards according to Nowak *et al.*

(2003). For each plot, the height and canopy of shrubs were measured. Trees whose diameter at breast height (DBH) higher than 2 cm were measured at 1.3 m above-ground level, height, under branch height (UNB), canopy size (CA) and health condition of each measured tree were recorded.

2.4 Biomass calculation and carbon storage estimation

Aboveground dry-weight biomass was estimated for each surveyed woody plant using biomass allometric growth equations obtained from the literatures (Table 1). These equations were geographically approximate to our study area (Liu and Li, 2012). If no species-specific allometric equation could be found, an equation for the species affiliated to the same genus or the same family was used (Davies *et al*., 2011). If no equations were found for a genus or a family, a generalized equation derived from the literature was used (Wang, 2006; Li *et al*., 2010; Liu and Li, 2012). Urban trees tend to have less aboveground biomass than trees in a natural forest because of pruning and maintenance and the biomass estimate was multiplied by a factor of 0.8 (Nowak *et al*., 1993). The individual tree biomass was converted to C by multiplying by a factor of 0.5 (Nowak and Crane, 2002; Escobedo *et al*., 2011).

The mean C density and total C storage were calculated as the following equations (1) and (2):

$$CD_i = \frac{\sum_{j=1}^{n} \frac{C_{ij}}{\mathrm{PA}}}{n} \tag{1}$$

$$TCS = \sum_{i=1}^{m} CD_i \times FC_i \tag{2}$$

where CD_i is the average C density for the ith type of urban forests; C_{ij} is the C storage for the jth sample plot at the ith type of urban forests; PA is the plot area which equals to 400 m^2 in this study; n is the plot number for the ith stratum; TCS is the estimated total C storage; m is the number of the stratum; and FC_i is the ith stratum forest cover.

Spatial distribution of C density and C storage were quantified and mapped in ArcGIS 10.0 software. The study area was divided into 2 km × 2 km grid squares. The C storage of each grid equals to the average C density multiplied by the forest cover of the grid.

2.5 Statistical analysis

The Kruskal-Wallis test (a non-parametrical analogous test) followed by the Nemenyi test were used to examine the differences in carbon storage between urban forest types and between different urbanization gradients. Data statistical analyses were performed using SPSS (version 19.0) and MS Excel (Microsoft, Redmond, WA).

3 Results

3.1 Urban forest cover

In the study area, the total urban forest cover was 106.81 km^2, which accounted for 20.38% of the total land area (Table 2). As for the different urban forest types, AF had the highest area (45.81 km^2), followed by RF (24.24 km^2), EF (19.44 km^2), LF (14.01 km^2) and PF (3.31 km^2), respectively (Table 2). Of the different urbanization gradients, the total forest cover gradually increased from the first ring to the fourth ring, but decreased slightly in the fifth ring. The rates of urban forest cover were 29.68% (third ring), 26.60% (second ring), 26.39% (forth ring), 22.07% (first ring) and 11.14% (fifth ring) of the total land cover, respectively (Table 2).

3.2 Carbon storage of species

In this study, 7778 woody plants were surveyed with 6746 trees and 1032 shrubs. The 88 species were identified, with 66 species of trees and 22 species of shrubs, which belonged to 50 genera and 24 families. The most dominant four species with abundance from high to low were *Salix matsudana*, *Populus davidiana*, *Pinus sylvestris* var. *mongolica* and *Picea asperata*.

Based on the surveyed data, a large proportion of C was stored in trees. The *P. davidiana* had the highest C storage (18.14%), followed by *S. matsudana* (12.45%), *Armeniaca mandshurica* (9.55%), *Amygdalus davidiana* var. davidiana (7.81%), *Prunus ussuriensis* (7.35%) and *Pinus tabulaeformis* var. *mukdensis* (5.29%) (Fig. 2). The six species accounted for 60.59% of the total C storage. Additionally, there 68 species stored C less than 5 × 10^3 kg which accounted for 11.96% of the total C storage.

3.3 Carbon storage of different types of urban forests

Great varieties were observed in C density and C storage of different types of urban forests. The results of the

Table 1 Dry biomass equations for species, and tree and shrub generalized equations

	Allometric growth equation				Reference
Pinus tabulaeformis	$B_{ag} = B_s + B_b + B_l$	$B_s = 0.11 \times D^{2.34}$	$B_b = 0.01 \times D^{2.58}$	$B_l = 0.0049 \times D^{2.48}$	(Liu and Li, 2012)
Ulmus	$B_{ag}=B_s + B_b + B_l$	$B_s = 0.043 \times D^{2.87}$	$B_b = 0.0074 \times D^{2.67}$	$B_l = 0.0028 \times D^{2.50}$	(Liu and Li, 2012)
Robinia pseudoacacia	$B_{ag} = B_s + B_b + B_l$	$B_s = 0.069 \times D^{2.54}$	$B_b = 0.068 \times D^{1.89}$	$B_l = 0.0015 \times D^{3.26}$	(Liu and Li, 2012)
Picea asperata	$B_{ag} = B_s + B_b + B_l$	$B_s = 0.057 \times D^{2.48}$	$B_b = 0.012 \times D^{2.41}$	$B_l = 0.083 \times D^{2.37}$	(Liu and Li, 2012)
Betula platyphylla	$B_{ag} = 0.1442 \times D^{2.367}$				(Wang, 2006)
Populus	$B_{ag} = 0.067 \times D^{2.558}$				(Wang, 2006)
Pinus koraiensis	$B_{ag} = 0.172 \times D^{2.144}$				(Wang, 2006)
Larix gmelinii	$B_{ag} = 0.0948 \times D^{2.451}$				(Wang, 2006)
Acer	$B_{ag} = 0.0851 \times D^{2.535}$				(Wang, 2006)
Fraxinus	$B_{ag} = 0.1368 \times D^{2.408}$				(Wang, 2006)
Juglans mandshurica	$B_{ag} = 0.1718 \times D^{2.287}$				(Wang, 2006)
Phellodendron amurense	$B_{ag} = 0.0875 \times D^{2.332}$				(Wang, 2006)
Tilia	$B_{ag} = 0.0404 \times D^{2.668}$				(Wang, 2006)
Quercus mongolica	$B_{ag} = 0.1005\times D^{2.456}$				(Wang, 2006)
Pinus sylvestris var. *sylvestriformis*	$B_{ag} = B_s + B_b + B_l$	$B_s = 0.0159 \times D^{2.949} + 0.6301 \times D^{0.759}$	$B_b = 0.0558 \times D^{2.483}$	$B_l = 0.0001 \times D^{4.293}$	(Zou *et al*., 1995)
Pinus sylvestris var. *mongolica*	$B_{ag} = B_s + B_b + B_l$	$B_s = 0.0439 \times (D^2H)^{0.8852}$	$B_b = 0.0239 \times D^{4.1912}H^{-2.3076}$	$B_l = 0.1082 \times D^{2.7169}H^{-1.3955}$	(Jia *et al*., 2008)
Platycladus	$B_{ag} = B_s + B_b + B_l$	$B_s = 131.37 \times (D^2H)^{0.5969} + 36.32 \times (D^2H)^{0.6758}$	$B_b = 27.40 \times (D^2H)^{0.5973} + 49.65 \times (D^2H)^{0.5975} + 5.51 \times (D^2H)^{0.5879}$	$B_l = 37.87 \times (D^2H)^{0.5976}$	(Chang *et al*., 1997)
Rosaceae	$B_{ag} = 0.2159 \times D^{1.7041}$				(Wu *et al*., 2012)
Tree generalized equation	$B_{ag} = 0.0881 \times D^{2.467}$				(Wang, 2006)
Philadelphus schrenkii	$B_{ag} = 0.0345 \times H^{2.51}$				(Li *et al*., 2010)
Lonicera	$B_{ag} = 0.1808 \times CA^{1.395}$				(Li *et al*., 2010)
Spiraea salicifolia	$B_{ag} = 0.0930 \times CAH^{0.912}$				(Li *et al*., 2010)
Shrub generalized equation	$B_{ag} = 0.1007 \times CAH^{0.925}$				(Li *et al*., 2010)

Notes: B_{ag} is the aboveground biomass for the whole woody plant (kg); B_s, B_b and B_l are biomass for stem, branch, leaf, respectively; D is the diameter at breast height (cm); H is the height (m); CA is the canopy area (cm^2)

Table 2 Cover of different types and urbanization gradients of urban forests

Area (km^2)	First ring	Second ring	Third ring	Forth ring	Fifth ring	Total area
RF	0.45	1.69	5.20	5.17	11.72	24.24
AF	1.48	7.48	17.62	10.71	8.52	45.81
LF	1.69	2.90	4.35	2.71	2.35	14.01
EF	–	2.38	1.40	13.32	2.35	19.44
PF	–	–	0.92	2.40	–	3.31
Total forest cover	3.62	14.46	29.48	34.31	24.94	106.81
Total land cover	16.41	54.35	99.32	130.01	223.97	524.06
Rate of forest cover (%)	22.07	26.60	29.68	26.39	11.14	20.38

Notes: RF, road forest; AF, attached forest; LF, landscape and relaxation forest; EF, ecological and public welfare forest; PF, production and management forest

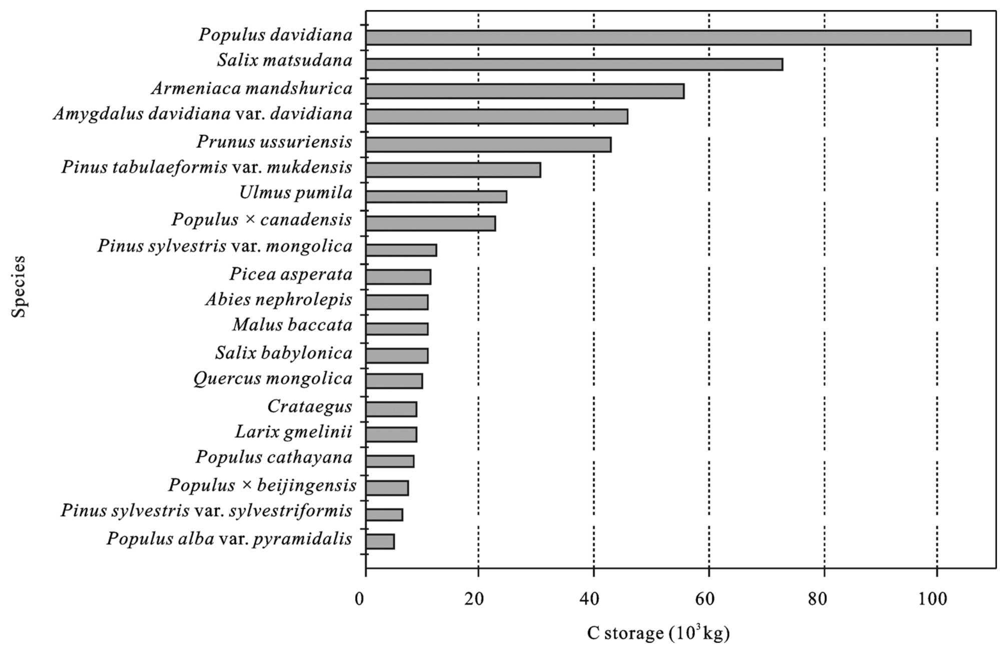

Fig. 2 Species carbon (C) storage higher than 5×10^3 kg

mean C densities for urban forest types showed that LF had the highest mean C density with 5.41 kg/m^2, and PF had the lowest mean C density with 1.46 kg/m^2. Significant differences in mean C density were found between PF and other types of urban forests ($P < 0.05$) (Fig. 3a). Moreover, there were significant differences in C density among urban forest types in the fourth and the fifth ring (Fig. 4). In the fourth ring, the C density of AF and RF were significantly higher than that of PF. In the fifth ring, the C density of EF was significantly higher than that of RF and LF ($P < 0.05$) (Fig. 4). As for the total C storage of types of urban forests, AF had the highest C storage with 2.16×10^8 kg, followed by RF (9.21×10^7 kg), EF (8.45×10^7 kg), LF (7.58×10^7 kg) and PF (4.85×10^6 kg), which accounted for 45.66%, 19.45%, 17.85%, 16.01% and 1.02% of the total C storage, respectively (Fig. 3b).

3.4 Carbon storage of gradients of urbanization

Significant differences ($P < 0.05$) in mean C density were found among gradients of urbanization (Fig. 3c). The mean C density decreased from the first ring to the fourth ring with the value from 6.99 kg/m^2 to 2.87 kg/m^2, and then slightly increased to 3.22 kg/m^2 at the fifth ring (Fig. 3c). The C densities from the first to third ring were significant higher than that in the fourth and fifth ring ($P < 0.05$). Comparing the C density in the same forest type of the different ring, the mean C density of LF in the first ring was significant higher than that in other rings ($P < 0.05$), but the mean C density of EF in the third ring was significant higher than that in the fourth ring ($P < 0.05$) (Fig. 4). And there were no significant differences for other types of urban forests in the different rings ($P < 0.05$) (Fig. 4). As the estimated C storage, the third ring had the highest value of 1.41×10^8, followed by the fourth ring (9.85×10^7 kg) and fifth ring (8.03×10^7 kg), the first ring had the lowest value of 2.53×10^7 kg (Fig. 3d).

High spatial heterogeneity in C density and C storage were observed across the city (Fig. 5). The mean C density was 4.41 kg/m^2 of all plots. The highest C density grids with the value of 6.71–12.92 kg/m^2 were mainly

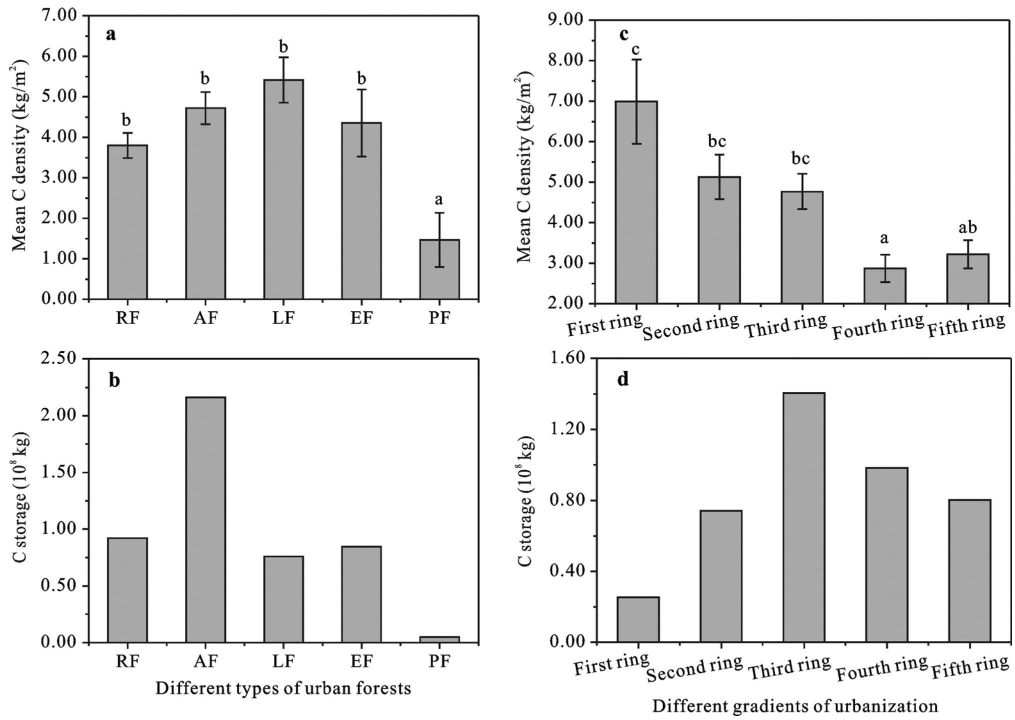

Fig. 3 Carbon (C) density and estimated C storage of different types of urban forests and among gradients of urbanization. Values of C density are means ± standard errors (SE). Means with different letters were significantly different. RF, road forest; AF, attached forest; LF, landscape and relaxation forest; EF, ecological and public welfare forest; PF, production and management forest

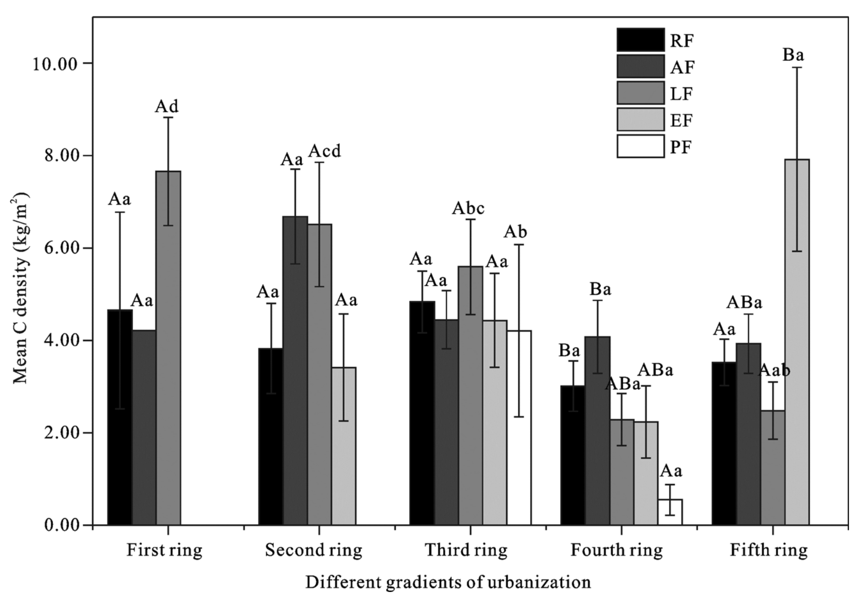

Fig. 4 Mean (±SE) carbon (C) density of different forest types in different urbanization gradients. Means with different letters were significantly different. The capital letter was for different forest types in the same ring, and the lowercase letter was for the same forest type in the different ring. RF, road forest; AF, attached forest; LF, landscape and relaxation forest; EF, ecological and public welfare forest; PF, production and management forest

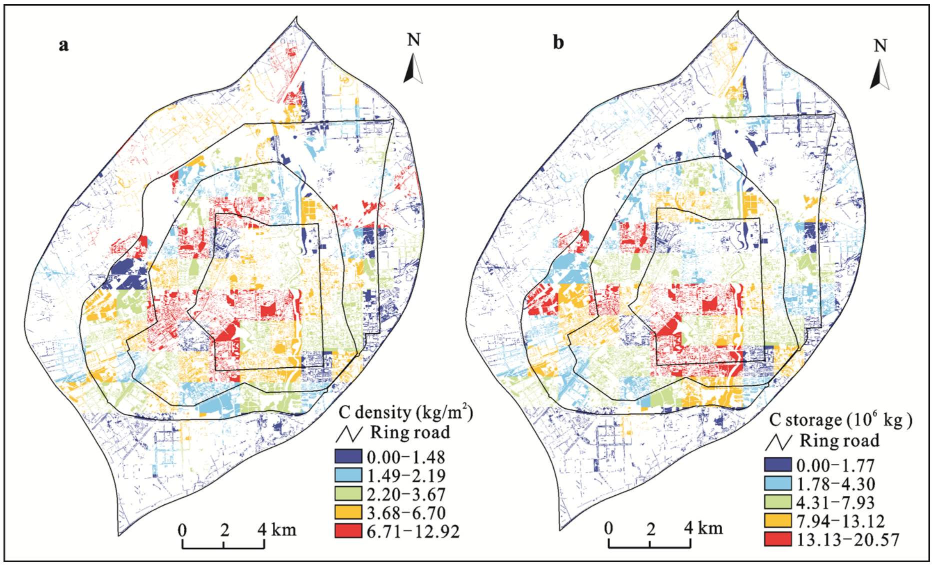

Fig. 5 Spatial distribution of carbon (C) density (a) and C storage (b). The study area was divided into 2 km × 2 km grid squares in ArcGIS 10.0 software, and C storage equals to the average C density multiply by the forest cover of each grid

distributed around the urban parks (Fig. 5a). The estimated total C stored in urban forests across Changchun was about 4.74×10^8 kg. The highest C storage grids with the value of 13.13×10^6–20.57×10^6 kg mainly distributed around the Nanhu Park and in the western part of the third ring and fourth ring (Fig. 5b).

4 Discussion

4.1 Effect of urban forest type on carbon storage

Our results indicated that there were large differences in C density and C storage among different types of urban forests. Liu and Li (2012) found that AF had the highest C density, followed by RF, LF, EF and PF, respectively. In our study, LF, had the highest C density, followed by AF, EF, RF and PF (Fig. 3a). The difference could be attributed to the urban forest structures in different cities. In Shenyang City, Liaoning Province, AF had the highest C density because of its more big trees than other types of urban forests (Liu and Li, 2012). In Changchun, the higher mean density of woody plants and DBH for LF and AF may be the important factors resulted in their higher C density (Table 3, Fig. 3a). The EF had a lower C density than LF and AF because of its uneven distributed DBH and the high standard errors (Table 3, Fig. 3a). Although RF had the highest mean DBH, the relative lower mean density of woody plants contributed to its lower C density (3.80 kg/m^2). The PF had the similar mean density of woody plants with RF, but it had the lowest C density with only 1.46 kg/m^2. This was mainly a result from the lowest mean DBH (Fig. 3a, Table 3).

Forest cover area was the important factor that contributed to the differences of C storage. The results of Liu and Li (2012) showed that EF had the highest C storage, followed by AF, LF, RF, and PF, which had the same trend with the forest cover area of different types of urban forests. In our study, AF had the highest C storage, followed by RF, EF, LF, and PF. This also had the same trend with their forest cover (Table 2, Fig. 3b).

Table 3 Structure characteristics of different types of urban forests

Forest type	No. of plot	No. of woody plant	Mean density (No. of woody plant/ha)	Mean DBH (cm)	Mean height (m)
RF	123	2436	495 (35)	19.77 (0.95)	7.26 (0.34)
AF	96	2508	653 (33)	14.11 (0.53)	5.99 (0.32)
LF	80	2122	663 (30)	15.35 (0.66)	7.44 (0.35)
EF	20	445	624 (118)	18.24 (2.47)	8.79 (0.96)
PF	12	267	444 (124)	8.53 (1.66)	4.59 (0.85)

Notes: Standard errors are given in parentheses. RF, road forest; AF, attached forest; LF, landscape and relaxation forest; EF, ecological and public welfare forest; PF, production and management forest

The above results indicated that forest structures and forest cover were the most important factors that affected the C storage of different urban forest types.

4.2 Effect of urbanization on carbon storage

The rapid development of urbanization has greatly affected the spatial distribution of urban forests, which has consequently affected their structures and C storage (Ren *et al*., 2012). Humans are largely responsible for altering and designing the urban forests and influencing the carbon storage (Strohbach and Haase, 2012). In arid regions, urbanization can increase carbon storage due to urban dwellers efforts in planting and irrigating shade trees (Golubiewski, 2006). In humid areas, urbanization has negative effect on forests and therefore reduces carbon storage (Imhoff *et al*., 2004). The results of the study on Xiamen City showed that the C storage increased from the city center (5%) to the suburbs (23%) (Ren *et al*., 2011). In our study, the C density in the city center was significantly higher than that in the fourth ring and the fifth ring. The total C storage decreased in the fourth ring and the fifth ring (Fig. 3d). This can be mainly attributed to the lower mean C density of the fourth ring and the fifth ring (Fig. 3c). During the process of urbanization in the study area, new green infrastructures keep up with the urban development. However, the newly planted woody plants are so young that the average DBH decreases from the first ring to the fourth ring (Table 4). These contributed to the gradually decreased C density (Fig. 3c). Meanwhile, the fifth ring belongs to the suburbs with a majority of remained farmland shelterbelt forest, which is the reason for the higher C density than that in the fourth ring. Planting trees of native species with fast-growth rates may further improve the capacity of C sequestration of urban forests (Liu and Li, 2012), especially in the fourth ring and the fifth ring where the forest cover rates were low. The results suggested that the process of urbanization had a great influence on the C storage changes of urban forests. Along with the growth of urban forest, it will play a pivotal function of C sink in the future.

4.3 Comparison of carbon density and carbon storage with other cities

Compared with other studies in China, the mean C density of Changchun was higher than that of Shenyang with 3.32 kg/m^2 (Liu and Li, 2012), Beijing with 4.37 kg/m^2 (Yang *et al*., 2005), Hangzhou City with 3.03 kg/m^2 (Zhao *et al*., 2010), and Xiamen with 2.08 kg/m^2 (Ren *et al*., 2011). Moreover, compared with the cities of other countries, the two cities of Seattle (8.9 kg/m^2) and Sacramento (4.69 kg/m^2) had a higher C density than Changchun (Nowak and Crane, 2002; Hutyra *et al*., 2011). Although the forest cover of Shenyang was higher than that of Changchun, the factor that affects C density may be the tree DBH distribution. Changchun has fewer small trees (DBH < 7.6 cm, approximately 18%) (Fig. 6) than that in Shenyang (DBH < 7.6 cm, nearly 50%) (Liu and Li, 2012). Seattle had a high C density may be on account of its high mean tree cover of 57% (Hutyra *et al*., 2011). And urban forest cover of Sacramento was only 13% but had a very high C density, which is primarily a reason of the unusually large structural diameter with approximately 10% of the trees having a DBH higher than 76 cm (McPherson, 1998; Nowak *et al*., 2013). Therefore, the differences in C density are mainly due to the different structures of the urban forests (Liu and Li, 2012).

In recent years, more and more studies on C storage of urban forests have been conducted. In terms of C estimates, because of the various approaches and an inconsistent definition of urban, it is difficult to compare the results between different cities (Raciti *et al*., 2012; McPherson *et al*., 2013). The study of Hangzhou

Table 4 Structure characteristics of urban forests among different gradients of urbanization

Gradient	No. of plot	No. of woody plant	Mean density (No. of woody plant/ha)	Mean DBH (cm)	Mean height (m)
First ring	25	579	579 (56)	19.03 (1.47)	7.96 (0.62)
Second ring	50	1084	542 (45)	18.33 (1.08)	8.70 (0.61)
Third ring	106	2788	658 (38)	15.89 (0.81)	6.39 (0.28)
Fourth ring	71	1574	554 (40)	14.08 (0.94)	5.95 (0.38)
Fifth ring	79	1753	555 (45)	17.70 (1.12)	7.06 (0.43)

Notes: Standard errors are given in parentheses. RF, road forest; AF, attached forest; LF, landscape and relaxation forest; EF, ecological and public welfare forest; PF, production and management forest

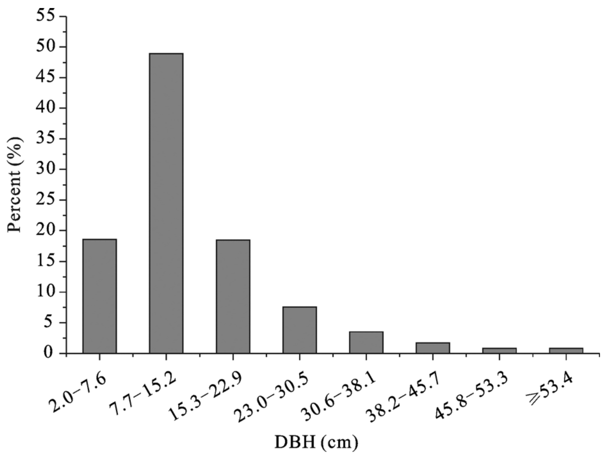

Fig. 6 Diameter at breast height (DBH) of trees in study area

contains the metropolitan area, surrounding cities, districts and counties. The total study area is 16 900 km^2 and the C storage is 1.17 × 10^{10} kg (Zhao *et al*., 2010). The central city of Beijing contains the four city districts plus parts of four suburban districts, which is approximately 300 km^2, and the C storage is 2 × 10^8 kg (Yang *et al*., 2005). In our study, the study area is 524.06 km^2 within the fifth ring road, and the estimated total C stored in urban forests was about 4.74 × 10^8 kg. Therefore, to understand how and why C storage varies within and between cities, researchers need to use more uniform methods to estimate C storage and define the urban border to facilitate comparisons (David *et al*., 2013; McPherson *et al*., 2013).

5 Conclusions

In this study, the C storage of species was assessed and the effects of forest type and urbanization on C storage of urban forests were analyzed. It was found that the mean C density with the value of 4.41 kg/m^2 in Changchun was higher than those in other cities of China, and *P. davidiana*, *S. matsudana* and *A. mandshurica* were the three species with the largest C storage. The results indicated that planting trees of native species with fast-growth rates may further improve the capacity of C sequestration of urban forests. In addition, the large differences in C density and C storage among different types of urban forests indicated that reasonable planning and management of urban forests can improve the urban C storage. The urban forests need more careful attention and management to maintain a healthy condition, especially trees in suburbs. The significant differences in C density and C storage along the urbanization gradient indicate the vital role of urbanization effects on the urban forest C storage. The lower forest cover and C density of the fourth ring and the fifth ring suggested the huge potential to increase C storage. Furthermore, lacking of biomass equations for urban trees is always a big limitation when calculating C storage. Future research is needed to develop species biomass equations for urban trees.

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