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Carbon Storage and Sequestration of Urban Street Trees in Beijing, China

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Anthropogenic carbon dioxide (CO_2) emissions from cities have significantly increased over the past several decades along with rapid urbanization. To what extent anthropogenic CO_2 emissions generated from cities can be offset through conserving or increasing carbon (C) stored within urban areas themselves is a significant scientific question. The role of urban street trees in offsetting anthropogenic CO_2 emissions still remains uncertain. Here, using data from field surveys, tree growth measurements, and governmental statistical yearbooks, we estimated the C storage and C sequestration capacity of street trees in Beijing. Results showed that the C density and C sequestration rate in Beijing's urban street trees were about 1/3∼1/2 of the corresponding magnitudes of non-urban forests in China. However, the total C sequestration of street trees in Beijing's urban districts was 3.1 ± 1.8 Gg C yr^{-1} (1 Gg = 10^9 g) in 2014, equivalent to only about 0.2% of its annual CO_2-equivalent emissions from total energy consumption, indicating a rather limited role in offsetting overall anthropogenic CO_2 emissions.

Keywords: urbanization, carbon cycle, urban vegetation, tree benefits, urban sustainability

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INTRODUCTION

More than half of the world's population now lives in urban areas, and this figure will continue to increase at a rate of 4% a decade by 2050 (UN, 2015). In China, urban population has grown from 17.4 to 53.7% between 1975 and 2013, and is expected to reach 60% by 2030 (SSB, 2014; UN, 2015). Fast urbanization imposes grand societal and environmental challenges such as compromised human health (Gong et al., 2012), alteration of local and regional climate (Chrysanthou et al., 2014; Zhou et al., 2014), loss of natural habitats and biodiversity (Alberti, 2005; Seto et al., 2012) and degradation of water and air quality (Zhao et al., 2006; Young et al., 2012). It is long and widely believed that forest patches in urban areas provide many ecological and social benefits, which partly mitigate urbanization-caused deterioration of the environment (Sanders, 1986; Akbari and Konopacki, 2004; Lohr et al., 2004; Nowak et al., 2013a, 2014). Nevertheless, those benefits might be overstated and potential costs are not clearly quantified (Pataki et al., 2011; Whitlow et al., 2014). Thus, more studies are needed to accurately assess each ecosystem service provided by urban forests and clearly communicate the scientific findings.

Cities are responsible for ∼75% of global anthropogenic carbon dioxide (CO_2) emissions (Seto et al., 2014). An interesting research topic is to quantify and understand the role of conserving or increasing carbon (C) stored within urban areas themselves in offsetting anthropogenic CO_2 emissions generated from cities. In recent decades, there has been much research conducted to quantify the C sequestration of urban forests (Abdollahi et al., 2000; Nowak and Crane, 2002; Pataki et al., 2006; Zhao et al., 2013; Raciti et al., 2014). For example, Davies et al. (2011) found that a substantial amount of carbon was stored within aboveground vegetation in Leicester, United Kingdom, and that trees account for more than 95% of this carbon pool. In some regions, especially arid areas, urban forests may store more carbon than adjacent suburban and rural areas, as a result of tree planting and urban greenspace management (McHale et al., 2009a). A few studies also suggest that vegetation carbon density and carbon accumulation rate in urban forests can be larger than that of adjacent natural forests (Davies et al., 2011; Hutyra et al., 2011). Therefore, accurate quantification of the C storage in various urban forests is critical to improve our understanding of the role of urban green space in the urban carbon balance. In addition, cities experience elevated temperature (i.e., urban "heat island" warming), CO_2 and nitrogen deposition, and are usually intensively managed relative to rural settings (Carreiro and Tripler, 2005; Churkina et al., 2015). These drastic differences between urban and natural systems suggest that characterizing C dynamics of urban forests is an important component of the carbon cycle science.

Since the 1990s, fine-resolution remote sensing, combined with ground observation data and modeling, has provided a useful way to quantify C storage and sequestration by urban forests (Brack, 2002; Nowak and Crane, 2002; Myeong et al., 2006; Rao et al., 2013). To illustrate, using field data and photo-interpretation of tree cover, Nowak et al. (2013b) estimated that annual sequestration in U.S. urban areas is 25.6 Tg C ($1\ \text{Tg} = 10^{12}$ g) which is equal to $2.0 billion in a carbon market. Similar work has also been conducted in some Chinese cities like Xiamen and Shenyang (Ren et al., 2011; Liu and Li, 2012). However, many of these studies ignored urban street trees which do not form a forest stand. In China, trees outside forests (TOF) including urban street trees store about 1339 Tg C, 16.5–20.7% of China's terrestrial vegetation carbon pool, making them a substantial component in China's C budget (Guo et al., 2014). Hence, it is important to include street trees in quantifying the urban forest C budget.

About 21 million people live in Beijing, the capital of China (BSB, 2015). Over the past three decades, urban area in Beijing has expanded from 801 to 2452 km^2, an annual rate of 3.7% (Wu et al., 2015). According to BSB (2014), forest coverage in Beijing's built-up area has reached 46.8% by 2013, and the canopy area of street trees amounts to 19% of the total area of road greenbelts. Nonetheless, we still do not have an accurate estimate of the carbon storage in Beijing's street trees, which is important for assessing the environmental benefits of urban trees. Hence, in this study we used field surveys, combined with tree growth measurement data and government statistics, to quantify the C storage and C sequestration rate of urban street trees in Beijing's urban districts.

DATA AND METHODS

Study Area

Beijing is located in the North China Plain between longitudes 115°25′–117°30′E, and latitudes 39°28′–41°25′N. It has a typical warm temperate continental monsoon climate with four distinct seasons. The average annual precipitation is 630 mm, and the mean annual temperature is 11.5°C. The Beijing municipal government administers an area of 16,807 km^2, including six city districts, eight suburban districts and two suburban counties. This study focuses on the six city districts (Dongcheng, Xicheng, Haidian, Chaoyang, Shijingshan, and Fengtai; **Figure 1**). Dongcheng and Xicheng, located in the center of Beijing, are highly protected from development because of their significant historical and cultural values. Haidian and Chaoyang are designated as rapid growing districts to support important economic and cultural functions of the city. Shijingshan and Fengtai are primary residential districts. A road system that currently contains five ring roads (the 2nd to 6th rings) is an important symbol of Beijing infrastructure, and well separates the old city (heavily urbanized) within the inner 2nd ring from recent developments (suburban area) between the outer 5th and 6th rings. Construction of actinomorphic ring roads often follows rapid urbanization (**Figure 2**).

Sampling Design

The field work follows a Stratified Random Sampling. Over the study area, we selected sample sites uniformly with an interval of 2 km and sampled trees on the closest roads. In total, 204 of the 984 roads in Beijing's six city districts were sampled (**Table 1**). Related information on the sampling sites is from Beijing Statistical Yearbook of urban landscaping (BSB, 2005).

Carbon Storage and Sequestration

We randomly selected 10 trees per street. According to our survey, most roads only have a single tree species and two rows of trees. In the rare case of two tree species along a street, we measured five trees for each species. For each tree, species name was recorded, and height, diameter at breast height (DBH, 1.3 m above the ground) and the distance to neighboring trees were measured. Biomass allometric equations for each species were used to calculate the dry biomass of each surveyed tree (**Table 2**). If there is not an established allometric equation for a single species, we used one from the same genus, or a generalized equation from Wang (2006). Dry biomass was converted to C by multiplying by 0.5 (Nowak and Crane, 2002).

Tree carbon storage for the entire study area can be extrapolated by the length of the greening streets using the formula below.

$$C_j = \frac{\sum_1^{10} C_i}{\sum_1^{10} l_{sample}} \times l_{green} \times 2 \tag{1}$$

$$C_{entire} = \frac{\sum C_j}{\sum l_{green}} \times L_{entire} \tag{2}$$

$$C_{density} = \frac{C_{entire}}{S_{area}} \tag{3}$$

C_i is the carbon storage or sequestration of a measured individual tree; l_{green} is the total greening length of the sampled street; l_{sample} is the distance between neighboring trees; C_j is the carbon storage or sequestration of one road; l_{entire} is the greening length of all

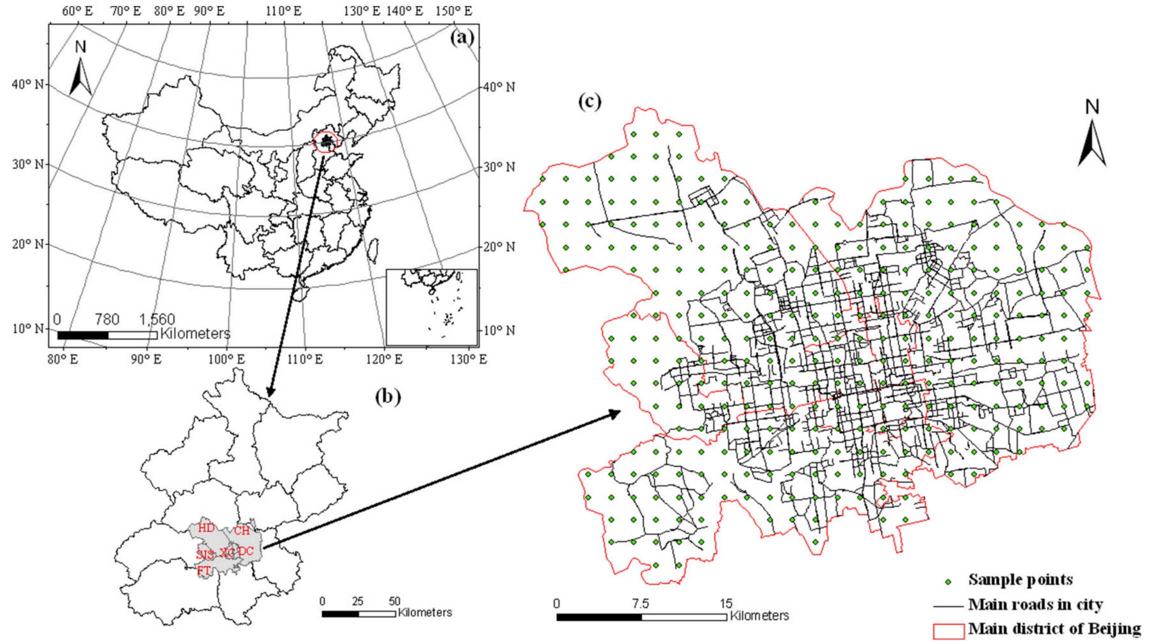

FIGURE 1 | The location of Beijing in China (A), the location of the study area: city districts of Beijing (B), and the sampling design plan (C). District Abbreviations: DC, Dongcheng; XC, Xicheng; CY, Chaoyang; HD, Haidian; FT, Fengtai; SJS, Shijingshan.

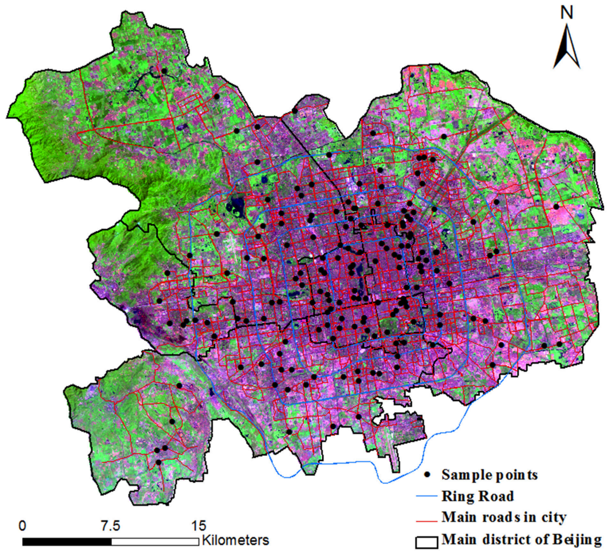

FIGURE 2 | Sampling locations of street trees.

TABLE 1 | Number and street length of sampled roads.

District	No. of roads		Street length (km)		Area (ha)
	All	Sampled	All	Sampled	
Dongcheng	137	28	120.24	28.08	480.7
Xicheng	115	30	156.57	36.67	708.8
Chaoyang	271	61	333.90	125.51	2011.9
Haidian	217	44	366.25	130.47	1181.2
Fengtai	184	33	288.30	75.32	986.9
Shijingshan	60	8	84.63	19.15	195.6

The area is the total area of roads in each district.

roads in the entire area or a given district; C_{entire} is the carbon storage or sequestration of the entire area or a given district; and $C_{density}$ is the density of carbon storage or sequestration of the entire area or a given district. S_{area} is the total road area of the entire study area or a given district.

Carbon sequestration was estimated based on annual DBH growth rates (Rowntree and Nowak, 1991). We installed growth rings on 152 trees at five urban parks in Beijing in 2013. The species include *Sophora japonica* (Linn.), *Broussonetia papyrifera* (Linn.), and *Sabina chinensis* (Linn.). DBH increments were measured once a month to ensure accurate quantification of C sequestration, and an annual average DBH increment for all species was used to calculate the sequestration. To get the corresponding height increment, we inferred the relationship between DBH and height from our previous measurements (**Table 3**). Finally, the increment of tree biomass can be calculated and be converted to carbon sequestration by multiplying by a factor of 0.5.

RESULTS

Structure of Urban Street Trees

We measured 2040 street trees that belong to 12 species. The dominant species sampled is *S. japonica* (Linn.) which accounts for more than 50% of the samples. Other common species include

TABLE 2 | Allometric equations used for biomass estimation in Beijing, China.

Species	Equation	References
Fraxinus spp.	$B = 2.1893 + 3.2949 \times 10^{-2}D^2H$	Tabacchi et al., 2011
Sophora japonica Linn	$B = 0.714 + 0.029D^2H$	He et al., 2007
Ginkgo biloba L	$B = -0.684 + 0.090D^2H$	He et al., 2007
Popular spp.	$B = 0.015 \times (D^2H)^{1.032}$	Li et al., 2007
Firmiana platanifolia (L. f.) Marsili	$\lg B = -1.161443 + 0.913291\lg(D^2H)$	Hope et al., 2006
Generalized equation	$B = 0.11 \times D^{2.47}$	Wang, 2006

B is the biomass for the whole tree; D is the diameter at breast height; and H is the total tree height. Generalized equation was applied to Koelreuteria paniculata Laxm., Pinus bungeana Zucc. ex Endl., Salix matsudana Koidz., Ailanthus altissima (Mill.) Swingle, Ulmus pumila Linn., and Acer mono Maxim.

TABLE 3 | Relationship between DBH and height of main tree species.

Species	Equation	R^2	Number
Sophora japonica Linn	$H = 1.4447D^{0.627}$	0.54	1100
Fraxinus spp.	$H = 1.0022D^{0.7787}$	0.68	265
Ginkgo biloba L	$H = 1.5268D^{0.636}$	0.66	195
Populus spp.	$H = 1.9454D^{0.6852}$	0.41	135
Firmiana platanifolia (L. f.) Marsili	$H = 1.3086D^{0.6658}$	0.57	155

Fraxinus chinensis Roxb., *Ginkgo biloba* L., and *Populus L.*. The sampling locations are shown in **Figure 2**.

Our sampling suggests that street trees in Beijing are mostly dominated by small trees, and the average DBH of all sampled trees is 23.1 cm. The DBH of more than 80% trees is <30 cm outer 3rd rings (**Figure 3**). Relationships between DBH and height of each species are shown in **Table 3**. The relationships between DBH and tree height for each species fit power law functions although the exponent and proportionality constant vary between tree species.

Carbon Storage and Sequestration of Urban Street Trees

The vegetation carbon storage of street trees in Beijing urban districts is 77.1 ± 4.1 Gg C with a sequestration rate of 3.1 ± 1.8 Gg C yr^{-1}. The C density of street trees is 13.9 ± 0.7 Mg C ha^{-1} with a rate of 0.5 ± 0.3 Mg C ha^{-1} yr^{-1}.

The street tree C density of each road is highly heterogeneous, ranging from 0.5 to 200 Mg ha^{-1}. Generally *Ginkgo biloba* L. and *Populus L.* trees have a higher density of C storage because of their larger size. The total C storage and sequestration of street trees in Chaoyang and Haidian are larger than that of the other districts (**Figures 4A,B**). With the lowest total road area, Shijingshan district has the largest C storage and sequestration per unit area (**Figures 4C,D**). Xicheng district has both relatively high C storage and sequestration for the total as well as per unit area, although Xicheng occupies a relatively small area (**Figure 4**).

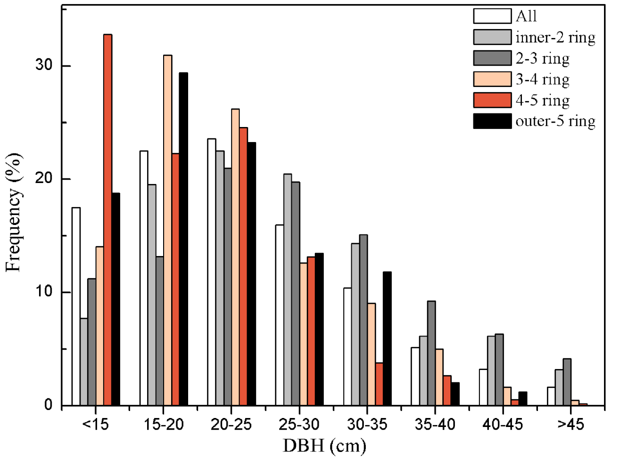

FIGURE 3 | Tree DBH distribution of urban street trees at different ring roads.

C storage is also highly variable between street trees at different locations, from the inner-2nd ring roads to the outer-5th ring roads (**Figure 5**). Trees at the 2nd–3rd ring and the outer-5th ring have a bigger density of C storage than those located at the 3rd–4th ring and the 4th–5th ring. The high-low-high pattern from city-center to suburban is found for both C density and sequestration rate.

We further investigate three parameters that may be responsible for the spatial heterogeneity in street tree C density in Beijing: individual tree size, tree density, and the area of road. Results suggest that tree size and tree density are positively correlated with C density (**Figures 6A,B**), while a power law relationship was observed between C density and road area with a negative exponent (**Figure 6C**).

DISCUSSION

The Potential of Urban Trees to Sequester Carbon

Urban and urbanizing areas were usually considered as sources of C emissions. Vegetation of urban areas was largely ignored or assumed to be negligible for the carbon cycle study (Churkina, 2008, 2016; Churkina et al., 2010). Our results suggest that urban street trees in Beijing are C sinks. The total vegetation C storage and C sequestration rate of Beijing city's street trees are 77.1 ± 4.1 Gg C and 3.1 ± 1.8 Gg C yr^{-1}, respectively. The C density (13.9 ± 0.7 Mg C ha^{-1}) and C sequestration rate (0.5 ± 0.3 Mg C ha^{-1} yr^{-1}) in Beijing's urban street trees were about 1/3∼1/2 of the corresponding magnitudes (40.1 Mg C ha^{-1} and 1.07 Mg C ha^{-1} yr^{-1}) of non-urban forests in China (Zhang et al., 2013). Trees in urban ecosystems are exposed to higher temperature, carbon concentration, and nitrogen deposition than trees in rural areas (Idso et al., 2002; Lovett et al., 2002). These by-products of urbanization are very likely to promote urban tree growth (Carreiro and Tripler, 2005). In addition, a lower ozone level in urban areas compared to rural environments may also benefit urban tree growth (Gregg et al., 2003). Given these advantages, as

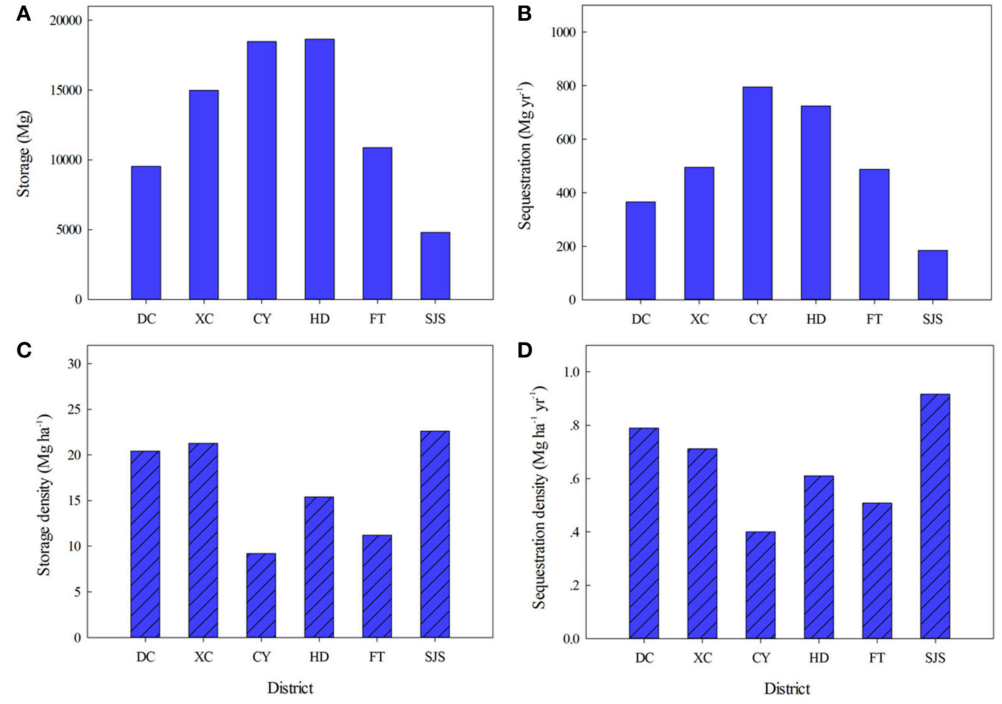

FIGURE 4 | Carbon storage (A) with its density (C) and annual sequestration (B) with its density (D) of street trees at Beijing's six city districts. District Abbreviations: DC, Dongcheng; XC, Xicheng; CY, Chaoyang; HD, Haidian; FT, Fengtai; SJS, Shijingshan.

well as enhanced greening management in urban areas, it is not surprising that the C density and C sequestration rate in Beijing's urban street trees were comparable in order of magnitude to those of non-urban forests in China.

According to data from government statistics (BSB, 2012, 2013, 2014), annual total energy consumed in the six city districts of Beijing between 2012 and 2014 were about 2.97 × 10^7 tons standard coal which is equal to 18.5 Tg C (1 g standard coal equals to 2.277 g CO_2; Liu and Li, 2012). Hence, annual carbon sequestration by Beijing city's street trees can only offset about 0.2% of Beijing's annual CO_2-equivalent emissions from total energy consumed. This ratio is similar to another study in Salt Lake Valley (Pataki et al., 2009), which simulated the effect of doubling the planting density of urban trees in reducing local emissions by 2030. The C sequestration of street trees becomes insignificant when compared with the total anthropogenic CO_2 emissions and therefore should not be considered as an effective mechanism to offset CO_2 emissions. As the local environments and human management activities vary considerably from city to city, more research is needed to better quantify direct C sequestration potential of urban trees and associated biogeochemical processes across various cities.

TABLE 4 | Density of carbon storage and sequestration capacity for urban forest in different cities.

City	Storage (Mg ha^{-1})	Sequestration (Mg ha^{-1} $year^{-1}$)	Tree density (No./ha)	References
Beijing, China	31.9	1.3	223	This study
Shenyang, China	33.22	2.84	569	Liu and Li, 2012
Hangzhou, China	30.25	1.66	465	Zhao et al., 2010
Daegu, Korea	24.9	NA	NA	Yoon et al., 2013
Baltimore, US	25.28	0.71	136	Nowak and Crane, 2002
Atlanta, US	35.74	1.23	276	Nowak and Crane, 2002
Jersey city, US	5.02	0.21	36	Nowak and Crane, 2002

Beijing, China is the extrapolated value, based on the value of urban street trees in this study, and the percentages of green space in urban streets and all urban areas. NA means no data.

Comparisons of Carbon Storage and Sequestration with Other Studies

The average C storage and sequestration of individual trees in Beijing city are 130.62 kg and 5.85 kg yr^{-1}, respectively, which are slightly lower than comparative results from Europe (138.62–377.14 kg per tree and 9.7–30.69 kg yr^{-1} per tree, respectively; Russo et al., 2014). This might be attributed to the differences in methodology (field measurement or modeling approach), tree species and tree age. For example, the 3rd–5th rings of Beijing are in fast development and roads are generally broader and planted with younger trees. The relatively lower C storage per tree in Beijing's new construction areas is also corroborated by another study which showed an average C storage per tree in the fourth ring road area (the area between the third ring

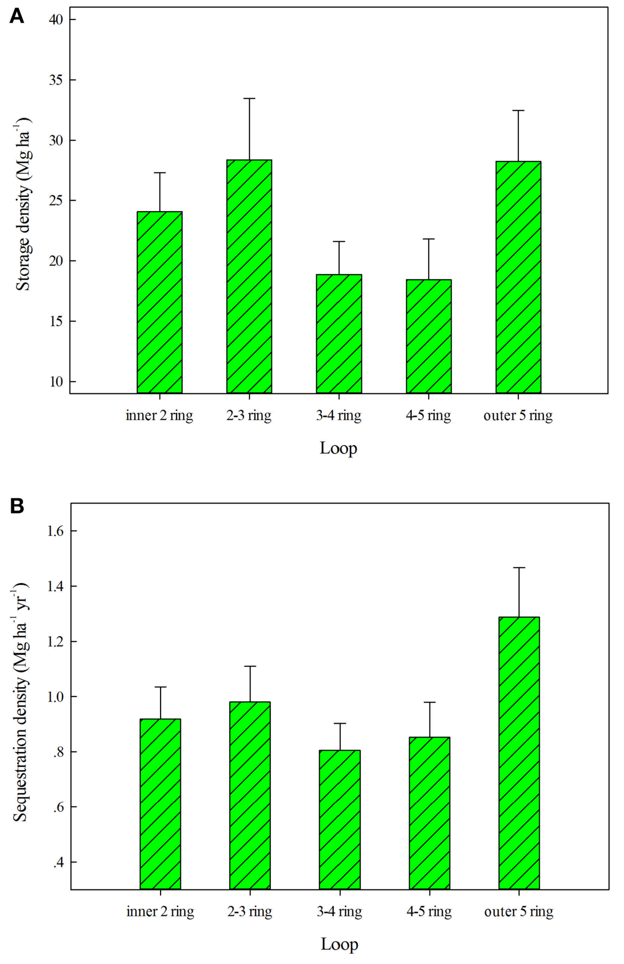

FIGURE 5 | Density of carbon storage (A) and annual carbon sequestration (B) from the inner 2nd-ring and the outer 5th-ring roads.

road and the fourth ring road) of only 84.2 kg (Yang et al., 2005).

Few studies have specifically focused on the density of C stock and sequestration in urban street trees (Soares et al., 2011). The density of C storage and sequestration of urban forests are shown in **Table 4**. In order to make our results comparative within as well as outside of this study, we use the value extrapolated to total area of the urban districts. The comparison suggests that C storage and sequestration per unit for urban trees in Beijing is at a higher level relative to other cities (**Table 4**), which might relate to the fact that in Beijing, the street tree planting protocol usually sets tree interval from 3 to 5 m which makes tree density in Beijing higher.

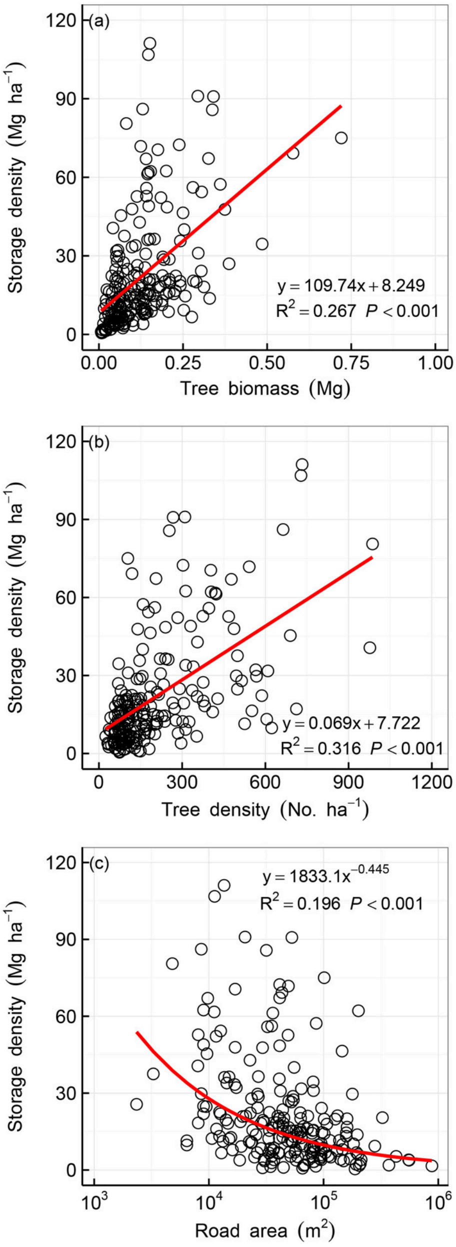

FIGURE 6 | Relationships between carbon density and tree size (A), tree density (B), and road area (C).

Some Limits of the Study

Despite of our tremendous efforts in accurately measuring and quantifying C stocks and annual C sequestrations by Beijing's city street trees, there are still several caveats in the current study. For instance, the increment of annual DBH growth was derived from data of only 2 year measurements, and only the mean value of all trees regardless of their species was used in the study due to the limited quantity of trees measured. Thus our results of tree DBH growth for the street trees in Beijing may not be representative enough, and any comparison based on that shall be interpreted with carefulness. Secondly, the annual height increment in this study is derived from the linear DBH-height relationships inferred from our data. The DBH-height equations can be another source of uncertainties (Peng et al., 2001). Thirdly, the C stock and sequestration estimates for urban trees were based on allometric equations developed from non-urban forests that may not be adequate for urban trees (McHale et al., 2009b).

Nonetheless, despite of all these uncertainties and caveats, the C sequestration rate in our study is within the range from previous studies on similar temperate urban trees (Whitford et al., 2001).

CONCLUSIONS

In the six city districts of Beijing, C stored and sequestrated by street trees is about 77.1 ± 4.1 Gg C and 3.1 ± 1.8 Gg C yr^{-1}, respectively. The C sequestration of street trees per unit area in Beijing is comparable in order of magnitude to that of non-urban forests. However, the annual net carbon sequestration in urban street trees across the entirety of Beijing's urban districts is equal to only 0.2% of its annual CO_2-equivalent emissions from total energy consumption. It should be realized that the C sequestration of street trees becomes insignificant when compared with the total anthropogenic CO_2 emissions and therefore should not be considered as an effective mechanism to offset CO_2 emissions in Beijing.

Site and species specific allometric equation and growth rate are a key perquisite for accurately estimating C storage and sequestration of urban trees. Further studies are needed to intensively monitor urban tree growth for a more diversified pool of tree species and develop a more sophisticated allometric growth model for urban trees. Such data and models will improve our understanding of the role of urban trees in the urban carbon balance and carbon cycle science.

AUTHOR CONTRIBUTIONS

SZ designed research; YT and SZ performed research and analyzed data; YT, SZ, and AC wrote the paper.

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