Characteristics of carbon storage in Shanghai's urban forest

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Urban forest has undergone rapid development in China over the last three decades because of the acceleration of urbanization. Urban forest thus plays an increasingly important role in carbon sequestration at a regional and national scale. As one of the most urbanized cities in China, Shanghai showed an increase of forest coverage from 3% in the 1990s to 13% in 2009. Based on CITY-green model and the second soil survey of Shanghai, the forest biomass carbon (FBC) was estimated to be 0.48 Tg in the urban area and, forest soil organic carbon (SOC) (0–100 cm soil depth) is 2.48 Tg in the urban and suburban areas, respectively. These values are relatively within the median and lower level compared with other Chinese megacities, with the FBC of 0.02 Tg in Harbin to 47.29 Tg in Chongqing and the forest SOC of 1.74 Tg in Nanjing to 418.67 Tg in Chongqing. For the different land-use types in Shanghai, the SOC density ranges from 13.8 (tidal field) to 38.6 t ha⁻¹ (agricultural land). On average, the forest SOC density (31.5 t ha⁻¹) in Shanghai is lower than that in agricultural lands (38.6 t ha⁻¹) and higher than that in lawns (26.5 t ha⁻¹) and gardens (21.3 t ha⁻¹). In Shanghai, the SOC density in newly established urban parks is generally lower than that in older parks. In the northern and southeastern suburban areas (e.g., Baoshan, Yangpu, and Nanhui districts), greenspace SOC density is higher than that in the central commercial areas (Hongkou, Putuo, Changning, and Zhabei districts) and in newly developed district (Pudong District). Uncertainties still exist in the estimation of urban forest carbon in Shanghai, as well as in other Chinese cities. Thus, future research directions are also discussed in this paper.

urban forest, carbon storage, biomass, soil, land-use types

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Forests cover one-third of the global land area and are the main components of terrestrial ecosystems. Forest biomass carbon (FBC) accounts for 77% of the total carbon storage in global vegetation, whereas forest soil carbon accounts for 39% of the total carbon storage in soils [1]. In the context of addressing global warming, the international community has accepted forestry management as an effective method to mitigate increasing atmospheric CO₂ concentrations. With the rapid global urbanization, urban forest is becoming an important component of global forest ecosystems particularly in terms of CO₂ sequestration [2]. Relative to rural areas, additional influencing factors, such as more intensive

silvicultural measures, urban heat islands, air pollution, elevated atmospheric CO₂, etc., affect the composition and growth of forests, as well as the potential of carbon sequestration in urban areas [3,4].

An accurate estimate of the carbon storage and sink potential in growing urban forests at the city level can be a challenge because of the complexity of urban forests in terms of distribution, tree composition, management measures, etc. Since the 1990s, major US cities, such as New York, Oakland, and Chicago, have begun accounting urban forest carbon storage [3–7]. For instance, based on the satellite remote sensing image and on the Normalized Difference Vegetation Index (NDVI) computed from a time sequence (1985–1999), Myeong [8] showed that the urban

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FBC storage in Syracuse, NY, was 0.1468, 0.1494, and 0.1487 Tg for 1985, 1992, and 1999, respectively. Hutyrá et al. [9] established 154 sample plots in the Seattle region to assess aboveground live and dead carbon stocks across multiple land cover classes. They showed the mean aboveground live biomass to be 89 t ha⁻¹, with an additional 11.8 t ha⁻¹ of coarse woody debris biomass. Some investigations on urban FBC storage were also conducted in other countries [10,11]. In a recent paper, Davies et al. [12] argued that previous studies may have underestimated the carbon storage in UK's urban forest. Further work is needed to estimate urban FBC storage more accurately, and gain a deeper understanding of the carbon distribution patterns in cities worldwide.

China is one of the most rapidly urbanized countries in the world, with half of its population residing in urban areas as of 2011 [13]. Massive urban forest plantations, green-spaces, and urban parks have been established in old downtown areas, in newly developed areas, and in suburban areas both in old and newly developed cities [14,15]. Numerous case studies have recently been conducted to investigate the carbon storage and potential of urban forest in Chinese cities [16–18]. For instance, based on the national forest inventory data, Fan et al. [19] showed that the total FBC of Beijing increased from 5.32 to 8.52 Tg between 1988 and 2003.

Shanghai, located in the middle latitude area (31°14'N, 121°29'E), is one of the largest cities in terms of population and has the highest urbanization level (80% in 2007) in China. The urban forest and greenspaces of Shanghai have rapidly developed over the last two decades. Some studies have been published about carbon storage in forests, green-spaces, parks, agricultural fields, etc. With a review of these published data, in this study, our aim is to demonstrate the characteristics of carbon storage in Shanghai's urban forest and possibly influential factors. Furthermore, we also discuss future research directions in this field based on a comparison of the studies in Shanghai as well as in other Chinese megacities.

1 Shanghai urban forest and carbon storage

1.1 Climate and vegetation in Shanghai

Shanghai is located in the northern subtropical biome and has a moderately moist and cool climate [20]. In Shanghai, mean annual temperature and mean annual precipitation are 15.8°C and 1100 mm, respectively. The soils, developed on alluvial materials, are strongly influenced by human activity. The zonal vegetation in Shanghai is mixed evergreen and deciduous broadleaf forests. Natural vegetation has almost been destroyed by long-term human activities, but only some small patches of natural secondary stands remain in Sheshan Hill and Jinshan Island [21].

In terms of natural flora, Shanghai has approximately 113 tree species, 85 shrubs, and 534 grasses [22,23]. With

urban greening and forestry development, a large number of trees, shrubs, and grasses have been historically introduced as greening plants in Shanghai. Currently, Shanghai's urban forest comprises 68 common tree species, of which the top 6 tree species include *Cinnamomum camphora*, *Platanus acerifolia*, *Pinaceae cedrus*, *Metasequoia glyptostroboides*, *Ginkgo biloba*, *Magnolia grandiflora* Linn, etc. [24].

1.2 Urban forest development and land-use change in Shanghai

Compared with other cities in China, Shanghai had very low forest coverage (only 3% in the early 1990s) before the 1990s, because of multiple natural and social reasons. In Shanghai, natural forest vegetation has been destroyed by agriculture and urbanization over the years. Only in the most recent 20 years did urban forest areas rapidly increase with the implementation of key forest projects, such as the “Out-Loop Forest-Belt Project” (1995) and the “Yanzhong Greenspace Project” (2000) in the central commercial area, as well as the “Huangpu River Water-Conservation Forest Project” (2003) in the suburban areas, etc. The forest coverage in Shanghai increased from 3.17% in 1999 to 12.58% in 2009, with an increase in the woodland area from 13700 to 79800 ha (Figure 1).

Over the last decade, land-use type has substantially changed with the acceleration of urbanization and industrialization, especially in suburban Shanghai, where one-third of the agricultural land has been converted into plantations since 2000 [25]. Greenspaces in Shanghai primarily include city parks and greenspace areas. In 1949, only 14 parks with an area of 65.88 ha remained, and the average area of public greenspaces was only 0.16 m² per person [26]. The public greenspace areas reached up to 24425.97 ha, with an average public greenspace area of 9.16 m² per person in 2003 [26]. Over the last 50 years, a regional difference among the decreasing trends of arable lands has become evident. From 1954 to 2003, the arable lands in Minhang, New Pudong and Baoshan districts decreased due to a dramatic increase in construction land facilitated by rapid economic growth. For instance, the arable land in the New Pudong District decreased from 22053 ha in 2000 to 17712 ha in 2003. Approximately 4313 ha of arable land was converted into residential and industrial land (2625 ha), traffic land (1151 ha), and unused land (1150 ha) [27].

An interesting phenomenon in Shanghai, as well as in other Chinese cities, is that with the rapid urbanization and economic development in the recent decade, the urban forest areas and forest coverage increased. For instance, during the 1999 to 2009 in Shanghai, the gross domestic production (GDP) increased from 4.19×10^{11} to 15.05×10^{11} RMB and the population from 15.67 million to 19.21 million. On the other hand, forest coverage increased from 3% to 13% (Figure 1). Evidently, this pattern was not similar to that in other countries. For instance, England, one of the most

Figure 1 Woodland area, forest coverage, population, and GDP in Shanghai from 1999 to 2009. Data were collected from the Shanghai Statistical Yearbook 2011 and the Shanghai Forest Resource Inventory Data 2009.

densely populated countries, already completed its urbanization process several hundred years ago [28]. With the urbanization in England, woodlands were massively transformed into agricultural and other industrial lands. This process reduced the woodland cover to less than 20%, the lowest in Europe. In the 1980s, the UK government worked on measures to develop the urban forest in populated areas with multifunctional purposes [29].

1.3 Characteristics of Shanghai urban forest

(i) Spatial distribution pattern. In Shanghai, urban forest distribution is highly uneven among districts. The suburban woodland area (682.76 km^2) is sevenfold that of the central area (91.46 km^2), and the mean forest coverage in the suburban districts is 3% higher than that in the central districts (Table 1). Among the suburban districts, Chongming has the largest forest area (243.14 km^2) and highest forest coverage (20.51%), whereas Baoshan has the smallest area (34.04 km^2), and Jinshan has the lowest forest coverage (8.33%).

The urban forest in Shanghai is mainly present in patches (e.g., ecologically beneficial forest, fruit plantations, and national forest parks) and in strips or belts (e.g., greenbelt forest, water conservation forests along a river, road shelterbelt forest, coastal protection forest, etc.). In Chongming Dongping National Forest Park, the largest patch of plantation (c. 330 ha) in Shanghai exists, the major fraction of which comprises *M. glyptostroboides* stands. Along the out-loop highway in Shanghai, the Out-Loop Forest Belt that comprises non-continuous stands is approximately 95 km long and 100 m wide.

In Shanghai suburban areas, most plantations, established in the original agriculture land and tidal areas, are located adjacent to roads or rivers. In general, stand patches often display regular shapes such as squares and rectangles. In terms of area, stand patches ranged from 0.067 to 82.950 ha,

Table 1 Forest areas and forest coverage in the downtown and suburban districts in Shanghai

Districts ^{a)}	Total land areas (km^2)	Woodland areas (km^2)	Forest coverage (%)
Total	6340.50	797.63	12.58
Downtown areas [*]	977.10	91.46	9.36
Suburban areas ^{**}	5363.40	682.76	12.73

a) *. Downtown areas include the Huangpu, Luwan, Xuhui, Changning, Jing'an, Putuo, Zhabei, Hongkou, and Yangpu districts. All data were collected from the Shanghai Forest Resource Inventory 2009. **. Suburban areas mean the Minhang, Baoshan, Jiading, New Pudong, Jinshan, Songjiang, Qingpu, Fengxian and Chongming districts.

smaller ones being more common. There are some distinct features in landscape ecology relative to forests in remote mountains.

(ii) Stand age structure. In Shanghai, most forests and greenspaces have been established over the last two decades. Thus, young plantations (<15 years) are dominant. For instance, Chongming County has the highest forest coverage (20% in 2009) among Shanghai's districts and counties, where the most plantations have been established since 2005 when an ecological island project was launched. Bay Forest Park was established in 1999, with approximately 1065 ha of young plantations.

At the stand level, managing uneven-aged stands in Shanghai urban forest to achieve a more attractive landscape and other ecological functions is preferred. However, even-aged stands remain dominant. One reason for such a phenomenon is that relative to even-aged stands, the establishment of uneven-aged stands entails higher investment cost and is more difficult in terms of silvicultural operation. Another reason is that up to now, fewer regeneration seedlings have been recruited in these young plantations. Thus it is still an unsolved issue for how to manage uneven stands in Shanghai urban forest.

(iii) Species composition. A total of 919 species, 510

genera, and 134 families of seed plants can be found in Shanghai's urban forest, greenspaces, and other vegetation areas [21]. Based on the forest resource inventory database (2009), the dominant tree species in the Shanghai area are *M. glyptostroboides*, *C. camphora*, *P. tremuloides*, *E. sylvestris*, *L. lucidum*, and *G. biloba*. These species cover 30% of the total forest area. Areas of mixed coniferous and broadleaf forest, as well as broadleaf mixed forest, were 24618 and 4603 ha, respectively, which account for one-third of the total forest area (Table 2). Another main forest type is the fruit forest (20380 ha in total, e.g., peach, citrus) (Table 2). In Shanghai, fruit plantations occupy 23.3% of the total urban forest area. These fruit plantations are intensively managed through agricultural measures, such as the application of fertilizers, irrigation, loosening of soil and weeding, and controlling of diseases and insects. For these fruit plantations, in terms of carbon storage, higher carbon concentration exists in the soils, but SOC is easily decomposed due to disturbance by agricultural activities.

(iv) Site conditions. In the Shanghai area, the average altitude is 5 m a.s.l., with the soils developed on alluvial material. Flat plains are easily flooded, particularly in July and August, when 70% of the annual precipitation (1100 mm) frequently occurs. In many sites, ground water level is frequently less than 1 m. This often causes a harmful impact on the survival and growth of some trees. Thus, draining ditches are often made in these stands. In addition, most of the plantations in Shanghai were been converted from agricultural land, with relatively fertile soils for tree growth, showing potentially higher biomass productivity.

2 Storage and density of carbon in different land-use types in Shanghai

2.1 Urban forest biomass carbon storage in Shanghai

Based on the fourth national forest inventory data (1989–

Table 2 Proportions of different type stands in Shanghai urban forests in 2009^{a)}

Forest types	Area (ha)	Proportion (%)
<i>Salix babylonica</i>	573.50	0.64
<i>Ligustrum lucidum</i>	640.72	0.71
<i>Ginkgo biloba</i>	1051.22	1.17
<i>Elaeocarpus sylvestris</i>	1101.46	1.23
<i>M. glyptostroboides</i>	3904.83	4.35
<i>Populus euramevicana</i> cv.1-214	4349.23	4.85
Broad-leaf mixed forest	4603.60	5.13
<i>C. camphora</i>	8021.40	8.94
Fruit bearing plantations	20830.09	23.22
Coniferous and broad-leaf mixed forest	24618.85	27.44
Others	20031.37	22.32
Total	79726.27	100

a) Data were based on the Shanghai Forest Resources Inventory Database (2009).

1993), Zhao et al. [30] estimated that the total FBC in Shanghai is 0.058 Tg. Lin et al. [31] showed that the annual net primary productivity (NPP) in Shanghai's urban forest is approximately $3.24 \times 10^5 \text{ t a}^{-1}$. Based on RS image digitization, Xu et al. [24] showed that the total FBC storage and the annual carbon sequestration continue to range from 0.48 and 6256 t a^{-1} in the urban area (within the downtown area which is circled by the out-loop forest belt), and the average FBC density and average FBC sequestration rate are 47.8 Tg and $0.625 \text{ t ha}^{-1} \text{ a}^{-1}$, respectively. The FBC sequestration rate is significantly positively correlated with canopy closure and stand density, but negatively correlated with the average diameter at breast height (DBH) [24].

The FBC and SOC densities show distinct differences in different aged forests of the same species or in different tree stands of the same age. Using the establishment of allometric models, Zhuang et al. [32] estimated that the above-ground FBC stocks for young (nine-year-old), middle-aged (16-year-old) and near-mature (31-year-old) *M. glyptostroboides* stands in Chongming Island were 13.11, 29.76, and 64.93 t ha^{-1} with annual carbon sequestration rates of 4.31, 2.83, and $2.54 \text{ t ha}^{-1} \text{ a}^{-1}$, respectively (Table 3). In some 9-year-old *C. camphora* stands in Shanghai, the FBC storage ranged from 49.0 to 59.8 t ha^{-1} (Table 3), which is higher than that of young (eight-year-old) *M. glyptostroboides* stands.

Compared with that in other subtropical areas, the FBC storage in Shanghai's urban forests is lower. Li et al. [35] found that the aboveground FBC storage in a 16-year-old *M. glyptostroboides* stand in Liuyang city, Hunan Province is 64.44 t ha^{-1} , which is clearly higher than that of the same-aged *M. glyptostroboides* stands in Shanghai. Shanghai's urban forest displays lower FBC density than the average carbon density of China's forest vegetation (57.78 t ha^{-1}) [36]. However, according to Liu et al. [37] and Xu et al. [38], the average biomass carbon density for young forests is only approximately $15.00\text{--}19.51 \text{ t ha}^{-1}$ in China and 26.58 t ha^{-1} in Eastern China, which are significantly lower than that in Shanghai (56.79 t ha^{-1}). In addition, *C. camphora* stands in Shanghai's urban forest display lower FBC than in other subtropical areas such as Hunan province [38–41]. Hunan province has considerably higher annual precipitation (1800–2000 mm) than Shanghai (1100 mm), which may be favorable for *C. camphora* growth.

The urban FBC (0.48 Tg) in Shanghai is at a median level and is somewhat lower than that in other Chinese cities. For instance, Hangzhou, 150 km southwest of Shanghai, has a dramatically higher value of FBC storage (11.74 Tg). This phenomenon may be attributed to the larger woodland area (1170000 ha) and higher forest coverage (64%) in Hangzhou in relation to the lower level (79000 ha, 12.58%) in Shanghai. These results also indicate that, although urban FBC sequestration in Shanghai remains at a lower level, urban FBC storage is enhanced by the increase in forest coverage and economic advancements.

2.2 Storage and density of SOC in different land-use types in Shanghai

Based on the second soil survey in Shanghai, the SOC storage from 0 to 100 cm soil depth is 57.6 Tg, and the average SOC density is 105.5 t ha⁻¹ [42]. Both SOC content and SOC density distinctly vary with the land-use types (rice paddies, upland, forest land, abandoned land, lawn, garden land, and tidal field) (Table 4). The SOC density in rice paddies (38.6 t ha⁻¹), dry land (31.7 t ha⁻¹), and forest lands (31.5 t ha⁻¹) are higher than those in abandoned lands (27.3 t ha⁻¹), lawns (26.5 t ha⁻¹), gardens (21.3 t ha⁻¹), and tidal fields (13.8 t ha⁻¹). The SOC density rank is as follows: paddy soil > calcareous alluvial soil > yellow brown soil > seashore saline. In spatial terms, the SOC density is higher in the West than in the East [42].

According to Liu et al. [43], the urban greenspace area (e.g., residential area, park greenspace, road green belts, etc.) in Shanghai comprises 13, 910 ha and has an average SOC density of 258 t ha⁻¹ in a 0 to 30 cm layer and 281 t ha⁻¹ in a 30–60 cm layer. Older parks have higher SOC density (201 t ha⁻¹) than younger parks (107 t ha⁻¹) [43]. The central commercial districts (Hongkou, Putuo, Changning, and

Zhabei) and the newly developed district (Pudong) have lower forest coverage and lower SOC density compared with the northern and southeastern parts of Shanghai (e.g., Baoshan and Nanhui districts), where a bigger woodland area exists in proportion to the greenspace [43].

Older stands were found to have a higher SOC storage than younger stands. For instance, Xiao et al. [20] estimated the SOC storage (0–40 cm depth soil) in young (8-year-old), mid-aged (15-year-old), and near-mature (30-year-olds) *M. glyptostroboides* stands in Chongming Island, Shanghai and showed that the SOC storage (0–100 cm soil depth) of different aged stands are 77.3, 88.9, and 91.5 t ha⁻¹, respectively. These *M. glyptostroboides* stands were established in the alluvial soils with originally lower SOC, and forest litter input may be a primary cause of carbon accumulation in the soils.

3 Comparison of carbon storage with other Chinese cities

Mainland China has 4 municipalities under the central government and 27 capital cities in the provinces. Amount

Table 3 Biomass and soil carbon storage in different plantation ecosystems in Shanghai

Forest types ^{a)}	Species	Age (a)	Density (trees ha ⁻¹)	DBH (cm)	Height (m)	Carbon storage		NPP (t ha ⁻¹ a ⁻¹)	Reference
						Trees (t ha ⁻¹)	Soil ^{b)} (t ha ⁻¹)		
ECF	<i>C. atlantica</i> ^{c)}	—	328	26.0	—	56.9	—	—	[24]
	<i>S. chinensis</i> cv. <i>Kaizuka</i> ^{c)}	—	618	17.0	—	42.2	—	—	[24]
EBF	<i>C. camphora</i>	—	—	—	—	54.1	—	—	[33]
	<i>C. camphora</i>	9	1750	11.2	7.7	56.8	68.2	—	Unpublished
	<i>C. camphora</i> ^{c)}	—	455	20.0	—	49.0	—	—	[24]
	<i>L. lucidum</i> Ait ^{c)}	—	670	12.0	—	53.1	—	—	[24]
DBF	<i>P. euramevicana</i> cv.1–214	—	—	—	—	21.0	—	—	[33]
	<i>P. euramevicana</i> cv.1–214 ^{c)}	—	329	22.0	—	57.1	—	—	[24]
	<i>G. biloba</i> ^{c)}	—	630	23.0	—	32.2	—	—	[24]
	<i>P. orientalis</i> ^{c)}	—	213	32.0	—	56.9	—	—	[24]
DCF	<i>M. glyptostroboides</i> ^{c)}	—	—	—	—	—	—	—	[32]
		9	1050	10.5	9.4	13.1	—	4.31	
		16	725	17.5	16.2	29.8	—	2.83	
	<i>M. glyptostroboides</i>	31	550	27.2	23.4	64.9	—	2.54	
		8	1050	7.3	5.4	4.59	77.3	—	[20]
		15	725	16.3	15	26.9	88.9	—	
		30	550	26.9	22.5	65.7	91.5	—	
	<i>M. glyptostroboides</i>	—	—	—	—	26.0	—	—	[33]
	<i>M. glyptostroboides</i> ^{c)}	—	1159	19.0	—	45.3	—	—	[24]
	<i>P. heterocyclus</i>	2–3	5866	7.2	9.9	15.7	130.4	—	[34]

a) ECF, EBF, DBF, DCF, and ES denote evergreen coniferous forest, evergreen broadleaf forest, deciduous broadleaf forest, deciduous coniferous forest, and evergreen shrubs, respectively. b) Data of soil carbon storage indicate total soil carbon storage at the soil depth from 0 to 100 cm, except for the data on the *C. camphora* stand (0 to 40 cm soil depth). c) Data of these trees were investigated from greenspaces.

Table 4 Soil bulk and carbon density of different land-use types in Shanghai

Land-use type ^{a)}	Depth (cm)	Soil bulk (g cm ⁻³)	SOC content (g kg ⁻¹)	SOC density (t ha ⁻¹)	SOC storage (10 ⁷ t)	Reference
Total land	0–100	–	–	105.5	5.76	[42]
Urban parks and greenspace						
Lawn	0–20	1.36	10.05	26.5	–	[42]
Greenspace	0–30	1.57	15.52	–	–	[43]
Garden land	0–20	1.17	9.40	21.3	–	[42]
Woodland						
Forest belt	0–5	–	14.67	–	–	[44]
Forest land	0–20	1.31	12.44	31.5	–	[45]
Tree nursery	0–5	–	13.69	–	–	[44]
Orchard						
Orchard	0–20	1.23	–	33.8	–	[33]
Orchard	0–5	0	13.03	–	–	[44]
Agricultural land						
Farm land	0–5	–	11.45	–	–	[44]
Farm land	0–100	–	–	25.8	11.5	[46]
Winter wheat	0–20	1.28	–	29.4	–	[33]
Paddy field	0–20	1.29	14.47	38.6	–	[45]
Vegetables	0–20	1.35	–	23.7	–	[38]
Others						
Upland	0–20	1.34	12.38	31.7	–	[45]
Abandoned land	0–20	1.23	11.10	27.3	–	[45]
Tidal flat	0–20	1.32	5.30	13.8	–	[45]

a) Values are the mean data of sampling sites that have different land-use types (lawn $n = 47$, paddy field $n = 30$, upland $n = 24$, forest land $n = 51$, garden land $n = 25$, abandoned land $n = 3$, tidal flat $n = 10$, etc.) in Shanghai.

these 31 cities, 21 cities were selected in this paper to display the features of carbon storage and potential in Chinese urban forests (Table 5). The capital cities of some provinces were not listed (Table 5) because of lack of data regarding these cities' urban forest carbon. Additionally, Shenzhen, the first special economic zone and the earliest open city in China in the 1990s, was listed because its administrative level is similar to that of the capital cities of the provinces in China.

Based on available data, the FBC storage in each city varies from 0.02 Tg in Harbin to 47.29 Tg in Chongqing (Table 5). In an urban forest, the FBC density varies from 2.4 t ha⁻¹, such as that in Hefei, to 49.5 t ha⁻¹, such as that in Shenyang (Table 5). A dominant factor, diameter distribution, may affect FBC density (t ha⁻¹). FBC density tends to increase with the proportion of mature forests with high diameters [6]. For example, the average FBC density of urban trees is only 2.4 t ha⁻¹ in Hefei, which is obviously lower than that of any other city listed in Table 5. However, Liu et al. [47] analyzed the reason why the urban forest, that is, a large proportion of young and middle-aged trees, in Hefei is mainly distributed in three counties. The near-mature forest had the highest FBC density, which reached 12.45 t ha⁻¹, whereas the young forest had a carbon density of only 0.32 t ha⁻¹.

In relation to studies on biomass carbon storage in urban forests, forest soil carbon has been investigated in fewer cities. The largest forest SOC storage (418.67 Tg) and SOC density (143.3 t ha⁻¹) were found in Chongqing, whereas the

smallest ones (1.74 Tg and 21.8 t ha⁻¹) were observed in Nanjing (Table 5). Compared with that in other Chinese cities, the SOC density (31.5 t ha⁻¹) in Shanghai is at a low level. For instance, the SOC density reaches up to 143.3 t ha⁻¹ in Chongqing urban forest. With 75.3% of mountain areas, Chongqing has a larger fraction of natural forests, which results in higher SOC density [68]. In contrast to Chongqing, Shanghai and Nanjing, both located in the Yangtze River delta plain, have a higher proportion of young plantations, which may have resulted in lower SOC density. Based on our survey of literature, urban forest SOC has only been investigated in several cities, e.g., Shanghai, Nanjing, Chongqing, etc., and more studies should be conducted to obtain an accurate estimate of urban forest SOC.

Urban and suburban areas generally have more serious air and soil pollution compared with rural areas. Such pollution significantly affects microbial communities and activities in soils and, consequently, the chemical composition and stability of SOC in urban forests [69,70]. Thus, in the field of SOC, the difference in the physical, chemical and biological properties of soils among urban areas as well as between urban areas and natural forests should be investigated.

4 Research directions in future

Relative to other forest ecosystems, urban forests are controlled by more social factors, which results in the greater

Table 5 Biomass and soil carbon storage in urban forest ecosystems in municipalities under the central government and in the capital cities of provinces

Regions	Cities	Woodland area (10 ⁴ ha)	Forest vegetation ^{a)}			Urban forest soil		Forest coverage (%)	Population (10 ⁷ person)	Total area (10 ⁴ km ²)	Reference
			<i>B</i> (10 ⁴ t)	<i>C</i> (10 ⁴ t)	<i>P</i> (t ha ⁻¹)	<i>C</i> (10 ⁴ t)	<i>D</i> (t ha ⁻¹)				
Northeast	Harbin	2.0	4.1 ^{b)}	1.9 ^{b)}	—	—	—	44.2	5.9	0.7	[17]
	Changchun	23	6.7 ^{b)}	3.4 ^{d)}	—	—	—	15.5	7.7	0.5	[48]
	Shenyang	44	102 ^{d)}	51	49.5	—	—	33.8	7.2	1.3	[49]
North	Beijing	105	1703	852	22.2	282.3	70.3	36.7	19.6	1.7	[19,50]
	Tianjin	3.4	111	50	14.7 ^{c)}	—	—	13.7	10.0	1.2	[51]
	Hohhot	51.5	1036 ^{d)}	518	10.1 ^{c)}	—	—	29.9	2.8	1.7	[52]
Northwest	Xian	26.1	1086 ^{d)}	543	20.8	—	—	45.0	8.7	1.0	[53]
Central	Zhengzhou	1.5	58.6	29.3	19.5 ^{c)}	—	—	25.7	2.9	0.7	[54]
	Hefei	4.8	23.1	11.5	2.4	—	—	15.8	4.3	0.7	[47]
	Wuhan	10.5	—	—	—	—	—	33.0	8.7	0.8	[55]
Eastern	Changsha	58.4	1653.8 ^{d)}	926.3	15.9	4952.3 ^{c)}	84.8	50.0	7.0	1.0	[56,57]
	Nanjing	8.0	280	136	16.9	174.1	21.8	20.6	8.0	0.7	[58]
	Shanghai	7.9	95.6 ^{d)}	47.8 ^{b)}	47.8 ^{b)}	248.9 ^{c)}	31.5	12.6	23.0	0.6	[22,33]
Southwest	Hangzhou	117	2348 ^{d)}	1174	30.25	—	—	64	6.7	1.7	[59]
	Chengdu	24.4	1438 ^{d)}	718.9	19.87	—	—	36.8	14.0	1.2	[60]
	Chongqing	292	9458 ^{d)}	4729	16.2	41867	143.3 ^{c)}	35	28.8	8.2	[61,62]
Southeast	Guiyang	18.3	900	405	22.1 ^{c)}	1682	91.9	34.7	4.3	0.8	[63,64]
	Kunming	94.9	2831 ^{d)}	1274	13.4 ^{c)}	—	—	45.1	5.1	2.1	[65]
	Guangzhou	28.0	1528	764	24.7	2816.3	78.1	38.2	12.7	0.7	[16,66]
	Shenzhen	7.47	394 ^{d)}	197	24.6	—	—	39.9	14.3	0.2	[67]
	Xiamen	7.5	228	114	15.14	—	—	45	3.5	0.17	[18]

a) *B* denotes forest biomass, *C* denotes carbon storage, *P* denotes FBC density, and *D* denotes forest SOC density. b) Data on *B*, *C*, and *P* in Harbin and Shanghai indicate the values, i.e., in the central area not included in the suburban area. Data of *B* and *C* in Changchun denote the greenbelt around the city. "—" indicates no data collected. c) The value was calculated based on the data of woodland area, *C*, *P*, and *D*. d) conversion factor for biomass to carbon storage is 0.5.

complexity and difficulties of carbon investigation. For instance, urban forests have more highly fragmented patches compared with other types of forests, which results in greater uncertainties in the estimation of forest biomass carbon. In urban areas, street-line trees are important components of urban forests. However, general allometric biomass equations are unsuitable for these urban trees because these trees are frequently pruned for landscaping. This condition results in the difficulty in accurately estimating the biomass of these trees. In general, urban soils are heavily disturbed. As a result, collecting representative soils for the measurement of carbon concentration is difficult.

Based on the review of literature in this paper, more studies are needed to obtain a more accurate estimate of forest biomass and soil carbon in Shanghai as well as other Chinese cities. First, a set of systematical sample stands could be set up for urban forest in Chinese megacities. Based on these sample stands, local biomass-volume regression equations for important specific tree species can be established. For most cities in which urban forest biomass was estimated (Table 5), a generalized biomass-volume equation was borrowed, which could result in higher uncertainties.

Second, a feasible investigation method on street-line tree biomass carbon in urban areas could be established with the introduction of new technology. For instance, a non-destructive method for the estimation of isolated tree

biomass [71] that could be modified to estimate street-line tree biomass can be employed.

Third, forest soils in urban areas have physical, chemical and biological properties that are distinct from soils in rural areas. Compared with investigations of biomass carbon, fewer studies on soil carbon in Chinese urban forest have been conducted (Table 5). Thus, efforts must be exerted to understand the chemical composition of soil carbon in urban forests to show the characteristics of SOC stability and to determine how the SOC respond to global change.

Fourth, for many Chinese cities, there are higher proportions of young plantations at a fast-growing stage in urban forest, with higher potential of sequestering atmospheric carbon. So one important issue is to study the potential of carbon storage and sequestration in urban forest ecosystems and the influential factors so that the carbon-sink function could be played.

5 Concluding remarks

Based on the review of published data, we presented the characteristics of urban forests as well as carbon storage in Shanghai. Relative to studies in other capital cities of Chinese provinces, the subject of urban forest carbon has been more intensively studied in Shanghai. Total forest area, forest coverage, as well as the FBC and SOC in Shanghai are

at a median and somewhat low level compared with those in other Chinese megacities. In Shanghai, more carbon is stored in suburban forests than in the downtown areas. The old parks have greater SOC density than newly established ones. Relative to other tree plantations in Shanghai's urban forest, *C. camphora* stands have the highest FBC density (56.8 t ha^{-1}). In terms of land-use types in Shanghai, the SOC density ranked as follows: farmland > orchard > woodland > urban parks and greenspaces > others. Compared with other Chinese megacities (e.g., Beijing, Hangzhou, and Guangzhou), Shanghai's urban forest principally comprises young plantations (<15 years) transferred from farmlands. These young plantations have a high potential for carbon sequestration. Uncertainties remain in the estimation of forest carbon storage in Shanghai as well as in the other Chinese cities, and more studies should be conducted on this subject in future.

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