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Carbon Storages and Densities of Different Ecosystems in Changzhou City, China: Subtropical Forests, Urban Green Spaces, and Wetlands

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Abstract: Climate change mitigation and carbon neutrality are current hot topics. Forests, urban green spaces, and wetland ecosystems are recognized as important carbon sinks. The Yangtze River Delta region in Eastern China, which plays a pivotal role in China's economic and social development, is rich in such carbon-sink resources. There is, however, a lack of regional carbon data. The investigation of carbon storage and carbon densities of forest, urban green space, and wetland ecosystems is, therefore, of great importance. In this study, the forest resource management map (including wetland) and green space system planning map of Changzhou city, combined with a field investigation and laboratory experimental analysis, were used to estimate the carbon storages and carbon densities of the forest, urban green space, and wetland ecosystems in Changzhou city. The average carbon density and carbon storage in Changzhou were 83.34 ± 4.91 Mg C ha^{-1} and 11.30 ± 0.67 Tg C, respectively, of which soil accounted for 74%, plants accounted for 25%, and litter accounted for less than 1%. The forest ecosystem contributed the most to the carbon pool (72%), with the green space ecosystem and the wetland ecosystem each accounting for 14% of the carbon pools. Clearly, the forest, green space, and wetland ecosystems in Changzhou city have a large carbon storage capacity. This study is of significance as it provides data on the carbon sink functions of forest, green space, and wetland ecosystems at the provincial and national regional scales.

Keywords: carbon storage; carbon density; soil carbon; plant carbon; litter carbon

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1. Introduction

Terrestrial ecosystems play a key role in the global carbon cycle [1,2] and are important for mitigating climate change and achieving "carbon neutrality" [3,4]. The Chinese government has announced that it will achieve "carbon neutral" by 2060 [5]. Conservation and the use of carbon sink resources are considered key strategies for mitigating the effects of climate change [6]. Carbon sink resources, therefore, need to be strengthened, and the quantification of ecosystems needs to be promoted [7]. Forest, urban green space, and wetland ecosystems are common carbon sink ecosystems. These ecosystems are thought to mitigate climate change by sequestering atmospheric CO_2 through plants, soils, and sediments [8,9]. By determining the carbon storage and carbon density of different ecosystems, a theoretical basis can be provided for formulating and adopting corresponding carbon sequestration strategies.

As an important part of terrestrial ecosystems, forests play an important role in mitigating the greenhouse effect and affecting the global carbon cycle. Forests capture atmospheric carbon dioxide and store it in tree biomass and soil organic matter [10–12]. Globally, carbon is mainly stored in forest vegetation and soil. The carbon sequestration function of forest vegetation is an important indicator of the stability and health of forest ecosystems [13,14]. Similarly, forest soil organic carbon (SOC) is an important indicator of soil quality [15–17]. Forest vegetation and forest soil account for 44% and 45%, respectively, of the total forest carbon storage, followed by forest litter, which accounts for 6% [11]. Some researchers estimate that, globally, forest soils account for nearly 70% of the total forest ecosystem carbon storage [18]. Stock estimation is a classic research method for determining forest ecosystem carbon storage [19]. Using regional forest inventory data such as forest type, age, stand density, stand volume, mean tree height, and diameter at breast height (DBH), forest carbon stocks have been estimated [20]. In recent years, the four most commonly used methods to estimate vegetation carbon storage based on inventory data are the average biomass method, volume-derived method, biomass regression equation method, and continuous conversion factor method [21]. For a more accurate measure of regional scale carbon storage, some studies have not only estimated the carbon storage of common ecological forest species but also included bamboo forests, shrub forests, economic forests, and medicinal forests in the calculations [22–24]. Recent studies have also shown that forest biodiversity can promote carbon storage and increase the carbon sink capacity [25,26]. A large number of studies on forest carbon storage have focused on tropical, temperate, and boreal regions [5,27,28]. There are few studies, however, on the carbon storage in subtropical regions [29], and the forest carbon storage in the Yangtze River Delta region has not been reported. It is, therefore, important to obtain data on the forest ecosystem carbon storage of the Yangtze River Delta to supplement that in subtropical East China and to provide a reference for the future estimations of forest carbon storage at the national scale.

Urban green spaces are a vital part of urban green infrastructure and play an important role in mitigating climate change and the urban heat island effect [30,31]. On the one hand, green vegetation can absorb atmospheric CO_2 through photosynthesis [32,33]. The CO_2 is then converted into the above and belowground biomasses, and the carbon is stored in the form of stems, branches, and roots [34]. Urban trees in the United States are estimated to store 643.2 million tons of carbon in total and have a total carbon sequestration rate of 25.6 million tons per year [33]. The carbon density of urban green spaces in China is relatively low. Studies have found that as long as urban green spaces are effectively managed, urban vegetation can still absorb and accumulate a large amount of carbon and has great potential as a passive carbon sink [30]. On the other hand, urban green spaces have rich vegetation and high density. The vegetation litter decays, storing carbon in the soil [35,36]. There are, however, only a few studies on the soil carbon storage of China's green spaces [37]. A comprehensive estimate of the carbon storages and carbon densities of urban green space ecosystems is, therefore, necessary.

Wetland ecosystems have a strong carbon accumulation and high organic carbon storage capacity [38,39]. Their potential for mitigating climate change has attracted increasing attention [40]. Although they occupy only 5% to 8% of the earth's surface, their carbon storage accounts for 20% to 30% of the total carbon storage of terrestrial ecosystems [41–44]. Of this, more than 90% of carbon storage occurs in sediments [45]. Due to the increasing effects of climate change and human activities, the global wetland area has decreased by nearly 50% [46], and this will cause a decline in the overall carbon storage capacity [47]. With the intensification of global warming, the decomposition of wetland SOC will increase, promoting the conversion of carbon sinks into carbon sources [48]. At present, a lot of research on wetland carbon storage has been carried out around the world, such as in India [49], Mexico [50], Colombia [51], and China [48,52–55]. The wetland carbon storage in the Yangtze River Delta region of Eastern China, however, has not been reported, and its estimation is needed to provide a reference for the development of wetland conservation and carbon storage strategies.

The Yangtze River Delta region lies in the east of China and is one of the most active economic development regions in China. Changzhou city is one of its representative cities and has abundant carbon sink resources. This study used the forest resource management map (including wetland area) and the green space system planning map of Changzhou city, combined with a field investigation and laboratory experimental analysis, to estimate the carbon storages and carbon densities of the forest, urban green space, and wetland ecosystems in Changzhou city. This paper aims to provide data for estimating ecosystem carbon storage at the provincial or national scale and a reference for formulating scientific and rational carbon sequestration strategies for forest, urban green space, and wetland ecosystems.

2. Material and Methods

2.1. Study Area

Changzhou is a prefecture-level city in Jiangsu Province, China, located in the middle of the Yangtze River Delta (31°09′ N to 32°04′ N, 119°08′ E to 120°12′ E). The city covers an area of 4373 km^2, and the permanent population is 5.3662 million. It currently governs six municipal districts, namely, Jintan District, Wujin District, Xinbei District, Tianning District, Zhonglou District, and Jingkai District, and manages one county-level city, namely, Liyang city. With its warm and cloudy climate, it is characterized as a typical northern subtropical monsoon climate zone. The annual average temperature is 17.5 °C, and the annual average precipitation is 1100 to 1200 mm. The landform type is alluvial plain, most of which is alluvial clay. Changzhou has a dense river network, including the Yangtze River, Taihu Lake, Changdang Lake, Gehu Lake, and the Beijing–Hangzhou Grand Canal. The vegetation is dominated by mid-subtropical evergreen broad-leaved forests and northern subtropical deciduous and evergreen broad-leaved mixed forests.

2.2. Data Collection

2.2.1. Area and Classification of Ecosystems

The area and location of forest and wetland ecosystems come from the Changzhou Forest Resources Management Map (in 2020). Forests with an area greater than 50 ha were defined as the dominant forest tree species (groups). A total of 26 dominant tree species (groups) in Changzhou were screened out, and their locations and areas were determined. Tree species with an area of less than 50 ha were classified into similar tree species of dominant tree species. In addition, the map of 2020 was used to determine the location of river wetlands, lake wetlands, and artificial wetlands in Changzhou city. Their areas were determined according to administrative divisions and divided into seven parts. According to the "Urban Green Space Classification Standard" (CJJ/T85-2017) [56] of the Ministry of Housing and Urban–Rural Development, the types of green spaces were divided into five categories, that is, park green space, protective green space, square green space, attached green space, and regional green space. According to the "Changzhou City Green Space System Planning (2004–2020)", the area and location of each urban green space was determined.

2.2.2. Field Investigation and Sampling

Field investigation and sampling work were performed in Changzhou city from June to September 2022. In total, 86 forest sample plots were defined according to the forest resource management map of Changzhou City (2020), 54 green space sample plots were defined according to the "Changzhou City Green Space System Planning" (2004–2020), and 33 wetland sampling points were defined according to administrative region (Figure 1). A 20 m × 20 m tree survey plot was defined, and all tree species with a DBH greater than 5 cm were measured. Geographical location, DBH, tree height, crown diameter, and tree species were recorded. A 2 m × 2 m bush plot was defined, the main species and their coverage were recorded, and all shrubs and herbs in the sample were harvested and brought back to the laboratory for drying at 65 °C, weighing, and determination of carbon content. A 1 m soil profile was made in each forest plot, and each profile was divided into four layers: ~0 to 20 cm, ~20 to 40 cm, ~40 to 60 cm, and ~60 to 100 cm. Because the green space soil is mainly an infill, a 40 cm soil profile was made for each green space plot and divided into 0 to 20 cm and 20 to 40 cm. Wetland sediment samples (~0–20 cm) were collected using an adjustable-length KHT0204 piston sediment column sampler. Finally, the soil samples of the corresponding soil layers were collected and brought back to the laboratory to be air-dried, ground, and passed through a 2 mm sieve to measure the SOC content.

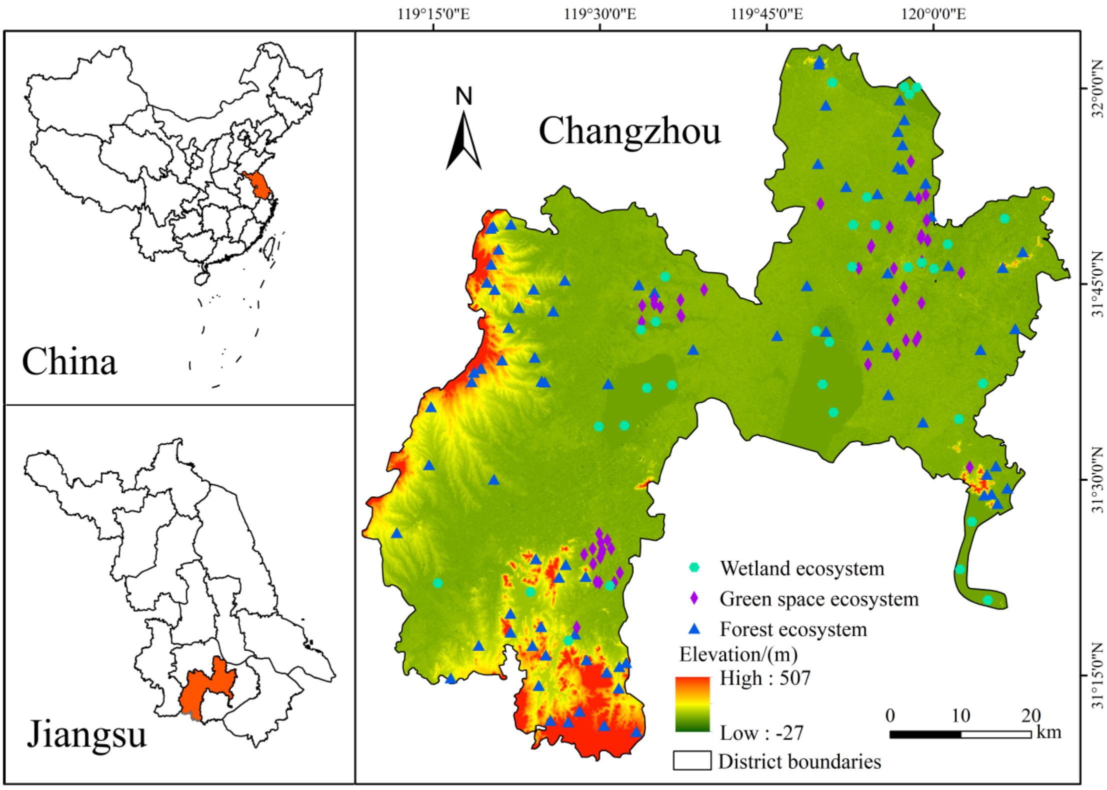

Figure 1. Map of survey sites in the study area.

2.3. Data Analysis

2.3.1. Measurement and Estimation of Plant and Litter Biomass and Carbon

The biomass allometry equation was obtained from the literature [57–59] and the norm "Guidelines on Carbon Accounting and Monitoring for Afforestation Project" (LY/T 2253-2014) (State Forestry Administration, 2014) (Appendix 2) [60]. The equation was used to calculate the biomass of dominant tree species (groups) (Table 1) based on tree height and crown diameter, and DBH was obtained. The total biomass per tree (W_S) was directly calculated, or the ratio of belowground biomass (W_R) to aboveground biomass (W_T) of R_j (Table 1) (Equation (1)) was used to calculate belowground biomass and aboveground biomass, respectively (Equation (2)). The biomass per unit area (S_{W_S}) was calculated as the ratio of total biomass ($\sum W_S$) to area (A) (Equation (3)). Plant carbon storage (M_P) was calculated by multiplying the total biomass ($\sum W_S$) of the tree species (groups) by the corresponding carbon content (CF_j) (Table 1) (Equation (4)). The litter carbon storage (M_L) accounted for 4% of the IPCC's default value [61], which was 4% of the corresponding tree species (groups) plant carbon storage (M_P) (Equation (5)). Plant carbon density (S_M) was calculated as the ratio of total plant carbon storage ($\sum M$) to area (A) (Equation (6)) ("AR-CM-001-V01 Carbon Sink Afforestation Project Methodology" [61]).

$$R_j = \frac{W_R}{W_T} \tag{1}$$

$$W_S = W_T + W_R \tag{2}$$

$$S_{Ws} = \frac{\sum Ws}{A} \tag{3}$$

$$M_P = \sum Ws \times CF_j \tag{4}$$

$$M_L = W_P \times 4\% \tag{5}$$

$$S_M = \frac{\sum M}{A} \tag{6}$$

where R_J is the ratio of the belowground plant biomass to the aboveground plant biomass (%), W_R is the belowground plant biomass (Mg), W_T is the aboveground plant biomass (Mg), W_S is the total plant biomass (Mg), S_{Ws} is the biomass per unit area (Mg ha^{-1}), A is the dominant tree species (groups) area (ha), M_P is the plant carbon storage (Mg C), CFj is the carbon content (%), M_L is the litter carbon storage (Mg C), and S_M is the plant carbon density (Mg C ha^{-1}).

Table 1. Biomass allometric equations of dominant tree species (group) in the study area.

Tree Species (Groups)	Biomass Allometric Equations	R_j	CF_j
Mixed broad-leaved forests	$W_T = 0.0421\ (D^2H)^{0.9703}$	0.262	0.490
Phyllostachys edulis	$W_S = 213.4164\ D^{-0.5805}H^{2.3131}$	/	0.504
Pinus massoniana	$W_T = 0.01672\ (D^2H)^{0.8559}$	0.264	0.511
Cinnamomum camphora	$W_S = 0.056\ (D^2H)^{0.850}$	/	0.492
Castanea mollissima	$W_T = 0.0711\ (D^2H)^{0.9104}$	0.261	0.497
Pinus elliottii	$W_S = 0.0767\ (D^2H)^{0.8971}$	/	0.511
Other sclerophyll broad-leaved forests	$W_T = 0.0711\ (D^2H)^{0.9104}$	0.261	0.497
Cunninghamia lanceolata	$W_S = 0.0657\ (D^2H)^{0.8896}$	/	0.520
Malacophyll broad-leaved forests	$W_R = 0.0459\ H^{0.1067}D^{2.0247}$	0.289	0.485
Mixed bamboo forests	$W_S = 0.140\ H^{0.543}D^{11.062}$	/	0.500
Quercus spp.	$W_T = 0.1199\ (D^2H)^{0.8509}$	0.292	0.500
Populus	$W_1 = 0.0074\ (D^2H)^{1.069;}$ $W_2 = 0.0042\ (D^2H)^{0.9911;}$ $W_3 = 0.0715\ (D^2H)^{0.4489;}$ $W_T = W_1 + W_2 + W_3$ $W_R = 0.0551\ (D^2H)^{0.7061}$	/	0.496
Camellia sinensis	$W_S = 0.140\ H^{0.543}D^{11.062}$	/	0.500
Metasequoia glyptostroboides	$W_S = -5.826 + 0.047D^2H$	/	0.501
Pyrus	$W_T = 0.0711\ (D^2H)^{0.9104}$	0.261	0.497
Other medicinal forests	$W_S = 0.140\ H^{0.543}D^{11.062}$	/	0.500
Salix	$W_R = 0.0459\ H^{0.1067}D^{2.0247}$	0.288	0.485
Other economic forests	$W_T = 0.0711\ (D^2H)^{0.9104}$	0.289	0.485
Prunus persica	$W_R = 0.0459\ H^{0.1067}D^{2.0247}$	0.289	0.485
Cupressus funebris	$W_T = 0.02479\ D^{2.0333}$	0.22	0.510
Pinus thunbergii	$W_T = 0.0711\ (D^2H)^{0.9104}$	0.280	0.515
Other pine forests	$W_1 = 0.0600\ H^{0.7934}D^{1.8005}$ $W_{23} = 0.1377\ D^{1.4873}L^{0.4052}$ $W_R = 0.0417\ H^{-0.0780}D^{2.2618}$ $W_S = W_1 + W_{23} + W_R$	/	0.511
Morus alba	$W_R = 0.0459\ H^{0.1067}D^{2.0247}$	0.289	0.485

W_1, W_2, W_3, W_T, W_R, and Ws represent the biomass of the trunk, branch, leaf, aboveground plant biomass, belowground plant biomass, and total plant biomass, respectively. D is diameter at breast height (cm), H is height (m), and L is crown diameter (m). R_j is the ratio of belowground plant biomass to aboveground plant biomass, and CF_j is the plant carbon content. The *Phyllostachys edulis* biomass allometry equation was derived from Zhang [57]. The biomass allometry equations for Mixed bamboo forests, *Camellia sinensis*, Other medicinal forests, and Other pine forests were derived from Qian [58]. The biomass allometry equation for *Quercus* spp. was derived from Lin [59]. Other biomass allometry equations were derived from "Guidelines on Carbon Accounting and Monitoring for Afforestation Project" (LY/T 2253-2014) (State Forestry Administration, 2014) (Appendix 2) [60].

2.3.2. Estimation of Soil Carbon

The soil organic carbon (SOC) was determined using the potassium dichromate external heating oxidation-ferrous sulfate titration technique [62]. A 5 mL volume of 0.8 M $K_2Cr_2O_7$ and 5 mL of H_2SO_4 were added to 0.1 g of air-dried soil and passed through a 0.149 mm sieve, which was then boiled in an oil bath at 170–180 °C for five min and cooled, after which an indicator was added and titrated with 0.2 M $FeSO_4$.

The organic carbon density and storage of each soil was calculated from the field survey data using Equations (7) and (8) ("AR-CM-001-V01 Carbon Sink Afforestation Project Methodology" [61]):

$$S_{OCD} = \sum_{i=1}^{n} C_i \times D_i \times E_i \times (1 - G_i)/100 \quad (7)$$

$$M_S = A \times S_{OCD} \quad (8)$$

where S_{OCD} is the SOC density (Mg C/ha), C_i is the carbon content of the different soil layers (g kg^{-1}), D_i is the soil bulk density (g cm^{-3}), E_i is the soil thickness (cm), G_i is the volume percentage of gravel with a diameter > 2 mm (%), M_S is the SOC storage (Mg C), and A is the soil area (ha).

2.4. Statistical Analysis

The data were analyzed using SPSS 22.0, and the plots were drawn using ArcGIS 10.6 and RStudio 4.2.2. The organic carbon density and storage at different soil depths were determined. The Kolmogorov–Smirnov test was first applied to check for the normality of the data. For data conforming to a normal distribution, a one-way analysis of variance (ANOVA) was performed. After multiple comparisons, the Tukey test was selected for homogeneity of variance, and Tamhane's T2 test was selected for heterogeneity of variance. Significance was considered at $p < 0.05$.

3. Results

3.1. Forest Ecosystem Carbon Density and Carbon Storage

3.1.1. Area and Biomass of Dominant Tree Species in the Forest Ecosystem

The forest area of Changzhou city measured 61,285.37 ha, and there were 26 main dominant tree species (groups) (Table 2). Among them, the area of Other shrub forests was the largest, accounting for about 20% of the total forest area. The area of Mixed coniferous forests was the smallest, accounting for only 0.08% of the total forest area. In terms of ecosystem, the biomass per unit area of forest plants was 74.32 ± 36.98 Mg ha^{-1}, and the total biomass reached 4.55 ± 2.27 Tg (Table 2). In terms of individual tree species (groups), the unit biomasses of Mixed coniferous forests and *Metasequoia glyptostroboides* were the highest, measuring 122.70 ± 10.70 Mg ha^{-1} and 120.04 ± 51.36 Mg ha^{-1}, respectively. The Mixed broad-leaved forests (0.90 ± 0.24 Tg), however, had the highest total biomass, accounting for about 20% of the total forest plant biomass. *Morus alba* had the lowest biomass per unit area (4.35 ± 1.05 Mg ha^{-1}) and the lowest total biomass (343.03 ± 82.91 Mg).

Table 2. Area and biomass of main dominant tree species (groups) in forest ecosystems.

Tree Species (Groups)	Area (ha)	Biomass per Unit Area (Mg ha^{-1})	Total Biomass (Mg)
Other shrub forests	12,269.66	18.80 ± 5.12	230,669.60 ± 62,820.66
Mixed broad-leaved forests	9023.88	99.80 ± 26.35	900,559.61 ± 237,813.57
Phyllostachys edulis	5021.99	87.60 ± 12.56	439,921.92 ± 63,072.64
Pinus massoniana	4904.15	87.09 ± 9.96	427,113.79 ± 48,869.33
Cinnamomum camphora	4687.33	85.35 ± 5.36	400,065.62 ± 25,142.1
Castanea mollissima	4408.13	89.38 ± 15.85	394,004.41 ± 69,878.05
Pinus elliottii	3699.43	98.81 ± 23.19	365,530.80 ± 85,772.58
Other sclerophyll broad-leaved forests	3569.27	72.23 ± 11.96	257,825.45 ± 42,678.90
Cunninghamia lanceolata	2805.61	105.63 ± 30.56	296,345.17 ± 85,733.24

Table 2. *Cont.*

Tree Species (Groups)	Area (ha)	Biomass per Unit Area (Mg ha^{-1})	Total Biomass (Mg)
Malacophyll broad-leaved forests	2315.77	66.07 ± 8.35	153,014.34 ± 19,334.88
Mixed bamboo forests	1447.98	57.91 ± 7.17	83,854.74 ± 10,378.72
Quercus spp.	1410.08	95.00 ± 3.61	133,958.00 ± 5084.13
Populus	1007.52	115.65 ± 28.84	116,523.61 ± 29,061.57
Mixed coniferous and broad-leaved forests	991.00	114.07 ± 33.95	113,038.59 ± 33,642
Camellia sinensis	874.26	19.38 ± 3.48	16,944.33 ± 3046.37
Metasequoia glyptostroboides	604.46	120.04 ± 51.36	72,561.42 ± 31,043.75
Pyrus	548.44	65.43 ± 21.24	35,883.28 ± 11,650.84
Other medicinal forests	356.30	57.43 ± 5.40	20,460.37 ± 1924.7
Salix	337.49	65.39 ± 8.23	22,069.12 ± 2776.83
Other economic forests	277.57	66.81 ± 31.07	18,543.50 ± 8624.92
Prunus persica	194.11	87.63 ± 9.94	17,009.27 ± 1929.78
Cupressus funebris	173.99	75.00 ± 14.1	13,049.53 ± 2452.77
Pinus thunbergii	121.37	89.47 ± 21.06	10,859.08 ± 2556.66
Other pine forests	105.66	78.22 ± 32.37	8265.40 ± 3420.47
Morus alba	78.85	4.35 ± 1.05	343.03 ± 82.91
Mixed coniferous forests	51.10	122.7 ± 10.7	6269.36 ± 546.85
Total	61,285.37	74.32 ± 36.98	4,554,683.34 ± 2,266,564.36

3.1.2. Forest Plant and Litter Carbon Density and Carbon Storage

The carbon density of the forest plants was 36.63 ± 5.43 Mg C ha^{-1} (Table S1), accounting for 27% of the total forest ecosystem carbon density (Figure 2). In terms of single tree species (groups), *Metasequoia glyptostroboides* had a higher plant carbon density (55%), and *Morus alba* had a lower plant carbon density (1%) (Figure 2). In addition, the total carbon storage of the forest plants was 2.24 ± 0.33 Tg C (Table S1). Among these dominant tree species (groups), Mixed broad-leaved forests and *Phyllostachys edulis* contributed the most to carbon storage, and the sum of the two accounted for about 30% of the total plant carbon storage (Figure 3). *Morus alba* had the lowest carbon storage, accounting for only 0.01% of the total plant carbon storage (Figure 3).

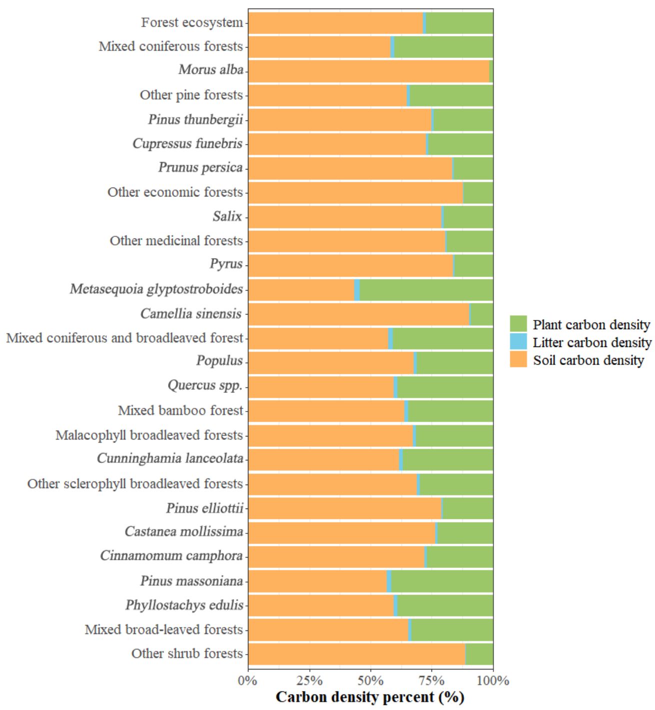

Figure 2. Percentage of carbon density of different carbon pools in forest ecosystems and tree species (groups).

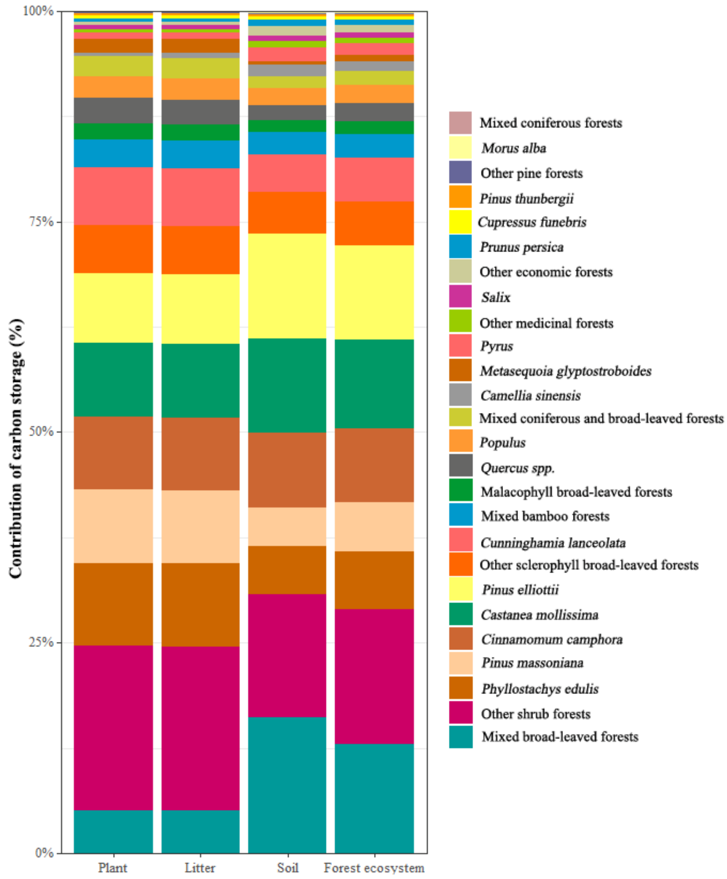

Figure 3. Percentage of carbon storage of tree species (groups) from different carbon pools in forest ecosystems.

The forest litter carbon density and carbon storage were 1.47 $\pm$ 0.22 Mg C ha^{-1} and 90,017.12 $\pm$ 13,436.70 Mg C (Table S1), respectively. Among these dominant tree species (groups), Mixed coniferous forests had the highest litter carbon density (2.50 $\pm$ 0.22 Mg C ha^{-1}), and Mixed broad-leaved forests had the highest litter carbon storage (about 20%). The litter carbon density and carbon storage of *Morus alba*, however, were the lowest (Figure 3).

3.1.3. Forest Soil Carbon Density and Carbon Storage

Although the average forest soil carbon density was 95.73 $\pm$ 6.36 Mg C ha^{-1} (Table S1), the soil carbon densities of Other economic forests and *Prunus persica* were higher (Figure 4). In addition, although the total carbon storage of forest soil was 5.87 $\pm$ 0.39 Tg C (Table S1), the carbon storages of Other shrub forests and Mixed broad-leaved forests were higher, with the two accumulatively accounting for 30% of the total forest soil carbon storage (Figure 3). In terms of the forest soil profile, the carbon density and carbon storage decreased significantly with soil depth layer ($p < 0.001$) (Figures 4 and 5) (Table 3). In addition, the soil carbon storage was mainly distributed in the surface layer, that is, 0 to 40 cm, accounting for about 70% of the total carbon storage of the soil profile (Figure 5).

Table 3. Effects of soil depth on forest soil carbon density and carbon storage.

Index	Soil Depth	
	F Value	*p* Value
Soil carbon density	101.349	<0.001 ***
Soil carbon storage	16.446	<0.001 ***

Represents statistical significance, with *** $p < 0.001$; $n = 312$.

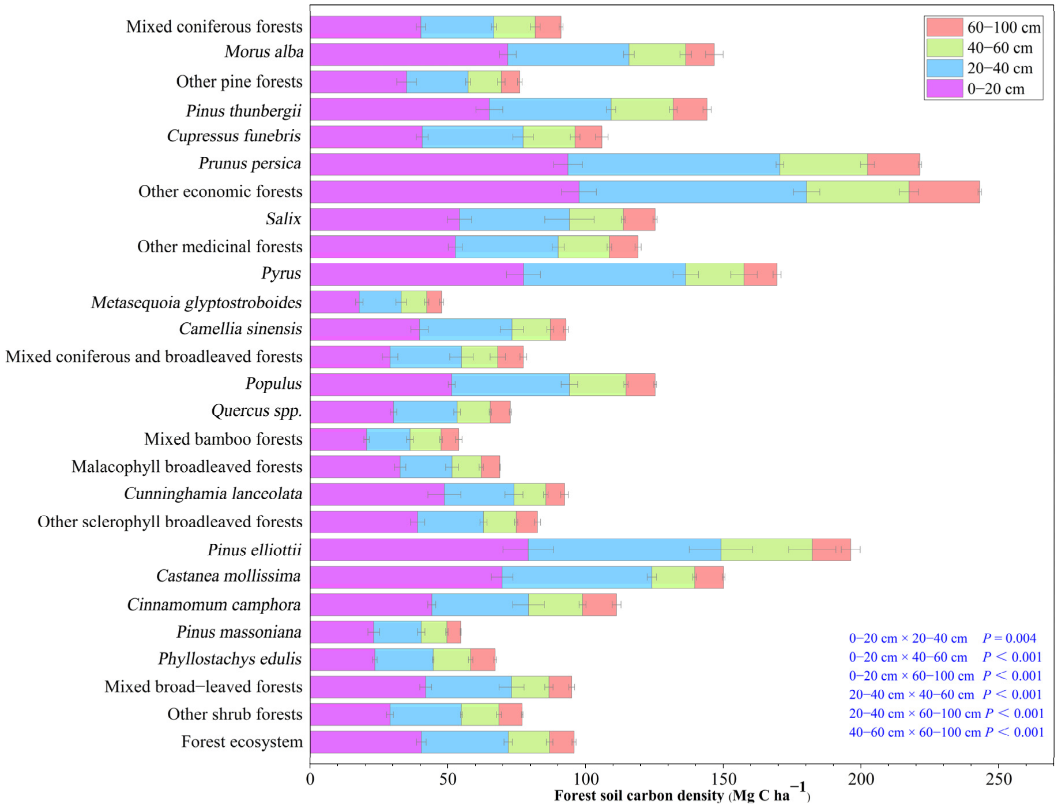

Figure 4. Soil carbon density at different depths in the forest ecosystem.

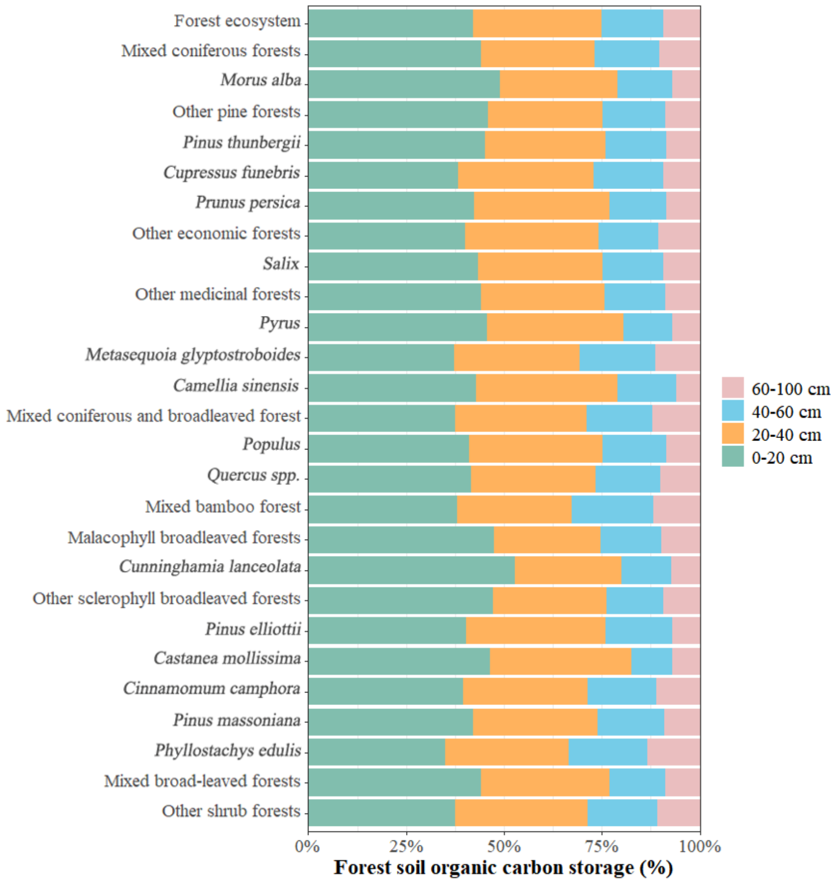

Figure 5. Percentage of soil carbon storage at different depths in the forest ecosystem.

3.1.4. Total Carbon Density and Carbon Storage of Forest Ecosystems

The total organic carbon density of the forest ecosystem was 133.83 ± 3.20 Mg C ha^{-1} (Table S1). Among them, plant (27%) and soil (72%) contributed the most, and litter accounted for only 1% (Figure 2). The total carbon storage of the forest ecosystem was 8.20 ± 0.10 Tg C (Table S1). The sum of the carbon storage of Other shrub forests and Mixed broad-leaved forests accounted for nearly 30% of the total carbon storage, and the accumulation of the top 10 dominant tree species (groups) exceeded 80% of the total carbon storage (Figure 3).

3.2. Green Space Ecosystem Carbon Density and Carbon Storage

The total area of the green space ecosystem in Changzhou measured 11,933.61 ha, of which the area of the attached green space was the largest, and the area of the square green space was the smallest. The carbon density and carbon storage of the green land plants were 48.51 ± 15.33 Mg C ha^{-1} and 0.58 ± 0.18 Tg C, respectively (Table S2). It is worth noting that the plant carbon storage of the attached green space, the park green space, and the protective green space each accounted for almost 30% of the total plant carbon storage (Figure 6). The carbon density and carbon storage of the green space soil were 81.39 ± 18.57 Mg C ha^{-1} and 0.97 ± 0.22 Tg C, respectively (Table S2). The attached green space had the highest soil carbon storage. In addition, the sum of the soil carbon storage of the attached green space and the park green space reached 80% of the total green space soil carbon storage (Figure 6). The total carbon density and carbon storage of the green space ecosystem were 129.90 ± 18.57 Mg C ha^{-1} and 1.55 ± 0.22 Tg C, respectively. The main contributors of this carbon storage were plants (37%) and soil (62%). Litter accounted for only 1% (Table S2). In general, the carbon storage of the green space ecosystem was mainly due to the attached green space and the park green space, which, together, accounted for 75% of the total carbon storage (Figure 6).

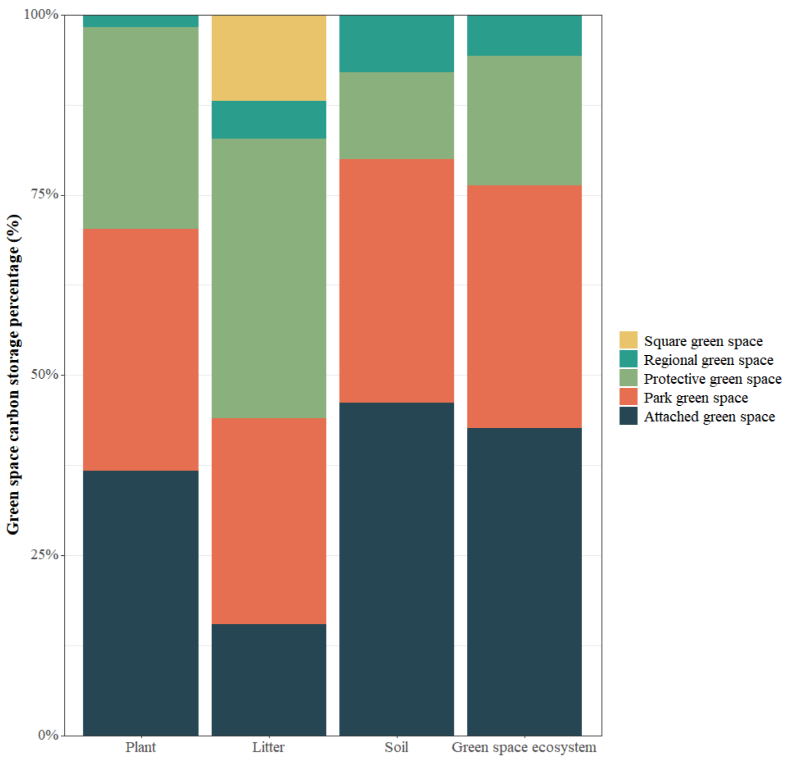

Figure 6. Percentage of carbon storage of each carbon pool in the green space ecosystem.

3.3. Wetland Ecosystem Carbon Density and Carbon Storage

The wetland area of Changzhou city measured 74,307.42 ha (Table 4). It was divided into seven parts according to the administrative area. The city's wetlands were mainly distributed in Wujin District, Jintan District, and Liyang District, with the wetland area of these three districts accounting for 95% of the total wetland area. Similarly, soil carbon storage in Wujin District, Jintan District, and Liyang District accounted for 95% of the total wetland soil carbon storage (Table 4). In addition, the average carbon density of the wetland soil was 20.83 ± 5.34 Mg C ha^{-1}. It is worth noting that the wetland area in the Economic Development Zone was the smallest but had the highest soil carbon density (40.23 ± 32.41 Mg C ha^{-1}) (Table 4).

Table 4. Carbon density and carbon storage of wetland in each district.

District	Wetland Area (ha)	Soil Carbon Density (Mg C ha^{-1})	Soil Carbon Storage (Mg C)
Wujin District	26,044.02	22.11 ± 6.24	575,901.18 ± 162,521.86
Jintan District	24,392.80	20.43 ± 6.76	498,379.74 ± 164,816.03
Liyang City	20,563.43	19.31 ± 7.00	397,093.01 ± 143,872.14
Xinbei District	2792.83	23.89 ± 3.96	64,104.38 ± 11,047.58
Tianning District	332.67	20.29 ± 3.53	6750.32 ± 1173.52
Bell Tower District	93.39	19.80 ± 0.61	1849.21 ± 56.65
Economic Development Zone	88.28	40.23 ± 32.41	3551.68 ± 2860.85
Total	74,307.42	20.83 ± 5.34	1,547,629.52 ± 397,102.00

3.4. Total Ecosystem Carbon Density and Carbon Storage

The average carbon density of the three carbon sink ecosystems in Changzhou was 83.34 ± 4.91 Mg C ha^{-1} (Table S3). From the perspective of carbon pools, the Changzhou regional carbon storage contributors were plant (25%), soil (74%), and litter (1%) (Figure 7). In addition, the average carbon density of forest ecosystems was the highest, and that of wetland ecosystem was the lowest. The average carbon density of green space ecosystems was in the middle (Figure 8). The total carbon storage of the three major carbon sink ecosystems in Changzhou was 11.30 ± 0.67 Tg C (Table S3). Soil accounted for 74%, plants accounted for 25%, and litter accounted for less than 1% of the total carbon storage (Figure 7). Forest ecosystems clearly contributed the most (72%) to carbon storage, with green space ecosystems and wetland ecosystems accounting for 14% each (Figure 7).

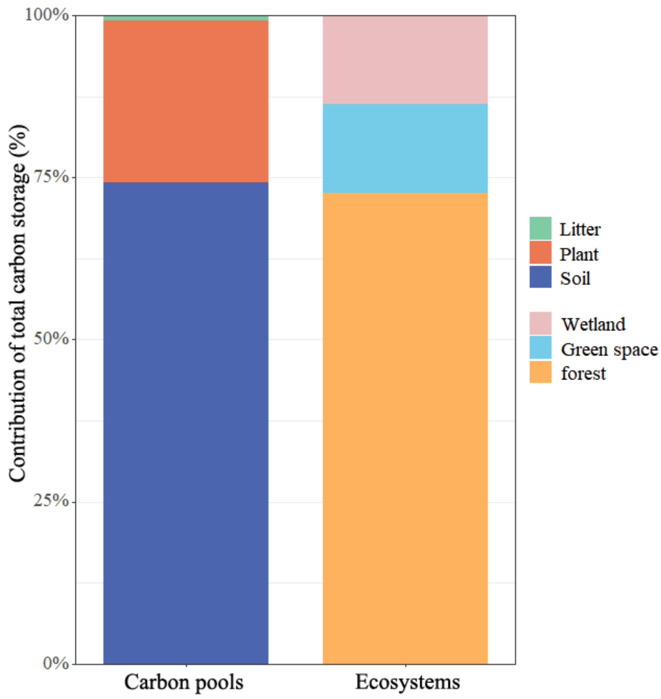

Figure 7. Percentage of total carbon storage in different carbon pools and ecosystems.

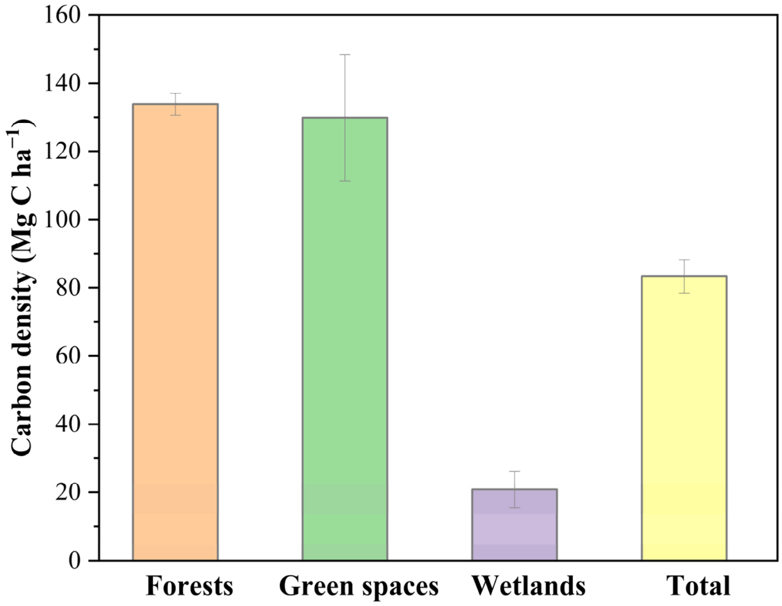

Figure 8. Carbon density of different ecosystems.

4. Discussion

4.1. Forest Ecosystem Biomass and Carbon Density

Forest ecosystems are important carbon pools and play a key role as terrestrial ecosystem carbon sinks. Forest biomass is widely used to assess the patterns, processes, and dynamics of the forest ecosystem's carbon cycle at the local, regional, and global scales [63]. There are several studies on the aboveground biomass of single tree species (groups) [64]. There are, however, fewer studies on the biomass of tree species (groups) at the regional scale, and these studies provide uncertain results [65]. The estimation of forest biomass and carbon storage using regional forest resource patch maps, field survey data, and laboratory experiments is considered accurate and reliable [66]. In the present study, the biomass of each species (group) was obtained using the allometric growth model. For example, the biomass per unit area of bamboo stood at the top for Jiangsu Province [67], and this was mainly due to the geographical location. The *Phyllostachys edulis* forests in Jiangsu Province are mainly located in Southern Jiangsu [68]. The density of *Pinus massoniana* was much lower than the national average (127.65 Mg ha^{-1}), and this is mainly due to factors such as climate, tree age, and tree density [64].

Carbon content, based on the biomass of each tree species (group), was used to calculate carbon storage and carbon density. The carbon density and carbon storage of the Changzhou forest ecosystem vegetation were 38.10 ± 5.65 Mg C ha^{-1} and 2.34 ± 0.35 Tg C, respectively (Table S1), and this comprised both plant and litter carbon. The Changzhou forest ecosystem vegetation's carbon density was slightly lower than that of the Middle tropics (44.23 Mg C ha^{-1}) and South tropics (44.96 Mg C ha^{-1}) [69]. This may be because, in the present study, some shrub and economic tree species were included, resulting in an overall low carbon density. In addition, based on the carbon density and carbon storage data of the forest vegetation in Changzhou city, Jiangsu Province, in 2010 (17.72 Mg C ha^{-1}, 1.41 Tg C) and 2015 (21.31 Mg C ha^{-1}, 2.09 Tg C), forest vegetation was found to present carbon sink properties from 2010 to 2020. In this study, the average plant carbon density of other shrubs was lower than that of shrubs in the Heshan forest ecosystem of South tropical Guangdong Province (14.96 ± 1.09 Mg C ha^{-1}). The vegetation carbon density of *Cunninghamia lanceolate* (57.12 ± 16.53 Mg C ha^{-1}) in the Yangtze River Basin was at the medium level (~25.32 to 90.89 Mg C ha^{-1}). In addition, the carbon density of *Populus* (57.36 ± 14.31 Mg C ha^{-1}) was much higher than the average carbon density of *Populus* in Changzhou in 2010 (22.25 Mg C ha^{-1}) [70]. The vegetation carbon density of various tree species was low in the subtropical zone, but the vegetation carbon storage increased compared with the past, suggesting that the forest vegetation in Changzhou has been acting as a carbon sink. The forest soil carbon pool is also an important indicator for determining the carbon sequestration potential of forest ecosystems [71,72]. The forest soil carbon density (95.73 ± 6.36 Mg C ha^{-1}) in Changzhou, in the present study, was found to be lower than the average forest soil carbon density in China (122.72 Mg C ha^{-1}) [73]. This may be because Changzhou forest is mainly a young forest. In addition, forest organic carbon density was mainly determined by forest litter import and humification, and it increased with an increase in forest age [74]. The organic carbon density was greatly affected by plant roots and root exudates, and it increased with an increase in forest age [75]. The soil profile showed that organic carbon density decreased significantly with an increase in soil depth (Figure 4), and this is consistent with the results of several studies [57,76]. It is well-known that forest vegetation and soil are the two most important sources of carbon pools in the forest ecosystem. Hou [67] estimated that the carbon storage of forest soil in the Yangtze River Economic Belt accounted for 81.46% of the total forest ecosystem carbon storage in 2020. This is higher than estimated in our study, where the carbon storage of forest soil in Changzhou accounted for about 72% of the forest ecosystem. The estimation by Hou, however, is significantly higher than the estimated soil carbon contribution (65.98%) of the forest ecosystem in the Northwest Altai Mountains [27].

4.2. Greenland and Wetland Ecosystems' Carbon Density

Urban green space ecosystems have great potential for climate change mitigation [30,66,77]. Urban green spaces are also an important part of urban green infrastructure. Chen [30] estimated that the average carbon density of vegetation in the green infrastructure of 35 cities was 21.34 Mg C ha^{-1}. In the present study, green spaces were comprehensively divided into five categories, and the carbon density of urban green space vegetation in Changzhou was estimated as 48.51 ± 15.33 Mg C ha^{-1}, which is relatively high. In recent years, many studies have focused on the carbon density and carbon storage of green space soils [78–82]. Climate and city-specific factors, such as urban age, urban area, urban population, and urban management, however, may affect the urban soil carbon [8,83]. Our estimates of soil carbon density in the green space ecosystems was, therefore, compared with those of warm temperate and subtropical regions in China. In the present study, the soil carbon density in the ~0 to 20 cm layer (45.22 ± 8.18 Mg C ha^{-1}) was higher than that measured in the warm temperate zone (39.80 Mg C ha^{-1}) [84] and the subtropical zone (25.90 ± 1.31 Mg C ha^{-1}) [79]. Moreover, the soil carbon density in the ~0 to 40 cm layer (81.39 ± 18.57 Mg C ha^{-1}) was higher than that measured in the ~0 to 50 cm layer (74.08 ± 20.20 Mg C ha^{-1}) in nearby Shanghai [82]. Clearly, the green soil in Changzhou is efficient at storing carbon. The soil of the urban green space in Changzhou was backfill and underwent some compaction and management. As a result, the organic carbon content was mainly located on the surface [85]. We, therefore, only performed an analysis of carbon storage and carbon density at the ~0 to 40 cm depth. We also found that the soil carbon density in the green space was lower than that of natural forests [86]. It is worth noting, however, that the soil carbon storage in Changzhou's green space was more than 60% of the total carbon storage of the green space, highlighting soil as an important carbon pool in the green space ecosystem. Tao et al. [87] estimated that the average carbon density of the urban green space ecosystem in Changzhou from ~1986 to 2011 was 73.82 Mg C ha^{-1} (~0–100 cm). In recent years, Changzhou City's economy has developed rapidly, and the construction of urban green spaces has also been steadily advancing. The carbon density of urban green spaces has reached 129.90 ± 18.57 Mg C ha^{-1}, which is slightly lower than the carbon density of forest ecosystems (133.83 ± 3.20 Mg C ha^{-1}) (Figure 8).

Carbon stored in the inland freshwater wetlands is known as blue–green carbon [88,89]. Water is the main factor affecting the carbon pool in inland freshwater wetlands. Continuous anaerobic conditions in flooded water lead to slow decomposition and the deposition of organic matter in wetlands, increasing organic carbon storage in the soil [90,91]. The SOC content in the wetlands of China was estimated to account for ~85.4% to 93.5% of the total organic carbon of the wetland ecosystems [92]. In addition, freshwater wetland soils can absorb ~1.38 to 2.26 Mg C ha^{-1} y^{-1}, which is much higher than that of forest soils [41,93]. Located in the Yangtze River Delta, Changzhou has numerous rivers, lakes, and constructed wetlands, which are of significance as temporary storage areas for SOC [52,94,95]. In the present study, the soil carbon density in the ~0 to 20 cm layer of the wetland ecosystem (20.83 $\pm$ 5.34 Mg C ha^{-1}) was estimated to be similar to that of the adjacent Chaohu Lake (~0–20 cm, 22.80 Mg C ha^{-1}) [48] and the Ningxia Plain wetland (~0–40 cm, 26.69 Mg C ha^{-1}) [52]. It was, however, slightly lower than that of the Northern Gulf of Mexico wetlands (~0–10/15 cm, ~34–47 Mg C ha^{-1}) [50] and much lower than that of the subalpine lake delta wetlands (~0–30 cm, ~140–1256 Mg C ha^{-1}) [54]. The SOC pool is subject to dynamic equilibrium processes and varies depending on the input and output of carbon sources [96]. Wetland soil carbon is, in particular, highly sensitive to changes in the surrounding environment [97]. The Changzhou wetland ecosystems mainly include the Yangtze River, the Beijing–Hangzhou Grand Canal, and some constructed wetlands. These wetlands are distributed in areas of dense population, developed shipping, and rapid economic development, and they are subject to obvious human interference [98,99]. This is an important reason for the low carbon density and storage of these wetland soils. In addition, due to the limitations of field sample collection, we only collected ~0–20 cm of wetland sediment carbon for measurements, so the carbon density of the wetland ecosystem in Changzhou City was lower than that of the forest and urban green space ecosystems (Figure 8).

5. Conclusions

Forests, green spaces, and wetlands are important carbon storage ecosystems in Changzhou. In this study, the forest resource management map (including wetland) and green space system planning map of Changzhou city, combined with field investigation and laboratory experimental analysis, were used to estimate the carbon storages and densities of the forest, urban green space, and wetland ecosystems in Changzhou city. Forest ecosystems contributed the most to carbon storage (72%), while green space ecosystems and wetland ecosystems each accounted for 14% of the total carbon storage. The average carbon density of the forest ecosystem was the highest, and that of the wetland ecosystem was the lowest. The average carbon density of the green space ecosystem was in the middle. Clearly, the forest, green space, and wetland ecosystems in Changzhou city all had large carbon storage potentials, with the soil carbon storage being the largest and the carbon density decreasing with an increase in soil depth. In the current era of global warming and climate change, the results of the present study are useful for understanding the carbon density and carbon storage status of regional forests, green spaces, and wetland ecosystems, and they provide a reference for regional carbon sink research. Our future work will focus in-depth on the dynamic changes of regional carbon storage and carbon density to obtain a deeper and more comprehensive understanding of carbon sequestration in regional forest, green space, and wetland ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15020303/s1, Table S1: Carbon density and storage of each forest type; Table S2: Carbon density and carbon storage of each green space type; Table S3: Carbon density and carbon storage of each ecosystem.

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Data Availability Statement: The data presented in this study are available on request from the corresponding authors. The data is not publicly available due to confidentiality.

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