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Article

A Basin-Scale Estimation of Carbon Stocks of a Forest Ecosystem Characterized by Spatial Distribution and Contributive Features in the Liuxihe River Basin of Pearl River Delta

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Abstract: Forest ecosystems make a greater contribution to carbon (C) stocks than any other terrestrial ecosystem. To understand the role of regional forest ecosystems in global climate change and carbon exchange, forest C stocks and their spatial distribution within the small (2300 km^2) Liuxihe River basin in China were analyzed to determine the different contributors to the C stocks. Forest C stocks were quantified by measuring the biomass of trees, understory vegetation, litter and roots, as well as soil organic C, using data from field samples and laboratory experiments. The results showed that forests stored 38.04 Tg·C in the entire basin, with secondary and planted forests accounting for 89.82% and 10.18%, respectively, of the stored C. Five types of forests, a subtropical evergreen broad-leaved forest, a subtropical coniferous and broad-leaved mixed forest, a subtropical coniferous forest, a timber forest, and a non-wood forest, stored 257.55 ± 15.01, 218.92 ± 9.59, 195.24 ± 18.29, 177.42 ± 17.55, and 117.86 ± 6.04 Mg·C·ha^{-1}, respectively. In the forest ecosystem C stocks of the basin, soils on average contributed about 73.78%, not including root underground biomass. The results of this study, which provide baseline forest C stock data for ecosystem services and regional C flux research, are useful to support the basin-scale forest management and land use change.

Keywords: natural secondary forest; planted forest; vegetation biomass carbon; soil organic carbon

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1. Introduction

Forest ecosystems represent the most important carbon (C) sink of all terrestrial ecosystems. The quality and dynamics of regional forest coverage, including afforestation, deforestation, and forest conservation, therefore are very important factors in mitigating climate change in the context of sustainable development [1–3]. Forest management is very important if carbon sequestration is to partially offset CO_2 emissions [4–6]. During the 1950s and 1960s in China, natural forests were largely destroyed, and then secondary forests naturally formed during the following 50 years. In the same period, afforestation and reforestation was widely performed. Thus, the main forest components are natural secondary forest and planted forests, like in the Liuxihe River basin. The Food and Agricultural Organization of the United Nations (FAO) (2010) reported that global forests exhibited a net gain in area from 2000 to 2010, primarily resulting from large-scale afforestation and forest conservation in China [7].

It has been fully recognized that the forest C stocks are affected by specific forest management strategies [8]. Different forest management activities cause differences in the magnitude of C stocks and the patterns of C sequestration in forest ecosystems [9]. Due to the long-term stable C sequestration, which is one of the important ecosystem services provided by forests, more and more natural secondary forests have been protected under strict conservation measures [10–12]. Planted forests are mostly managed for commercial purposes, with periodic logging and harvesting, to meet the world’s demand for industrial raw materials and food [13–15]. Nevertheless, besides the high

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economic value, planted forests play an important role in C sequestration, both at a regional and global scale [16,17].

Forest ecosystems store large amounts of biomass C and soil C, and many recent studies of C stocks have examined the climax communities of forests while the consideration of understory vegetation has been commonly neglected [18–20]. The composition of tree species must affect the forest canopy and the understory vegetation, and it could continue to affect soil properties [21,22]. Both arbor and understory layers consist of the living biomass C pools in forests, which are can be above and/or below the ground floor. The litter mass remaining represents a critical pathway linking the above-and belowground processes. Forest litter is the main carrier and medium between the vegetation and soil C pools [23–25], and litter decomposition may have a substantial impact on forest soil C stocks [26]. Typical vegetation C densities range from 120 to 194 $Mg·C·ha^{-1}$ in tropical forests and from 60 to 130 $Mg·C·ha^{-1}$ in temperate forests [27], and about two-thirds of the total C in forest ecosystems is contained in soils [28]. Spatial estimations of forest soil C stocks are generally performed by landscape models [29] and digital terrain models [30,31] using RS (remote sensing) and GIS (geographic information system) technologies. Many studies estimated that soil C stocks in forests have a potential role in reducing the concentration of CO_2 in the atmosphere [32–34]. The accumulation of soil organic C (SOC) in forest soils largely depends on soil types [35], stand age [36], and plant community composition [37,38]. Although vegetation C has increased, soil C is highly variable in both time and space owing to different forest vegetation structures [39] and management practices [40]. It is hypothesized that the C sinks of forest ecosystems within a basin are related to multiple factors (such as their floristic composition, the conservation and/or logging practices that they are subjected to, and local environmental factors), and that the differences in C stocks and ecosystem services exist between different ecosystems because of differences in management pattern and forest community structures.

In the study area of the Liuxihe River basin, most primary forests have been exhausted due to over-exploitation resulting from the development of both the population and the industries in the region. The extensive forest logging began in the 1950s in the study area, and continued up until the early 1960s. It is noteworthy that new forests have covered about 75% of the entire basin area as a result of reforestation efforts and the protection of natural forests, including both private and government-owned plantations. The local plantations use 7–15 year logging cycles in timber forests and annual harvests in non-wood forests. Forest management has diverse goals, such as conservation, timber production, non-wood forest products, and management treatments include mimicking natural forest disturbances, dynamic intermediate felling, and site preparation. The C stocks and ecosystem services of the Liuxihe River basin, with its large areas of secondary and planted forests, as well as developed industries downstream of the basin, have not been examined. The method to assess C stocks under a basin scale has been developed based on detailed multiple forest inventory and GIS techniques. In addition, the spatial and contributive features of different C pools were useful to understand the ecosystem services and regional C flux. Based on the results from this study, further decision supports can be provided for considerations surrounding basin-scale forest management and land use change.

2. Materials and Methods

2.1. Study Area and Sample Site

The Liuxihe River basin, located in northern Pearl River Delta, southern China, is an important source of drinking water for Guangzhou (Figure 1). The main river is approximately 171 km long, and the basin covers an area of approximately 2300 km^2. It has a subtropical monsoonal climate, with an average annual temperature, precipitation, and relative humidity of 22.7 °C, 1727 mm, and 76.6%, respectively. The topography of its upstream area comprises mostly hills and streamlets, and plains and hills are found in its middle and lower reaches. Soil parent materials are mainly granite, quartz, and sandshale, and the soil classification mainly includes yellow ferralsols, latosols, and paddy soil. The Liuxihe Reservoir is located in the middle reach of the basin.

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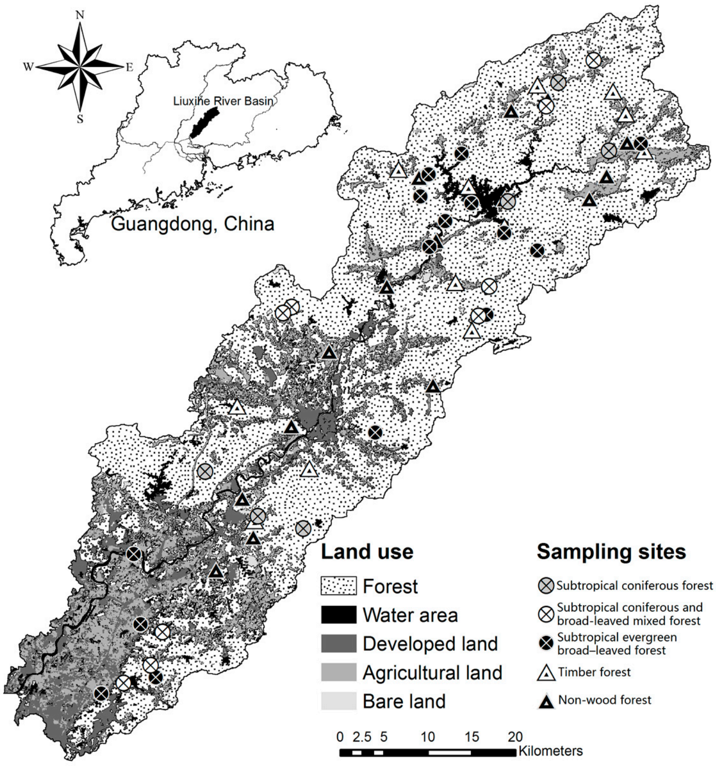

Figure 1. Land use in the study area and the distribution of the sampling sites.

Natural forest conservation areas and plantation sites represent two widely applied forest management patterns in the Liuxihe River basin. Therefore, the natural secondary forest and planted forest were identified to be the major forest types. Natural secondary forests and planted forests were further classified based on remote sensing characteristics and local plantation map data, respectively. The zonal vegetation is a south subtropical evergreen broad-leaved forest (SBF), and *Castanopsis fissa* *Castanopsis fissa* (Champ. Ex Benth.) Rehd. & E. H. Wils., *Cryptocarya concinna* Hance, *Castanea henryi* (Skan) Rehd. & E. H. Wils., *Ficus variolosa* Lindl. Ex Benth., *Castanopsis carlesii* (Hemsl.) Hayata, and *Elaeocarpus sylvestris* (Lour.) Poir. are the dominant species. Subtropical coniferous forests (SCFs) and subtropical coniferous and broad-leaved mixed forests (SCBFs) are widely distributed in the basin, and the forest communities are at an early or middle stage of succession. SCF, SCBF, and SBF were selected as sampling types of secondary forest (Table 1), and two types of planted forest, a timber forest (TF) and a non-wood forest (NF), were also sampled (Table 1). Plot series were listed in Table 1 in order to provide details of the sites and classifications of the associated vegetation communities.

Table 1. Sampling communities of different forest types.

Forest Type		Community	Forest Age (Years)	Area (ha)	Plot Series	Number of Replicates
Natural secondary forest	SCF	*Pinus massoniana* Lamb. + *Adina pilulifera* (Lam.) Franch. ex Drake	20–25	12,747	a	3
		Cunninghamia lanceolata (Lamb.) Hook. + *Psychotria rubra* (Lour.) Poir.	20–25		b	3
	SCBF	*Pinus massoniana* + *Castanea henryi* (Skan) Rehd. & E. H. Wils. + *Schima superb* Gardner & Champ.	25–30	23,962	a	3
		Pinus massoniana Lamb. + *Castanopsis fissa* (Champ. Ex Benth.) Rehd. & E. H. Wils. + *Schima superb*	30–35		b	3

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		Cunninghamia lanceolata + *Schima superb* + *Psychotria rubra* (Lour.) Poir.	30–35		c	3
	SBF	*Castanopsis fissa* + *Castanopsis carlesii* (Hemsl.) Hayata + *Schima superb*	30–35	102,643	a	3
		Cryptocarya concinna Hance + *Castanea henryi* + *Schima superb*	40–50		b	3
		Ficus variolosa Lindl. Ex Benth. + *Castanopsis faberi* Hance + *Lithocarpus glaber* (Thunb.) Nakai	45–55		c	3
		Castanopsis carlesii + *Cinnamomum porrectum* (Roxb.) Kosterm + *Machilus chinensis* (Benth.) Hemsl.	45–55		d	3
		Elaeocarpus sylvestris (Lour.) Poir. + *Sloanea sinensis* (Hance) Hemsl. + *Pithecellobium clypearia* (Jack) Benth.	45–55		e	3
Planted forest	TF	*Pinus massoniana*	5–15	2319	a	3
		Cunninghamia lanceolata	5–15	1371	b	3
		Eucalyptus urophylla S. T. Blakely	3–7	3358	c	3
		Phyllostachys heterocycla (Carr.) Mitford' Pubescens'	—	3079	d	3
	NF	*Litchi chinensis* Sonn.	6–30	16,543	a	9
		Vatica mangachapoi Blanco	5–10	492	b	3
		Citrus reticulata Blanco	5–10	580	c	3

SCF, subtropical coniferous forests; SCBF, subtropical coniferous and broad-leaved mixed forests; SBF, subtropical evergreen broad-leaved forest; TF, timber forest; NF, non-wood forest.

The sampling plot size was 30 × 30 m^2, with three replicates, except for the Litchi community, which had nine replicates because numerous Litchi forests are present in the basin. A total of 57 plots were sampled (Figure 1).

2.2. Sampling and Measurements

Five pools of forest ecosystem C stocks, aboveground trees, understory vegetation, litter, roots, and soil were assessed in the investigation. Within each sampling area, the aboveground C stock was obtained by measuring the biomass of living trees, shrubs, grasses, and forest litter. The belowground C stock was obtained by measuring tree roots and soil organic carbon (SOC).

All vegetation species, community structure characteristics in each sample plots, and geographic coordinates, orientations, and gradients were surveyed. For tree biomass measurements, the DBH (diameter at breast height, 1.3 m) and height of each individual tree were measured. Tree biomass (including aboveground trees and underground roots) was calculated using the allometric biomass regression models proposed by Feng et al., Li et al., and Chen et al. (Table 2) [41–43]. The tree C stock was calculated by multiplying tree biomass by the wood carbon concentration [44,45]. Biomass of the understory vegetation and litter were measured by the harvest method. Three 1 m × 1 m subplots were randomly distributed within each 30 m × 30 m plot. All shrubs, herbaceous plants, non-woody vegetation, fallen branches, leaves, and other downed woody debris within the area were collected and weighed on site after removing any soil and rocks, then a portion of the samples was brought to the laboratory. The fresh samples were oven-dried to constant weight at 70 °C for 72 h. Dry weight data were obtained and converted to biomass. Dried understory vegetation and litter samples were ground and sieved through a 0.25 mm mesh. Carbon concentrations of understory vegetation and litter were measured in the laboratory according to standard procedures [46]. Carbon stocks of the understory vegetation and litter were calculated as the biomass multiplied by the carbon concentration.

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Table 2. Allometric biomass regression models for tree biomass calculations.

Tree Species	Regression Equation (B[1], D[2], H[3]) and the Statistics
Pinus massoniana	$B_A = 0.0245(D^2H)^{1.0209}$, $R^2 = 0.97$; $B_R = 0.0126(D^2H)^{0.9024}$, $R^2 = 0.97$ [43]
Cunninghamia lanceolata	$B_A = 0.093(D^2H)^{0.8030}$, $R^2 = 0.98$; $B_R = 0.0073D^{2.3125}$, $R^2 = 0.99$ [42]
Eucalyptus urophylla	$B_A = 0.1691(D^2H)^{0.7472}$, $R^2 = 0.95$; $B_R = 0.1723(D^2H)^{0.5630}$, $R^2 = 0.90$ [43]
Phyllostachys heterocycla	$B_A = 0.6439D^{1.5373}$, $R^2 = 0.91$; $B_{R1} = 0.3404D^{1.1899}$, $R^2 = 0.97$, $B_{R2} = 0.3087D^{1.2892}$, $R^2 = 0.80$, $B_R = B_{R1} + B_{R2}$, [41]
Cryptocarya concinna, *Cinnamomum porrectum,* *Machilus chinensis*	$B_S = 0.0440(D^2H)^{0.9169}$, $R^2 = 0.99$; $B_P = 0.023(D^2H)^{0.7115}$, $R^2 = 0.95$; $B_B = 0.0104(D^2H)^{0.9994}$, $R^2 = 0.92$; $B_L = 0.0188(D^2H)^{0.8024}$, $R^2 = 0.91$; $B_A = B_S + B_P + B_B + B_L$; $B_R = 0.0197(D^2H)^{0.8963}$, $R^2 = 0.99$ [41]
Castanea henryi, *Castanopsis fissa,* *Castanopsis carlesii,* *Castanopsis faberi,* *Lithocarpus glaber*	$B_A = 0.120(D^2H)^{0.8509}$, $R^2 = 0.99$; $B_R = 0.098 + 0.0176(D^2H)$, $R^2 = 0.99$ [41]
Others	$B_A = (D^2H)/(0.0014(D^2H) + 15.990)$, $R^2 = 0.99$; $B_R = 0.376 + 0.0162(D^2H)$, $R^2 = 0.99$ [41]

[1] B, biomass (dry weight, kg); B_A, above-ground biomass; B_R, root biomass; B_S, stem biomass; B_P, peel biomass; B_B, branch biomass; B_L, leaf biomass; B_{R1}, rhizome biomass of *P. heterocycla*; B_{R2}, root fibril biomass of *P. heterocycla*. [2] D, DBH (cm). [3] H, tree height (m).

We randomly sampled three soil profiles in each 30 m × 30 m plot. The soil layers were grouped into six depth intervals: 5 (0–10), 15 (10–20), 25 (20–30), 40 (30–50), 60 (50–70), and 85 (70–100) cm. First, each layer of the soil samples was sealed in plastic bags, brought back to the laboratory, air-dried, and sieved through a 0.15 mm mesh before performing the chemical analyses. Some soil samples taken with cutting rings were used to measure the soil bulk density and moisture content. SOC content (%) was detected by wet combustion with $K_2Cr_2O_7$ [47]. SOC stock, representing the average density of soil organic C ($Mg \cdot C \cdot ha^{-1}$) for the top 100 cm of the soil profile, was calculated using the following formula:

$$SOC\text{stock} = \sum_{i=1}^{n} C_i \times D_i \times E_i(1 - G_i)/10 \tag{1}$$

Here C_i = the soil organic C proportion ($g \cdot kg^{-1}$), D_i = soil bulk density ($g \cdot cm^{-3}$), E_i = soil thickness (cm), G_i = gravel content (diameter > 2 mm) in the soil volume, n = the number of soil layers, and i = the stratum sequence of the soil.

The planted forest TF and NF were divided as TFa, TFb, TFc, and TFd; NFa, NFb, and NFc, respectively, and their C stocks were calculated by weighted average with areas of each sub type. However, the C stocks of SCF, SCBF, and SBF were calculated by arithmetic average.

2.3. Statistical Analysis

A one-factor analysis of variance (ANOVA; with $\alpha \leq 0.05$ being significant), followed by a Student-Newman-Keuls (S-N-K), was used to test for significant differences in the aboveground tree C, understory C, litter C, root C, soil C, and vegetation C stocks ($Mg \cdot C \cdot ha^{-1}$) of the five forest types. A single factor linear regression analysis was used to investigate the relationships between SOC contents (%) at six different soil depths and for the aboveground biomass C. A nonlinear regression analysis was applied to investigate the relationship between SOC contents (%) and soil depth, for describing the distribution trend of SOC content (%) in different forests. Regression analysis and curve plotting were done by SigmaPlot 13. Normal distributions were tested using the Shapiro-Wilks

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test, and homogeneity of variance was analyzed using Levene's test. All statistical analyses were performed using SPSS 19.0 for Windows (IBM SPSS Statistics Inc. Beijing, China).

Two remote sensing images were used to extract land uses: Landsat 8 OLI_TIRS 30 m images taken on 29 November 2013 and 16 January 2014. The software ENVI 5.2 and ArcGIS 10.2 were used to treat those images (for example, using atmospheric correction, geo-rectification, and mosaic, and through combining supervised classification with visual interpretation). The overall accuracy and kappa coefficient were calculated by class confusion matrix in ENVI, and the reported results of the validation were acceptable. Five land use types were mapped in Figure 1, including forest, water area, developed land, agricultural land, and bare land. Based on the preliminary interpretation results and wide forest inventory, more detailed classification was implemented within planted forests, including TFa, TFb, TFc, and TFd, and NFa, NFb, and NFc.

3. Results

3.1. Plant Communities

Based on the field investigation, the natural secondary forests in the Liuxihe River basin could be divided into three categories: SCFs dominated by *P. massoniana* and *C. lanceolata*, SCBFs dominated by *P. massoniana*, *C. lanceolata*, *C. henryi*, *C. fissa*, and *S. superba*, and SBFs dominated by *C. fissa*, *C. concinna*, *F. variolosa*, *C. carlesii*, and *E. sylvestris* (Table 1). The shrub and herb accessory species in the SCFs and SCBFs were *A. pilulifera*, *D. dichotoma*, and *B. orientale*. The subdominant tree species in the SBFs were *C. carlesii*, *C. henryi*, *C. faberi*, *C. porrectum*, and *S. sinensis* (Table 1).

The TFs could be divided into four vegetation zones based on the tree species composition, and they were dominated by *P. assoniana*, *C. lanceolata*, *E. urophylla*, and *P. heterocycla*. The NFs could be divided into three types based on their dominant fruit trees: *L. chinensis*, *V. mangachapoi*, and *C. reticulata* (Table 1).

3.2. Vegetation Carbon

The natural secondary forests' C concentrations in understory vegetation and litter presented decreasing trend from broad-leaved to coniferous forests (Table 3). The lowest understory vegetation and litter C concentrations were respectively 38.90% ± 1.78% and 40.53% ± 0.62% from non-wood forests.

Table 3. Carbon concentration (mean ± SE) of understory vegetation and litter.

Forest Type	Carbon Concentration (%)	
	Understory	Litter
SCF	45.07 ± 0.84	46.71 ± 0.19
SCBF	42.54 ± 0.51	43.95 ± 0.74
SBF	41.37 ± 0.56	42.40 ± 0.40
TF	40.41 ± 2.02	42.90 ± 2.78
NF	38.90 ± 1.78	40.53 ± 0.62

The SBF had the highest vegetation C stock (66.86 ± 3.99 $Mg{\cdot}C{\cdot}ha^{-1}$) out of all measured forest types (Figure 2). The vegetation C stock of the NF (26.78 ± 6.27 $Mg{\cdot}C{\cdot}ha^{-1}$) was significantly lower than those of other forest types (ANOVA, $p < 0.05$). By comparing the variations in C stocks, the standard errors of the secondary forests (SBF: 3.88, SCBF: 4.91, SCF: 3.99) were lower than those of the TF (7.62) and NF (6.27). This could imply that the secondary forest communities are more similar in terms of their biomass than the planted forests. In all forest types, the aboveground trees always contributed the highest C stocks, compared to the roots and understory vegetation. Especially for SCF, the C pools of aboveground trees occupied a total vegetation C stock as high as 83.21%. Regarding the comparison of the root C pool and understory vegetation C pool among different forest types, NF and SCBF accounted for the highest proportions (17.01% and 12.59%), respectively.

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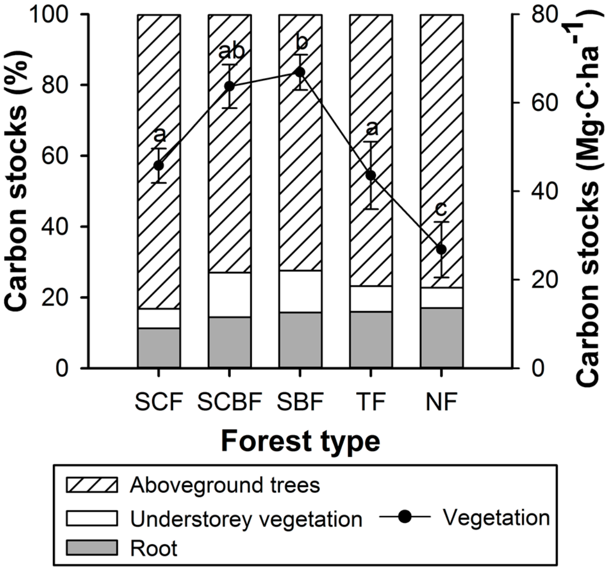

Figure 2. Vegetation biomass carbon pools in different forests. Different letters indicate significant differences across forest types (Student-Newman-Keuls (S-N-K) test, $p < 0.05$). Error bars denote standard errors.

3.3. Litter Carbon

The variation in the litter C stocks of the different forests differed from the variations in biomass (Figure 3). The litter C stock of the SCBF was higher than those of the other forests. In the succession theory of community ecology, SCFs and SCBFs are considered to be in the developing stage when the number of plant species is increasing, and SBFs are in the stable stage in the southern subtropical area. Here, SCBFs generally tend to develop into SBFs in the study area leading to partial similarity of their plant species. Thus, the litter biomasses and C stocks of SCBF and SBF were not significantly different. The litter C stocks of the TF and NF were obviously lower, especially that of the NF, because of close proximity to population centers.

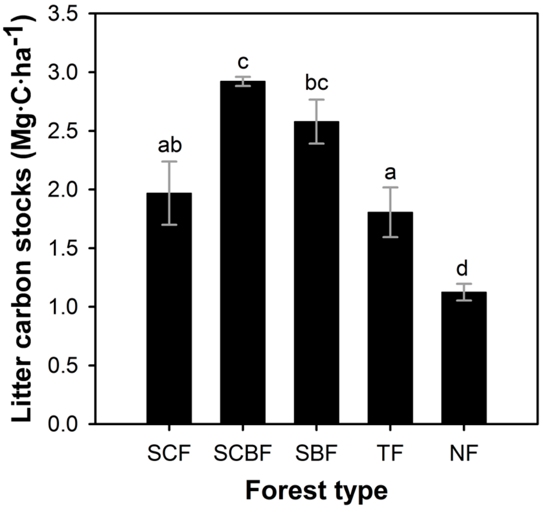

Figure 3. Litter carbon stocks in different forests. Different letters indicate significant differences across forest types (S-N-K test, $p < 0.05$). Error bars denote standard errors.

A linear regression model ($R^2 = 0.9508$, $p < 0.01$) in Figure 4 was derived from forest inventory data and statistical analysis. The regression results showed litter C stocks had a strong positive linear dependence relation with the aboveground biomass C stocks of the measured forests.

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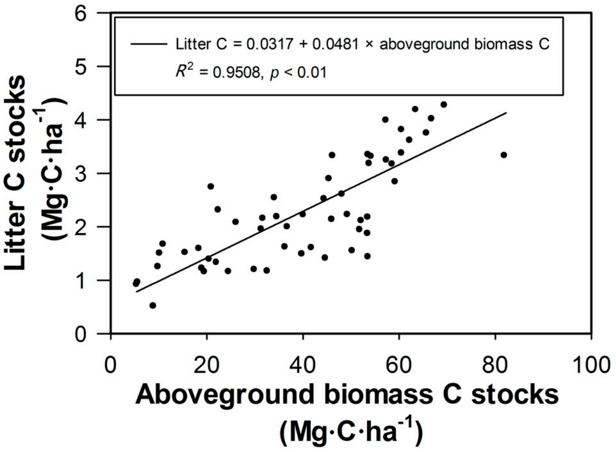

Figure 4. Correlations between the aboveground biomass (trees and understory) C stocks and litter C stocks of the forests.

3.4. Soil Organic Carbon

The soil samples for SOC contents (%) determination were taken from the soil profile at six depth levels: 5 (0–10), 15 (10–20), 25 (20–30), 40 (30–50), 60 (50–70), and 85 (70–100) cm. The SBF had the highest SOC content (3.37%) at 5 cm depth out of all measured forest types (Figure 5a). The vertical SOC contents distributions in the soil profiles were modeled by the formula SOC (%) = a + b/depth (Figure 5b) for the different forests. The fitting equations revealed how SOC contents varied with soil depth, and they modeled the SOC contents at any depth. The results showed that the differences in the SOC contents in the upper soil levels were greater than those in the lower levels. The lowest average SOC content was 0.42% from NF, at the depth of 85 cm.

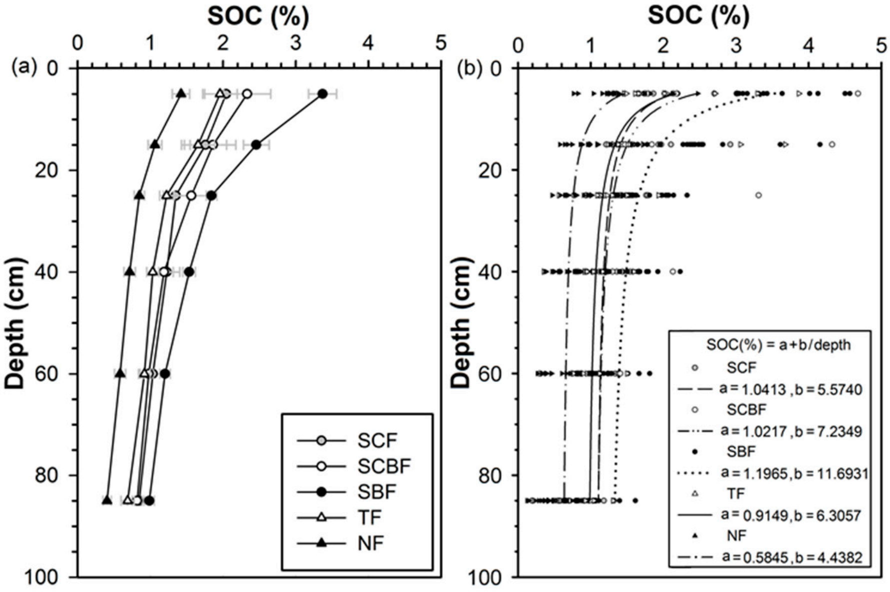

Figure 5. (**a**) Vertical distributions of soil organic C (SOC) (%) of the soil profiles at six levels, ranging from 0 to 100 cm depths; (**b**) Simulated models of the relationship between depth (cm) and SOC (%).

The simple, linear relationships between the SOC contents in the different levels of the soil profiles and the aboveground biomass are shown in Figure 6. The linear equations showed that the upper levels of the soil are more strongly related to the amount of biomass. The slope coefficients of the linear equations varied from 0.018 to 0.005, corresponding to soil levels from 5 to 85 cm. This means that the aboveground biomass differentially affects the SOC contents of the different soil

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levels. Soil C is transferred from litter, and it is transferred from higher to lower levels within the soil at different rates. It is interesting to observe the relationship between soil depth and the coefficients of the regressive models (Figure 6). The relationship is shown below:

$$y = 189.2375 \times e^{-192.8142x} \ (R^2 = 0.9241, p < 0.001)$$

where y is the soil depth and x is the coefficient of the regressive model. The equation revealed that the effect of aboveground biomass on SOC gradually decreases with increasing soil depth.

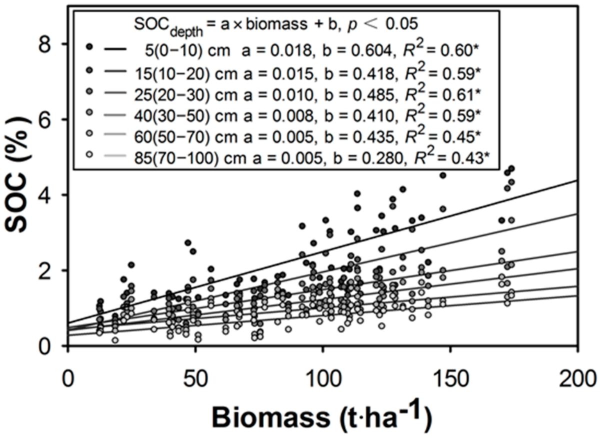

Figure 6. Correlations between SOC contents (%) at different levels of the soil profiles and the aboveground biomasses of the forests.

The widths of the boxes in Figure 7 indicate the sample size, which were 6, 9, 15, 12, and 15 for the NF, TF, SCF, SCBF, and SBF, respectively. The median values (solid lines) of the SCBF, TF, and NF were higher than their arithmetic means (dotted lines), while the opposite was true for the SOC stocks of the SCF and SBF. Nevertheless, the medians and means did not appear to be different. We calculated the weighted averages of the SOC stocks, using the different areas of the forests, to compare the soil C stocks in the entire Liuxihe River basin. The weighted averages were 89.95 ± 5.40, 131.61 ± 12.72, 147.50 ± 14.68, 152.32 ± 7.01, and 188.71 ± 11.26 Mg·C·ha^{-1} for the NF, TF, SCF, SCBF, and SBF, respectively.

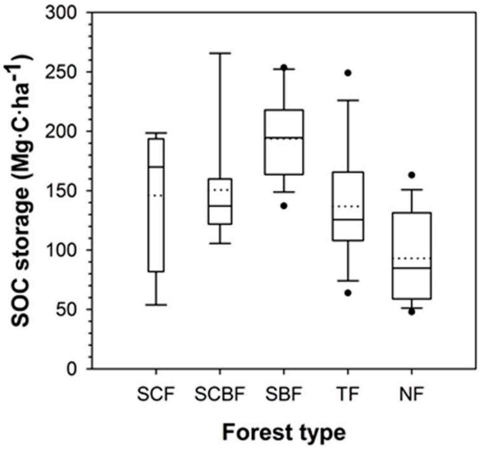

Figure 7. Box plot of SOC stocks of different forests in 0–100 cm soil profiles; box length denotes interquartile range; box width denotes sampling size; whiskers denote range of variability; solid lines denote median; dotted lines denote mean.

3.5. Structure of Forest Carbon Stocks

The ratios of belowground C stocks to aboveground C stocks ranged from 2.8 to 4.0 (Figure 8). This reveals that belowground C stocks are far greater than the aboveground C stocks. The soil C pool made increasing contributions to the C stocks of the forest ecosystem: 69.58%, 73.27%, 74.18%,

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75.55%, and 76.32% for the SCBF, SBF, TF, SCF, and NF, respectively. The ratios of soil: plant C ranged from 2.4 to 3.4. This indicates that the C stocks in this forest ecosystem mainly come from the soil.

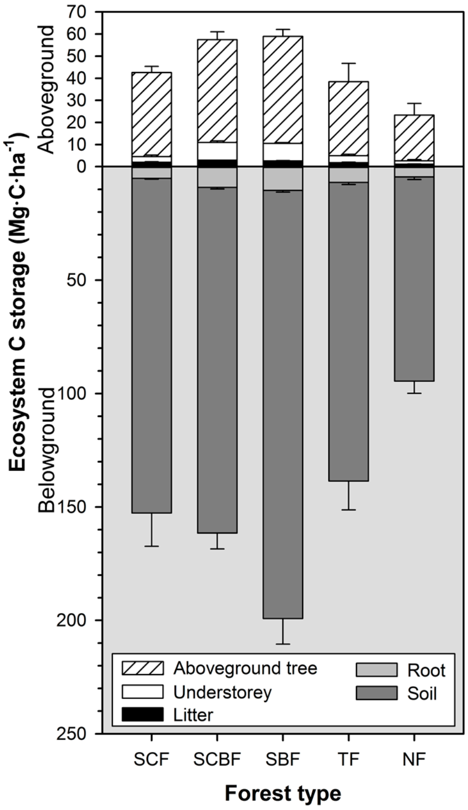

Figure 8. The total carbon stocks of different forests. Upper panel: aboveground C stock; bottom panel: belowground C stock. Vertical bars denote standard errors.

3.6. Spatial Distribution of Forest Ecosystem Carbon Stocks

By RS analysis and site investigations, forest community distributions in the Liuxihe River basin were obtained, and a map of the total C distribution in the entire basin was constructed using the forest community distribution and the C stocks of each forest community (Figure 9). The C pools of natural secondary forests were widely distributed throughout the entire basin, and the C pools of the planted forests were close to developed, urban, and agricultural lands. It is obvious that forests with higher C stocks tend to develop where vegetation can grow without human disturbance.

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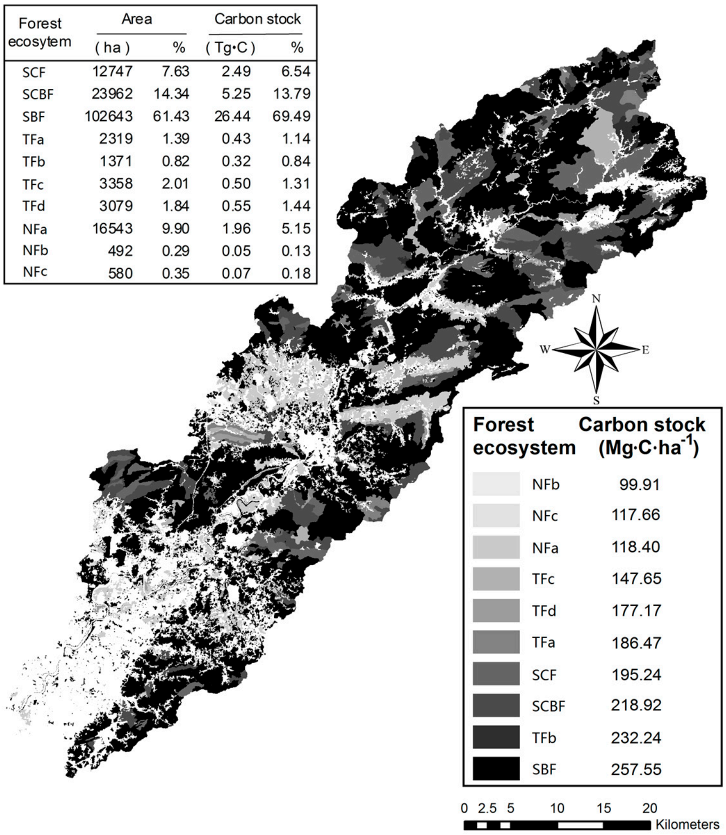

Forest ecosytem	Area (ha)	Area %	Carbon stock (Tg·C)	Carbon stock %
SCF	12747	7.63	2.49	6.54
SCBF	23962	14.34	5.25	13.79
SBF	102643	61.43	26.44	69.49
TFa	2319	1.39	0.43	1.14
TFb	1371	0.82	0.32	0.84
TFc	3358	2.01	0.50	1.31
TFd	3079	1.84	0.55	1.44
NFa	16543	9.90	1.96	5.15
NFb	492	0.29	0.05	0.13
NFc	580	0.35	0.07	0.18

Forest ecosystem	Carbon stock (Mg·C·ha^{-1})
NFb	99.91
NFc	117.66
NFa	118.40
TFc	147.65
TFd	177.17
TFa	186.47
SCF	195.24
SCBF	218.92
TFb	232.24
SBF	257.55

Figure 9. Distribution of forest ecosystem carbon stocks in the Liuxihe River basin. a, b, c, d: plot series representing the further subdivision of the forests measured (Table 1).

The estimate of the total forest C stock in the Liuxihe River basin was calculated to be 38.04 Tg·C. On the whole, the natural secondary forests provided a considerable fraction of the total C stock, as they accounted for 34.17 Tg·C (89.82%) of the entire basin forest C pool, with the SCF, SCBF, and SBF accounting for 6.54%, 13.79%, and 69.49%, respectively, of the total C stock. The C stock of the planted forests accounted for 3.87 Tg·C (10.18%) of the total C stock, with the TF and NF accounting for 4.72% and 5.46%, respectively, of the total C stock. Although the total natural secondary forest C stock was more than eight times that of the planted forests, the planted forests' C pool should not be neglected, as it accounted for 10% of the forest C and constituted 16.65% of the forest area.

4. Discussion

4.1. Forest Succession and Age Growth

Two different forest management patterns in the study area were obtained: long-term conservation and periodic logging (TFs: 7–15 years) and harvesting (NFs: annual). In natural secondary forests, natural succession led the floristic compositional change. The field inventory revealed that the number of dominant species in the SCBF and SBF was greater than that of the planted forests. Even though the SCF was in the early stage of succession, its vegetation communities had a more complex structure than those of the TF and NF (Table 1). The forest structure changes as vegetation grows, resulting in dynamic variations in the different stages of forest succession [15,48,49]. Natural secondary forests in the Liuxihe River basin are mostly far removed from human disturbances, with age ranges of 20–25, 25–35, and 30–55 for the SCF, SCBF, and SBF, respectively. Thus, natural secondary forest communities tend to become complex under natural conditions [50,51]. Conversely, for timber production and commercial purposes, single species were used in planted forests that were subject to intensive management treatments. Accordingly, artificial selection led the species stability in planted forests.

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Forest age plays an important role in determining the vegetation community structures, plant biomasses, and litter conditions. Therefore, forests with different ages contributed to the various C pools [52]. Luyssaert et al. [53] reported that forests between 15 and 800 years of age usually had a positive net C sequestration, and that older forests accumulated more C than younger forests did. According to this statement, it is noteworthy that, some of the old-growth planted forests could contain more C stocks than the natural secondary forests while young in age. In this study, planted forests were generally younger than the natural secondary forests due to the impact of artificial disturbances (such as logging and harvesting). Hence, the variation of C stocks caused by age difference between planted forests and natural secondary forests was inevitable.

In addition, Pregitzer and Euskirchen [54] estimated that the mean net C sequestration in the youngest forests (0–10 years) was negative, increasing at an early age gradually until reaching 30 years of age, and then decreasing with age growth. The comparison between planted forests and natural secondary forests at 0–10, 10–30 and >30 years would be able to provide more insights on carbon stock estimation of forest ecosystem. However, only a few planted forests older than 30 years of age were found in our study area. Thus, we could not make further comparisons with the C stocks of the older planted forests and natural secondary forests. This should be taken into account in future studies.

4.2. Carbon Stock Contributions of Different Forests

The vegetation C stocks of natural secondary forests in this study were less than other studies performed in the same climatic zone [55,56]. For example, two research studies reported that the Dinghushan Biosphere Reserve, which is in the same climatic zone as Liuxihe River basin, had a large number of natural primary forests and even more over-mature forests [55,56]. They presented the vegetation C stocks of the subtropical coniferous and broad-leaved mixed forest and subtropical evergreen broadleaved forest to be, respectively, 123.04 and 89.75 t·ha^{-1}, values which are both higher than those measured in our study (63.68 and 66.86 t·ha^{-1}). The vegetation C stock of the SBF reached as high as 66.86 Mg·C·ha^{-1}, which was 1.54- and 2.50-fold greater than those of the TF and NF, respectively, and 1.46- and 1.05-fold greater than those of the SCF and SCBF, respectively. This suggests that natural secondary forests that experience typical subtropical forest community succession supply greater vegetation C sequestration services than planted forests. This is in agreement with the results of previous studies of subtropical forests [55,56]. In accordance with similar results [57,58], generally, the contribution of understory C pools was smaller than those of aboveground trees and roots. Nevertheless, the understory vegetation could provide both biomass production and biodiversity benefits [59], as well as improved soil properties [60,61]. Many studies have shown that the proportion of biomass and C stocks in the understory vegetation is a significant part of annual nutrient and forest ecosystem C cycling [62,63]. The results showed that failing to account for C stocks in understory vegetation would lead to a 5%–14% underestimate of the total vegetation C in natural secondary forests and a 5%–10% underestimate in planted forests.

Litter C is a very small fraction of the total carbon, but it makes a very important contribution to the soil C because it is the link by which C is transferred from the aboveground pool to the soil pool. Our results clearly confirm that mature, natural secondary forests hold more litter C than planted forests. One apparent reason for this is that there is significantly more aboveground vegetation biomass in natural secondary forests. Additionally, litter in natural forests with mixed-species could reduce the soil fauna effect on the mass loss [64,65], while the litter of planted forests had lower complexity. Moreover, although new management treatments that mimic natural forest disturbances and dynamic intermediate felling have been used for decades in planted forests [66–68], cutting, harvesting, and intense land preparation reduced the quantity and quality of litter [66,69]. This decrease in litter negatively affects the suitable habitats of microbes and animals, as well as soil C allocation and nutrient cycles [70].

A strong correlation was observed between SOC content and aboveground biomass, including live plants and litter. Generally, forest biomass is not the only factor to affect SOC and soil properties [71,72]. Climatic factors [73], vegetation diversity [74,75], anthropogenic factors [76–78], and natural

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disturbances [79–81] also affect the SOC content of forest soils. Further research should analyze the dynamic mechanisms by which these factors affect the SOC content to provide more accurate estimates of forest soil C stocks, as well as strategies to maintain these C stocks. In this study, the soil C stocks of natural secondary forests were significantly higher than those of planted forests. Especially in NFs, annual harvesting operations and fertilization may cause drastic soil disturbances. Parker [82] reported that forest soils treated with $(NH_4)_2SO_4$ had lower C stocks than untreated soils. Many studies have shown that soil respiration will increase intensely after fruit harvesting and land preparation, and the excessive harvest of timber will also exacerbate the loss of soil due to soil erosion [83,84]. Zhou [85] demonstrated the importance of soil hydrological benefits, such as reduction of runoff and erosion, to the positive succession from a eucalypt forest to a mixed-forest ecosystem. Furthermore, planted forests output considerable amounts of C in the forms of raw materials and foods, while the falling parts (litter) of the biomasses of natural secondary forests decompose and are incorporated into the soils.

4.3. Variation and Distribution of Forest Ecosystem Carbon Stocks

The ratios of soil C to plant C in the SCBF, SBF, TF, SCF, and NF were 2.4, 2.8, 3.0, 3.2, and 3.4, respectively. This is similar to the values, which ranged from 1.2 to 3, for mid-latitude forests that were reported by Dixon [28]. Li et al. [86] reported that soils and trees were the two dominant C pools in eucalyptus plantations, accounting for 73.77% to 75.06% and 20.50% to 22.39% of the C pools, respectively. In accordance with similar research results, forest ecosystem C stocks in the Liuxihe River basin mainly come from the soil. In addition, because the vegetation biomass of natural secondary forests is greater than that of planted forests, the soil C in planted forests accounted for a slower increase in accumulation. This suggests that natural and anthropogenic factors influence C stocks by plants, while soil C, which gradually accumulates, changes slowly in response to these factors.

We mapped the distribution of vegetation communities based on RS images and our experimental data, and the results revealed the distribution of forest C stocks in the Liuxihe River basin (Figure 9). The total C stock of forests in the Liuxihe River basin was estimated to be 38.04 Tg·C. The upstream portion of the basin has the largest forest C stock, as there are relatively smaller urban areas and agricultural lands in this region. Because of changes in land use and land cover, the forest area and plant communities have been altered by human activities. Correspondingly, the soil C pools were affected by land use and the type of forest established. Guan et al. [87] reported that converting secondary forests to Chinese fir and Moso bamboo plantations significantly decreased the SOC. Carbon accumulation in soils could be maximized by maintaining longer (20–50 year) forest rotations throughout the long-term stable management regimes. Accurately quantifying forest C stocks may be an important consideration under basin-scale ecosystem services and regional C budget.

5. Conclusions

This study focused on forest ecosystem C stocks at the basin-scale to provide a better understanding of the differences in forest C stocks and to describe the spatial distribution of C stocks. A comprehensive method based on field investigations, experimental analysis, and RS technology was established to assess basin-scale forest ecosystem C stocks.

The results indicated that the natural secondary forest stored 89.82% of the forest C in the Liuxihe River basin under 83.35% of the forest area, while the planted forest stored 10.18% of the forest C under 16.65% of the forest area. The C stock of the SBF (257.55 ± 15.01 $Mg{\cdot}C{\cdot}ha^{-1}$) was the highest of all forest types, and the C stock of the NF (117.86 ± 26.78 $Mg{\cdot}C{\cdot}ha^{-1}$) was the lowest. In the study area, the forest ecosystem stored 38.04 Tg·C. The analysis of C stocks showed that the soil C pool accounted for the greatest proportion (more than 69%) of the forest C stock. Plant biomass accounted for the second greatest proportion of forest C stock, and it strongly influenced the litter C stock and SOC content, which were clearly influenced by soil depth.

The areas with lower forest C stocks were usually distributed near towns and agricultural lands, where plants and soils were subject to anthropogenic disturbances. Furthermore, the differences in

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the C stocks of the natural secondary forest and planted forest, as well as their spatial patterns, suggested that forest management could exert different impacts on the C stocks of natural secondary and planted forests. The results provide baseline forest C stock data for the Liuxihe River basin that could be applied for future ecosystem services research, and estimation of regional C budget and gross ecosystem production (GEP). In addition, there is still further work to be done to assess dynamic changes of forest C stocks, based on the current conditions and land use change.

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