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Effects of Stand Structure and Topography on Forest Vegetation Carbon Density in Jiangxi Province

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Abstract: Stand structure and topography are important factors affecting forest vegetation carbon density (FVCD). Revealing the interaction mechanisms between stand structure and topography on FVCD is of great significance for enhancing forest vegetation carbon storage and achieving regional carbon neutrality. Based on stratified sampling, systematic distribution and forest continuous inventory sample plots in Jiangxi province, the variation characteristics of FVCD and its correlations with stand structure and topographic factors were studied. The results are as follows: (1) The average FVCD in Jiangxi province was 44.23 Mg/ha, which was dominated by the carbon density of the arbor layer, accounting for about 81.39% of the total forest—far lower than the average level of global FVCD, which proved that the forest in Jiangxi province was dominated by middle-age and young forests with low carbon density, and also showed that the potential for forest vegetation carbon storage in Jiangxi province was huge. (2) Except for vegetation carbon densities of shrub and herb layers, the vegetation carbon densities of other forest layers in Jiangxi province were significantly different among different forest types. Volume per unit area was the most important factor affecting the vegetation carbon densities of arbor and total forest, and vegetation carbon density–volume models of the main forests were built for vegetation carbon density calculation in Jiangxi province. (3) The vegetation carbon densities of arbor layer, snag and log layer, and total forest increased significantly with increases in elevation and slope. Except for the shrub layer and herb layer, the vegetation carbon densities of the other layers and the total forest had extremely significant or significant differences between slope position gradients—indicating that the effect of topography on FVCD in Jiangxi province was significant, mainly through influencing of forest distribution and human disturbance intensity.

Keywords: stand characteristics; terrain factor; driving force; regression analysis

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1. Introduction

Forest vegetation carbon storage is the main body of terrestrial ecosystem carbon storage, which not only maintains a huge carbon pool of (550 ± 100) Pg (1 Pg = 1015 g), but also absorbs about 33% of the carbon emitted by human activities, playing a very important role in global carbon balance and potential carbon storage [1,2]. Since changes in forest vegetation carbon sequestration function reflects forest succession, human activities and environmental changes, it is an important indicator to measure the stability and health of the forest ecosystem; as such, the study of vegetation carbon storage becomes an important field of forest carbon storage research [3,4]. Scholars from Russia, Canada, the United States, China and other countries have studied regional or even global forest vegetation carbon storage and forest carbon cycles [5–8]. At present, the estimated global forest vegetation carbon storage is roughly 359–744 Pg [8], and the highest estimated forest vegetation carbon storage for China is 17 Pg in foreign materials [9]. Due to the complexity and

diversity of forest types in China, it is difficult to use a unified method for estimation of forest vegetation carbon storage, and the degree of preparation of basic data varies from place to place. As a result, the estimated forest vegetation carbon storage varies significantly at the national scale in China, at an average of 3.72–13.34 Pg [9–11]. Therefore, a bottom-up approach is necessary for more accurate estimation of forest vegetation carbon storage—that is, carbon storage of forest ecosystems at different regional scales is estimated first, and then carbon storage of forest ecosystems at the national scale is calculated [12].

Regional forest vegetation carbon storage is mainly determined by the areas and vegetation carbon densities of regional main forest types. Forestry land is under strict protection, and forest land change has been strictly controlled in China. Therefore, increasing forest vegetation carbon density (FVCD) has become the main way to enhance regional forest vegetation carbon storage. There are many factors affecting the FVCD, including natural factors [13] and social and economic factors [11]. As important natural factors, stand structure and topographic factors have significant effects on FVCD [14,15]. Due to the significant regional spatial heterogeneity of stand structure and landform, it is of great theoretical and practical significance to explore the variation of regional FVCD and its interaction with stand structure and landform factors, so as to regulate the carbon storage of regional forest ecosystems and achieve regional carbon neutrality.

Jiangxi Province is the main collective forest region in south China, with rich forest resources. According to the data of the ninth Forest Resources inventory of China, by the end of 2016, the total forest area of forestry land (i.e., arbor forest land and bamboo forestland with a canopy density above 0.2, shrub land, open forestland, cutting sites, burned sites, unformed forestland, nursery sites and suitable forestland planned by the people's government at or above the county level) in Jiangxi Province was 10,799,000 ha, accounting for about 64.69% of the total forest land area. Among them, the arbor forest area (dominated by arbor tree species) was 8,084,800 ha, accounting for about 74.87% of the total forest forestry land area. The main forest types include conifer forest dominated by *Cunninghamia lanceolata* (Lamb.) Hook., *Pinus Massoniana* Lamb., evergreen broadleaf forest and mixed conifer and broadleaf forest [16]. Although there are some reports on forest vegetation carbon storage/density in Jiangxi Province, except for a very small number of studies based on remote sensing images [17], those reports are mainly based on forest resource inventory data [18–22] or researches of typical forests (e.g., evergreen broad-leaved forest, *Phyllostachys edulis* (Carriere) J. Houzeau forest, *C. lanceolata* forest) in typical areas [23–27], and thus, there is a lack of research on FVCD and its driving forces based on systematic distribution at the provincial scale.

In view of the current research situation of FVCD in Jiangxi Province and research demands for regional carbon neutrality, based on the comprehensive consideration of the forest types, age groups and other factors in Jiangxi province, this study conducted stratified sampling, systematic site distribution and a field sample survey of the forest subcompartment in Jiangxi Province to deeply study the variation of FVCD and its relationships with the stand structure and topographic factors. Therefore, the main objectives of this study are: (1) to reveal the variation characteristics of FVCD, stand structure and topographic factors in Jiangxi province; (2) to study the quantitative relationship between FVCD and stand structure factors in Jiangxi province and then to establish a quantitative model between FVCD and volume per unit area (VPUA) of main forests for Jiangxi province; (3) to explore the quantitative relationship between forest carbon density and topographic factors such as elevation and slope in Jiangxi province, and reveal the mechanism of topographic factors on FVCD in Jiangxi province. Stand structure has a wide definition, which includes both non-spatial structure and spatial structure [28,29]. The stand structure in this study refers to traditional stand characteristic factors such as stand density (SD), average diameter at breast height (ADBH), average tree height (AH), canopy density (CD) and volume per unit area (VPUA) and basal area at breast height per unit area (BA).

2. Materials and Methods

2.1. Study Area

Jiangxi Province is located in east China, between 24°29'14" to 30°04'41" north latitude and 113°34'36" to 118°28'58" east longitude, with a total forest area of 166,900 km². Jiangxi Province belongs to a humid monsoon climate zone in the mid-subtropics, with a warm climate, sufficient sunlight, long frost-free periods and abundant rainfall. According to statistics, the province's annual average temperature is 16.3–19.5 °C, the annual average precipitation is 1341–1940 mm, the annual sunshine duration is 1482–2085 h, the average relative humidity is 75–83%, and the average annual frost-free period is 240–307 d. The topography of Jiangxi is dominated by hills and mountains. Basins and valleys are widespread. Mountains and hills account for 36% and 42% of the province's area, respectively. Jiangxi Province is rich in forest resources. By the end of 2016, the forestry land area in the province was 10.799 million hectares, accounting for 64.69%; the forest area (i.e., arbor forest, bamboo forest and special shrub land prescribed by the State) was 10.2102 million hectares, accounting for 61.16%; and the arbor forest area was 8.0848 million hectares [18]. The arbor forests in Jiangxi Province mainly fall into the following types: (1) coniferous forests, i.e., *C. lanceolata* forest (CLF), *P. massoniana* forest (PMF) and other coniferous forest (OCF) dominated by *Pinus elliotii* Engelman, *Tsuga chinensis* (Franch.) Pritz. and *Metasequoia glyptostroboides* Hu et W. C. Cheng; (2) evergreen broad-leaved forest (EBF) dominated by *Quercus* sp. and *Schima superba* Gardner & Champ., and (3) mixed broadleaf-conifer forest (MBCF). The characteristics of the experimental stand are shown in Table 1. The arbor forests in Jiangxi Province are mainly young and middle-aged forests, and the forest quality is low. The unit area stock of arbor forest is 62.67 m³/ha, and that of the artificial forest is even lower, at only 48.23 m³/ha [16]—which is much lower than the average level of developed countries.

Table 1. Characteristics of experimental stands (Value ± SD).

Stands	Number of Plots (n)	Average Altitude (m)	AH (m)	ADBH (cm)	TD (n/ha)	CD (-)	Slope Degree (°)
EBF	81	340.49 ± 271.33	8.65 ± 2.83	12.18 ± 4.07	1284.05 ± 726.83	0.60 ± 0.19	24.59 ± 12.54
PMF	33	190.91 ± 137.96	7.72 ± 2.54	12.58 ± 4.27	917.15 ± 556.90	0.49 ± 0.17	17.06 ± 12.82
CLF	28	333.93 ± 323.88	8.22 ± 1.86	11.33 ± 2.56	1552.09 ± 839.47	0.63 ± 0.15	24.68 ± 8.91
OCF	17	357.06 ± 450.97	8.72 ± 2.78	12.28 ± 3.15	1289.97 ± 137.73	0.59 ± 0.14	19.82 ± 9.93
MBCF	52	316.63 ± 231.81	8.22 ± 2.49	10.53 ± 2.42	1691.97 ± 927.17	0.63 ± 0.16	23.33 ± 11.09

Note: EBF, Evergreen broadleaf forests; PMF, *P. massoniana* forest; CLF, *C. lanceolata* forest; OCF, Other coniferous forest; MBCF, Mixed broadleaf-conifer forest. The same below.

2.2. Field Survey and Sampling

Taking into account the stand factors such as forest type (coniferous forest, broad-leaved forest and mixed conifer and broad-leaved forests), forest age (young forest, middle-aged forest, sub-mature forest, mature forest and over-mature forest) and origins (natural forest and artificial forest) in Jiangxi province, random stratified sampling was carried out on the basis of 2600 forest continuous inventory sample plots (28.28 m × 28.28 m) in Jiangxi province; 211 forest continuous inventory sample plots were selected, and then a forest vegetation survey was carried out in the forest continuous inventory sample plots [30]. The spatial distribution of the 211 forest continuous inventory sample plots is shown in Figure 1.

Figure 1. Distribution of forest continuous inventory sample plots on the topographical map of Jiangxi province.

After the standard plot was set up, the following investigations were undertaken: (1) The basic information of the standard plot was investigated—the elevation, longitude, latitude and azimuth of the central point of each plot were measured by portable GPS instruments, the slope degree was measured by slope instruments, and the stand type, slope position and canopy density were determined by traditional community investigation methods. (2) All the living trees (diameter at breast height (DBH) ≥ 5 cm and height 5 m) and snags in the sample plot were measured. The DBH was measured with a girth diameter ruler, the tree heights were measured using a laser altimeter, and the name, DBH and tree height of each standing tree (living trees and snags) were recorded. For each snag, its decomposition state was determined firstly according to the method recommended by Rouvinen et al. [31], then an average standard snag for decay class 4 and 5 was selected and cut down, and the fresh weight of each organ was weighed; then, about 500 g samples of each organ were collected in order to determine the moisture content. (3) For logs, the log length, the DBH, the maximum diameter ($d_{\max}$) and the minimum diameter ($d_{\min}$) were determined in order to compute the log volume [$V = \pi l(d_{\max}^2 + d_{\min}^2)/8$]. Then, the method of Rouvinen et al. [31] was used to determine the decomposition state of logs, after which, an average standard log for decay class 4 and 5 was selected and cut down, and the fresh weight was firstly weighed using the harvesting method; then, 500 g samples of each decomposition state were collected and taken back to determine the moisture content. (4) Three 5 m $\times$ 5 m shrub plots were randomly established in each forest plot, and the shrubs with DBH < 5 cm and height ≥ 50 cm were investigated. The name, ground diameter, height and crown width of each shrub in a shrub plot were measured and recorded, and then, three average standard shrubs in each plot were selected according to the mean values of ground diameter, height and crown width, and the fresh weight

was weighed using harvesting methods; then, 500 g samples were collected to determine its moisture content. (5) A 1 m × 1 m herb plot was established in each shrub plot, and the name, height and coverage of each herb with height < 50 cm in each herb plot were measured and recorded, and the decomposed state of litter was determined using the method recommended by Zhang et al. [32] in each herb plot; then, the litters in different decomposed states were collected, and all the aboveground and underground parts of herbs in each herb plot were collected by harvesting methods. The fresh weights of the litters in different decomposed state, aboveground and underground parts of herbs each plot were first weighed, and then 300 g samples were taken back to determine the moisture content. The moisture content of snags, logs, shrubs, herbs and litter were determined by the oven method, that is, baking at 105 °C to constant weight and then weighing. The characteristics of the experimental stands are shown in Table 1.

2.3. Biomass Calculation

Based on the sample site survey data in each sample plot, the model of the relationship between biomass and DBH of each main tree species in Table 2 was used to calculate the biomass of standing trees and the snags of decay classes 1 to 3.

Table 2. Biomass–DBH allometric equations for main tree species.

Tree Species	Biomass Models	R ²	Source	Tree Species	Biomass Models	R ²	Source
<i>Alniphyllum fortunei</i> (Hemsl.) Makino	$W = 0.1548D^{2.4354}$	0.93 **	[33]	<i>Cyclobalanopsis glauca</i> (Thunberg) Oersted	$W = 12.1071D - 58.897$	0.99 **	[34]
<i>Castanopsis fargesii</i> Franch.	$W = 0.1230D^{2.5277}$	0.99 **		Evergreen broadleaf tree	$W = 12.4250D - 63.547$	0.99 **	
<i>Castanopsis tibetana</i> Hance	$W = 0.2149D^{2.2747}$	0.97 **		Deciduous broadleaf tree	$W = 0.4815D^2 - 3.672$	0.99 **	
<i>Lithocarpus glaber</i> (Thunb.) Nakai	$W = 0.4086D^{2.0880}$	0.93 **		<i>P. edulis</i>	$W = 0.055D^{2.572}$	0.97 **	[35]
<i>Sloanea sinensis</i> (Hance) Hemsl.	$W = 0.2358D^{2.2483}$	0.94 **		<i>Camellia oleifera</i> Abel.	$W = 0.151D^{2.017}$	0.98 **	
<i>Daphniphyllum oldhami</i> (Hemsl.) Rosenth.	$W = 0.1726D^{2.3686}$	0.96 **	[36]	<i>Quercus</i> sp.	$W = 0.174D^{2.390}$	0.95 **	
<i>Engelhardtia fenzlii</i> Merr.	$W = 0.1583D^{2.3232}$	0.88 **		Other hardwood	$W = 0.186D^{2.377}$	0.97 **	
<i>Manglietia yuyuanensis</i> Law.	$W = 0.1463D^{2.3845}$	0.95 **		Other sortwood	$W = 0.104D^{2.530}$	0.96 **	
<i>C. lanceolata</i>	$W = 0.096D^{2.410}$	0.99 **		Other <i>Pinus</i> sp.	$W = 0.428D^{2.009}$	0.99 **	
<i>P. massoniana</i>	$W = 0.428D^{2.009}$	0.99 **		<i>Octagon</i> sp.	$W = 0.206D^{2.277}$	0.93 **	[37]
<i>Eucalyptus</i> sp.	$W = 0.138D^{2.436}$	0.98 **		<i>Mytilaria laosensis</i> Lec.	$W = 0.6841D^{2.0158}$	0.86 **	

Note: **, significant at $p < 0.01$ level.

The snag biomass was calculated using the number, fresh weight and moisture contents of different decomposed state snags. The log biomass was computed according to the fresh weights and moisture contents of different decomposed state logs.

The shrub biomass was calculated according to the number of shrubs, the fresh weight and moisture content of average standard shrubs from each of the three 5 m × 5 m shrub plots. The herb biomass was computed according to the fresh weight and moisture content of herbs from the three 1 m × 1 m herb plots. The litter biomass was the sum of biomasses of three decomposition state litters, and the biomass of each decomposition state litter was calculated according to its litter fresh weights, moisture contents and the area of the litter plot.

2.4. Calculation of Vegetation Carbon Density

The vegetation carbon density at each forest level is equal to the product of the biomass density at each forest level and its carbon content. The vegetation carbon density of the total forest equal to the sum of the vegetation carbon densities of the arbor layer, shrub

layer, herb layer, litter layer and snag and log layer. The calculation model of vegetation carbon density at each layer is as follows:

$$CD_i = B_i \times C_i \quad (1)$$

where CD_i is the carbon density of i layer, Mg/ha; B_i is the biomass density of the i layer in the plot, Mg/ha; C_i is the carbon content of each i layer. The carbon contents of arbor, shrub, herb, litter, snag and log were calculated according to Table 3.

Table 3. Carbon concentration of different forest types.

Vegetable Layers	EBF	PMF	CLF	OCF	MBCF	Reference
Arbor and snag	0.5115	0.5523	0.5375	0.5431	0.5296	[38]
Shrub and litter	0.5000	0.5000	0.5000	0.5000	0.5000	[12]
Herb and snag	0.4500	0.4500	0.4500	0.4500	0.4500	[39]

2.5. Data Analysis

The calculations of the individual biomass, average tree height (AH), average tree DBH (ADBH), basal area at breast height, volume, and vegetation carbon density of each plot were all calculated in Microsoft Excel (2016). The AH and ADBH were computed using Formula (2), which is as follows:

$$AY = \sum_{i=1}^n Y_i / N \quad (2)$$

where AY is the AH or ADBH each forest plot respectively; Y_i is the height or DBH of i standing tree in a plot respectively; and N is the number of standing tree in a plot.

The BA and VPA were calculated respectively using Formula (3), which is as follows:

$$\rho = \frac{\sum_{i=1}^n \rho_i}{800} * 10,000 \quad (3)$$

where ρ is the BA or VPA each forest plot respectively, m^2/ha or m^3/ha ; ρ_i is the BA or the volume of i individual (standing tree, snag or log) in each forest plot, m^2 or m^3 ; 800 is the area of each forest plot, 800 m^2 ; 10,000 is the area a hectare, 10,000 m^2 . The BA of each individual was computed using the formula ($A = \pi DBH_i^2 / 4$), and the volume of each individual standing tree and snag was calculated using the unitary volume models of the main tree species provided in the “Commonly Used Table In Forestry Investigation” compiled by the Jiangxi Forestry Survey and Design Institute [40], and the log volume was calculated using the formula $V = \pi l (d_{max}^2 + d_{min}^2) / 8$ [41].

The tree density (TD) was calculated using the formula $y = N / 800 \times 10,000$ (N was the number of standing trees in the 800 m^2 forest plot).

The biomass per unit area each plot was computed using Formula (4), which is as follows:

$$B = \frac{B_t + B_{sl} + B_s + B_h + B_l}{800} * 10,000 \quad (4)$$

where B is the plant biomass, t/ha; B_t , B_{sl} , B_s , B_h and B_l are the biomass of trees, snags and logs, shrubs, herbs and litters each plot respectively, t; 800 is the area of each plot, m^2 ; and 10,000 is the area of each hectare, m^2 .

In Excel, the slope direction was divided into sunny slope (south slope), semi-sunny slope (east slope, southeast slope, west slope and southwest slope), semi-shady slope (northeast slope and northwest slope) and shady slope (north slope), and the slope position was divided into up slope (ridge and up slope), middle slope, down slope (valley and down slope) and flat land. Then, the statistical description, homogeneity test of variance, analysis of variance (ANOVA), multiple comparisons, correlation analysis and regression analysis were all undertaken using SPSS19.0 statistical software [42]. If the variance is not

uniform, the Tamhane method was used in multiple comparison after variance analysis, otherwise, the LSD method was used for multiple comparison.

3. Results

3.1. Descriptive Statistics of Vegetation Carbon Density

The average FVCD in Jiangxi province was 44.23 Mg/ha, the standard deviation was 2.20, the variation range was 2.11–177.58 Mg/ha, the skewness was 1.54 and the kurtosis was 5.93, which was bigger than 3.0, indicating that the FVCD in Jiangxi province has excessive kurtosis. The vegetation carbon density of forest communities in Jiangxi province was dominated by arbor, accounting for about 81.39% of the total forest, followed by the shrub layer, accounting for about 13.82% of the total forest, and then followed by snags and logs and litter; herb was the lowest, accounting for about 0.71% of the total forest. The skewness of vegetation carbon density in each layer was greater than zero, which showed positive skewness, indicating that the number of sample plots with vegetation carbon density less than the average of each layer was greater than the number of sample plots with vegetation carbon density higher than the average of each layer. This result was consistent with the fact that the forest in Jiangxi province was dominated by middle and young age vegetation with lower vegetation carbon density. The variation coefficient of vegetation carbon density at all levels was the highest in snags and logs, followed by the herb and shrub layer; the variation coefficients of vegetation carbon density of the arbor layer, litter layer and total forest were close (Table 4).

Table 4. Mean, standard deviation (SD), coefficient of variation (CV), minimum, maximum, range, skewness and kurtosis of vegetation carbon density.

Layers	Mean	SD	CV (%)	Minimum	Max	Skewness	Kurtosis
Arbor layer (Mg/ha)	36.00	29.71	5.68	0.61	163.51	1.54	5.91
Shrub layer (Mg/ha)	6.11	6.26	7.05	0.00	37.23	2.07	8.53
Herb layer (Mg/ha)	0.31	0.41	9.18	0.00	4.56	6.02	55.96
Litter layer (Mg/ha)	0.86	0.64	5.14	0.04	4.90	2.29	11.84
Snag and log layer (Mg/ha)	0.94	2.40	17.53	0.00	16.52	4.10	21.73
Total forest (Mg/ha)	44.23	31.95	4.97	2.11	177.58	1.54	5.94

3.2. Descriptive Statistics of Stand Structure and Topography

Except for canopy density (CD) skewness < 0, the skewness of BA, VPUA, ADBH, AH and TD were all >0, showing a right-skewed distribution. The variation coefficients of stand structure factors in Jiangxi forest were highest in volume per unit area, followed by BA, and the variation coefficients of CD, AH and ADBH were close (Table 4).

Among the topographic factors, the elevation of the sample plots had a positively skewed distribution (Table 4), and the forest plots were mainly distributed in the altitudinal gradients 50~500 m, which is consistent with the fact that landform is dominated by low mountains and hills in Jiangxi province. The slope of the sample plot showed a negative deviation, and the forest sample plots were mainly distributed in the slope degree gradients 10~40° (Table 5 and Figure 2).

3.3. Variation of Vegetation Carbon Density with Stand Structure

3.3.1. Variation of Vegetation Carbon Density with Stand Types

Except for the fact that there was insignificant differences in vegetation carbon densities of shrub and herb layers between the forest types, the vegetation carbon densities of the arbor, litter, snag and log, and total forest layers in the Jiangxi forest had significant differences ($p < 0.05$) or extremely differences ($p < 0.01$) among different forest types, in which the vegetation carbon density in arbor layer of EBF was extremely higher than that of PMF, and significantly higher than that of CLF. The vegetation carbon density of snags and logs in EBF was extremely higher than that of PMF, and the vegetation carbon density

of litter in EBF was significantly lower than that of OCF. The vegetation carbon density of EBF was extremely higher than that of CLF, and significantly higher than that of PMF and MBCF (Table 6).

Table 5. Mean, standard deviation (SD), coefficient of variation (CV), minimum, maximum, skewness and kurtosis of stand structure and topography.

Indicators	Mean	SD	CV (%)	Minimum	Max	Skewness	Kurtosis
BA (m ² /ha)	15.16	10.30	4.68	0.40	46.64	0.78	3.02
VPA (m ³ /ha)	76.01	60.73	5.50	1.07	341.26	1.20	4.58
ADBH (cm)	11.73	3.57	2.09	5.40	25.30	0.86	4.10
AH (m)	8.35	2.49	2.06	2.60	15.40	0.39	3.12
TD (n/ha)	1363.24	798.81	4.03	138.00	4938.00	1.10	4.81
CD (-)	0.59	0.18	2.05	0.20	0.95	−0.23	2.25
Elevation (m)	311.68	275.37	6.08	20.00	1800.00	2.05	9.21
Slope degree (°)	22.73	11.84	3.59	0.00	60.00	−0.10	2.57

Note: BA, Basal area at breast height; VPA, Volume per unit area; ADBH, Average diameter at breast height; AH, Average height of tree; TD, Tree density, CD, Canopy density.

Figure 2. Variation characteristics of plot quantity with altitude gradients and slope gradients.

Table 6. The ANOVA and multiple comparison of vegetation carbon density (mean $\pm$ SE) in different layers among stand types.

Layers	EBF (Mg/ha)	PMF (Mg/ha)	CLF (Mg/ha)	OCF (Mg/ha)	MBCF (Mg/ha)	p^1	F
Arbor layer	45.73 $\pm$ 4.28 Aa	26.68 $\pm$ 3.37 Bb	27.49 $\pm$ 3.49 ABb	34.61 $\pm$ 6.67 ABab	31.79 $\pm$ 2.75 ABab	0.000	4.05 **
Shrub layer	6.15 $\pm$ 0.69	6.35 $\pm$ 1.25	4.02 $\pm$ 0.67	5.92 $\pm$ 1.70	7.08 $\pm$ 0.91	0.167	1.10 ns
Herb layer	0.27 $\pm$ 0.03	0.35 $\pm$ 0.05	0.29 $\pm$ 0.05	0.36 $\pm$ 0.07	0.36 $\pm$ 0.10	0.173	0.50 ns
Litter layer	0.80 $\pm$ 0.08 b	0.99 $\pm$ 0.11 ab	0.81 $\pm$ 0.09 ab	1.14 $\pm$ 0.22 a	0.83 $\pm$ 0.07 ab	0.113	1.40 *
Snag and log layer	1.56 $\pm$ 0.37 Aa	0.17 $\pm$ 0.07 Bb	0.57 $\pm$ 0.36 ABab	1.08 $\pm$ 0.40 ABab	0.64 $\pm$ 0.23 ABab	0.000	2.64 **
Total forest	54.51 $\pm$ 4.61 Aa	34.54 $\pm$ 3.67 ABb	33.16 $\pm$ 3.39 Bb	43.11 $\pm$ 8.07 ABab	40.69 $\pm$ 2.78 ABb	0.000	4.09 **

Note: Means followed by different capital or lower-case letters differ significantly at $p < 0.01$ and $p < 0.05$, respectively (LSD's multiple-range test); ¹, the significance of the homogeneity of variance test; *, significant difference at $p < 0.01$ level; **, significant difference at $p < 0.01$ level; ns, no significant difference at $p < 0.05$ level. The same below.

3.3.2. Variation of Vegetation Carbon Density with Other Stand Structure Factors

Correlation analysis results showed that except for the insignificant correlation between shrub carbon density and stand structure, the vegetation carbon density of other forest layers and total forest in Jiangxi province was extremely or significantly correlated with some or all stand structure factors, in which the vegetation carbon density of arbor and total forest layers were extremely significantly positively correlated with all stand structure factors, and both had the highest correlation coefficient with volume per unit area. Herb carbon density was extremely significantly negatively correlated with CD, and

significantly negatively correlated with BA and VPUA. The litter carbon density was not significantly correlated with AH, but extremely significantly positively correlated with BA and VPUA, and significantly correlated with the rest of the stand structure factors. The carbon density of snags and logs was significantly positively correlated with AH, and extremely significantly positively correlated with all other stand structure factors (Table 7).

Table 7. Correlations between FVCD in each layer and stand quantitative characteristics.

Layers	BA	VPUA	ADBH	AH	TD	CD
Arbor layer	0.92 **	0.97 **	0.67 **	0.58 **	0.44 **	0.58 **
Shrub layer	−0.01	0.01	0.07	0.11	−0.04	−0.02
Herb layer	−0.17 *	−0.15 *	−0.10	−0.10	−0.16 *	−0.21 **
Litter layer	0.19 **	0.18 **	0.17 *	0.08	0.15 *	0.14 *
Snag and log layer	0.45 **	0.47 **	0.27 **	0.17 *	0.19 **	0.21 **
Total forest	0.89 **	0.94 **	0.66 **	0.57 **	0.42 **	0.55 **

Note: BA, Basal area at breast height; VPUA, Volume per unit area; ADBH, Average diameter at breast height; AH, Average height of tree; TD, Tree density, CD, Canopy density; *, significant correlation at $p < 0.05$ level; **, significant correlation at $p < 0.01$ level.

3.4. Variation of Vegetation Carbon Density with Topography

3.4.1. Variation of Vegetation Carbon Density with Altitude and Slope Degree

Correlation analysis results showed that except for the fact that the carbon densities of shrub, herb, and litter were not significantly correlated with altitude, the vegetation carbon density of arbor, snags and logs, and total forest layers were all significantly positively correlated with altitude, which indicates that the vegetation carbon density of arbor, snags and logs and total forest layers increased with elevation in Jiangxi province (Table 7). Correlation analysis results show that except for the insignificant correlation between the vegetation carbon densities of shrub, herb and litter and the slope degree, the vegetation carbon densities of arbor, snags and logs, and total forest layers all had extremely significant positive correlations with the slope degree, indicating that the vegetation carbon densities of arbor, snags and logs, and total forest layers increased with slope degree in Jiangxi province (Table 8).

Table 8. Correlation coefficients between forest vegetation carbon density in each layer and altitude and slope degree.

Indicators	Arbor	Shrub	Herb	Litter	Snag and Log	Total Forest
Altitude	0.30 **	0.13	−0.10	−0.01	0.31 **	0.33 **
Slope degree	0.29 **	0.01	−0.04	0.11	0.23 **	0.29 **

Note: **, extremely significant correlated at $p < 0.01$ level.

3.4.2. Variation of Vegetation Carbon Density under Slope Aspects

Except for the fact that the vegetation carbon densities of arbor, shrub, herb and snag and log layers were not significantly different between different slope directions, the vegetation carbon densities of forest litter and total forest layers in Jiangxi Province had significant differences among different slope aspect gradients. Of which, the vegetation carbon densities of total forest were highest on the sunny slope, and lowest on the no slope aspect area, while the carbon density of the litter layer was highest on the semi-sun slope and lowest on the no slope aspect, but there was no significant difference in the carbon density of the litter layer between semi-sun slope and the rest of the slope aspect (Table 9).

Table 9. Differences of vegetation carbon density between slope aspect gradients.

Layers	Sunny (Mg/ha)	Semi-Sunny (Mg/ha)	Semi-Shady (Mg/ha)	Shady (Mg/ha)	No slope Aspect (Mg/ha)	p^1	F
Arbor layer	47.81 ± 6.81	33.65 ± 2.53	42.12 ± 5.28	34.05 ± 6.60	23.62 ± 5.71	0.042	2.08 ns
Shrub layer	4.14 ± 0.89	6.30 ± 0.59	6.62 ± 0.91	6.42 ± 1.64	5.03 ± 1.53	0.276	0.67 ns
Herb layer	0.18 ± 0.03	0.29 ± 0.03	0.41 ± 0.11	0.31 ± 0.05	0.34 ± 0.08	0.156	1.05 ns
Litter layer	0.80 ± 0.12 ab	0.97 ± 0.07 a	0.78 ± 0.09 ab	0.84 ± 0.09 ab	0.50 ± 0.08 b	0.106	2.18 *
Snag and log layer	2.67 ± 1.13	0.83 ± 0.21	0.94 ± 0.31	0.59 ± 0.34	0.29 ± 0.16	0.000	2.91 ns
Total forest	55.60 ± 7.52 a	42.05 ± 2.72 ab	50.86 ± 5.57 a	42.2 ± 2.731 ab	29.78 ± 6.27 b	0.124	2.01 *

Note: ¹, the significance of the homogeneity of variance test; *, significant correlation at $p < 0.05$ level; ns, no significant difference at $p < 0.05$ level. The different letters indicates significant differences.

3.4.3. Variation of Vegetation Carbon Density under Slope Positions

There was no significant difference in the carbon densities of shrub and herb among different slope position gradients; there were not only significant differences ($p < 0.05$) in the carbon densities of arbor, snag and log and total layers among different slope positions, but also extremely significant differences ($p < 0.01$) in the vegetation carbon densities of litter layer. In addition, the vegetation carbon densities of arbor, litter, snag and log, and total forest layers were the highest on the upslope, and the lowest on the flat ground, indicating that the slope position had a significant impact on the FVCD in Jiangxi province (Table 10).

Table 10. Differences in vegetation carbon density (mean ± SE) between slope position gradients.

Layers	Upslope (Mg/ha)	Mesoslope (Mg/ha)	Downslope (Mg/ha)	Flat (Mg/ha)	p^1	F
Arbor layer	41.80 ± 3.66 a	41.08 ± 4.41 a	27.67 ± 2.42 b	23.57 ± 6.14 b	0.000	4.17 *
Shrub layer	6.33 ± 0.77	5.99 ± 0.76	6.22 ± 0.80	5.20 ± 1.64	0.983	0.14 ns
Herb layer	0.32 ± 0.04	0.36 ± 0.07	0.25 ± 0.03	0.36 ± 0.09	0.219	0.96 ns
Litter layer	1.06 ± 0.09 Aa	0.80 ± 0.07 Ab	0.81 ± 0.09 Ab	0.51 ± 0.09 Bb	0.289	3.93 **
Snag and log layer	1.75 ± 0.45 a	0.74 ± 0.18 ab	0.52 ± 0.22 ab	0.31 ± 0.17 b	0.000	3.65 *
Total forest	51.26 ± 4.03 a	48.97 ± 4.58 ab	35.46 ± 2.77 b	29.94 ± 6.73 b	0.004	4.28 *

Note: ¹, the significance of the homogeneity of variance test; *, significant difference at $p < 0.01$ level; **, significant difference at $p < 0.01$ level, ns, no significant difference at $p < 0.05$ level. The different letters indicates significant differences.

4. Discussion

4.1. Comparative Analysis with Previous Research

Forest vegetation carbon density is not only closely related to stand structure and quality, such as stand type, stand age and arbor density, but also restricted by topography and social and economic factors [8,9,43]. In addition, research results on vegetation carbon density vary with different research methods [20]. Excluding the differences in the study area, the age structure of the experimental sample plot and the research method, this study is basically consistent with the previous research results on FVCD in Jiangxi province or China (Table 11), indicating that the results of this study are scientific and reasonable. In this study, the FVCD in Jiangxi province is dominated by the arbor layer, accounting for about 81.39% of the total forest, which is consistent with the results of Wang Bin et al. (the vegetation carbon density of arbor in Jiangxi province accounted for 47.39–90.41% of the FVCD) [22], but lower than the research results of Chen Danfeng (the arbor carbon density of *C. lanceolata* forest, *P. massoniana* forest and *P. elliotii* forest in Jiangxi province accounted for 88.53%, 89.99% and 82.92% of the FVCD) [44], and 89.44% of *P. massoniana* forest in south Jiangxi province reported by Guo Liling et al. [45], and 98.98% of forest in middle Jiangxi province by Li Haifeng et al. [27].

Table 11. Comparative analysis with previous research on vegetation carbon density (Mg/ha).

Research		EBF	PMF	CLF	OCF	MBCF	Sampling Site
Sample Survey Method	Here [44]	54.51	34.54 68.54	33.16 88.56	43.11 43.47	40.69	Whole Jiangxi Whole Jiangxi
	[23]	51.85					Jiulian, Jinggang, Dagang, Matou and Wuyi mountain
	[46]	103.4	87.68	140.9	75.4	83.6	Qianyanzhou
	[47]	54.10–79.10					Jiulian mountain
	[20]		39.7	59.1	57.8		Southern–central Jiangxi
	[27]	43.0 (4.82–170.55)					Qianyanzhou–Jinggang belt transect
	[8]			36–42			Whole China
	Volume-derived Biomass Method	[48]	59.96	13.28	36.89	24.65	44.94
[49]		53.0	21.4	33.2	40.7	39.6	Whole Jiangxi
[17]		40.77–81.55					Whole Jiangxi
[20]			17.1	48.6	39.3		Southern–central Jiangxi
[12]		42.64	14.89	29.51	37.68	33.00	Whole Jiangxi
[19]		35.5	10.0	20.77	8.5	27.1	Whole Jiangxi
[43]				42.6–49.5			Whole China
[11]				41.3			Whole China

Based on the field sample survey data, an allometric equation was used to calculate the vegetation biomass and vegetation carbon density. The variation range of FVCD in Jiangxi province was 2.11–177.58 Mg/ha, with an average of 44.23 t/ha—slightly higher than the 41.32 Mg/ha by Zhao Min et al. [11], and close to the 42.6–49.5 Mg/ha found by Fang Jingyun et al. [43], indicating that the FVCD in Jiangxi province is close to the average level of China's forests, but far lower than 86.00 Mg/ha—the average global level of FVCD [50]. The main reasons for this may be that the arbor forests in Jiangxi province are mainly of middle and young age, and forest management in Jiangxi province is mainly extensive management with slow growth [16]. As a result, the FVCD in Jiangxi province is low. Meanwhile, this study also showed that the forest in Jiangxi Province has a great potential for vegetation carbon sequestration.

4.2. Effects of Stand Structure on Vegetation Carbon Density

Factors such as DBH, tree height, stand density, stand age, canopy and volume are important parameters in the stand biomass model [43,51–53], and forest vegetation carbon storage is extremely significantly correlated with stand biomass per unit area, resulting in a very significant correlation between FVCD and stand structure factors [12,54–58]. In this study, it was found that the vegetation carbon density of arbor, litter, snags and logs, and total forest layers all had significant differences between different forest types in Jiangxi province. The vegetation carbon density of arbors, herbs, litters, snags and logs and total forest layers were also significantly correlated with stand structure factors such as VA, AVUA, ADBH, AH, TD and CD, which indicated that stand structure restricted the FVCD in Jiangxi province. This result is consistent with previous research results in Jiangxi province. For example, Li et al. found that the FVCD in Jiangxi was significantly correlated with TD [27], and Wu et al. found significant differences in vegetation carbon density among *P. massoniana* forest, *P. elliotii* forest and *C. lanceolata* forest in the Poyang Lake Basin [59]. Wu et al. also found that the FVCD in Jiangxi province had significant differences between stand origin, stand types and age groups by using the volume-derived biomass method [19].

Zhang et al. also found significant differences in vegetation carbon density among stand types in their study of EBF in the Jiulianshan Nature Reserve in Jiangxi province [60]. In addition to the close relationship between vegetation carbon density and stand types, this study also found that there was a very significant correlation between FVCD and stand structure factors in Jiangxi, of which the highest correlation coefficient was between FVCD

and volume per unit area ($r = 0.94$; Table 7). It was found that there was a significant positive linear correlation between FVCD and volume per unit area in all the main forest communities in Jiangxi (Figure 3). The result was a FVCD-volume model of local plants in Jiangxi province, which can provide a simple accounting method for the study of forest vegetation carbon storage and carbon sequestration potential using forest inventory databases for Jiangxi province.

Figure 3. Models of FVCD (FVCD) and volume per unit area (VPUA) for main forest types in Jiangxi province.

4.3. Effects of Topography on Vegetation Carbon Density

Topography is an important factor affecting forest structure and vegetation carbon density [14,15,61]. This study found that the vegetation carbon densities of arbor, snags and logs, and total forest layers were significantly correlated with topographic factors, except for shrub and herb layers, and the vegetation carbon densities of forest increased with the increase of elevation and slope. The carbon density of litter differed significantly between slope aspect and slope position gradients. This result was consistent with previous regional research results in Jiangxi province. For example, Li et al. found that the vegetation carbon density in central Jiangxi province was significantly correlated with altitude [27]. Wu et al. studied the vegetation carbon density of the main forests in the Poyang Lake Basin and found that the vegetation carbon densities differed significantly between slope aspect and elevation gradients and increased with elevation [59]. However, the results of this study were also different from previous studies. For example, Li et al. concluded that vegetation carbon density in central Jiangxi decreased with the increase of altitude [27], while the results of this study showed that the vegetation carbon density in Jiangxi province increased with the increase of altitude. The reason for this difference may be related to the difference in study area. This study studied the forests of the whole Jiangxi province, while Li et al. studied the forests of the central Jiangxi Basin, which is a low hilly area. The forests in central Jiangxi province are mainly the planted forest, with trees all planted at the same time, where the vegetation carbon density of the plantations of the same age is mainly related to soil fertility. There is a high water erosion intensity in central Jiangxi

province, and the higher the altitude, the lower the soil fertility, resulting in a negative correlation between vegetation carbon density and altitude.

The effect of topography on vegetation carbon density in Jiangxi province is works in the following two ways: (1) It affects soil properties by restricting water and heat conditions [62], which in turn affect species composition, forest structure and function, and ultimately lead to differences in forest vegetation carbon density [14,63]. Correlation analysis showed that there were extreme or significant correlations between terrain factors (altitude and slope) and forest structure factors, which indirectly proved the effect mechanism of topography on FVCD for Jiangxi province (Table 12). (2) Landform affects the regional land use and population distribution patterns, and then restricts the distribution, utilization and management level of regional forest resources, and finally affects the FVCD. Population density and arable land resources in Jiangxi decrease with altitude [64,65], and the forest is mainly distributed in the Ganjiang, Fuhe, Xinjiang, Xiushui and Raohe five rivers and their source mountains, with complex terrains, high mountains, steep slopes, and inconvenient transportation [66]. As a result, natural forests in Jiangxi province are mainly distributed in river source areas with large slopes, high altitudes and less human interference, while artificial forests are mainly distributed in basins and hilly areas with convenient transportation, low altitudes, low slopes and greater human interference. Therefore, the lower the altitude, the higher the proportion of planted forests dominated by young and middle-aged forests, and the higher the altitude, the higher the proportion of natural forests, ultimately leading to increases in the carbon density of forest plants in Jiangxi with increases in altitude and slope.

Table 12. Relationships between forest structure and altitude and slope degree respectively.

Indicators	BA	VPUA	ADBH	AH	TD	CD
Altitude	0.29 **	0.31 **	0.16 *	0.09	0.14 *	0.17 *
Slope degree	0.29 **	0.28 **	0.18 *	0.17 *	0.23 **	0.29 **

Note: * and **, obviously and extremely significant correlated at $p < 0.01$ level respectively.

5. Conclusions

By using the traditional quadrature survey method and allometric growth equation to obtain biomass, and then systematically study the quantitative characteristics of FVCD, stand structure and topographic factors, and their interaction in Jiangxi province, the following research conclusions were drawn: (1) The average FVCD of Jiangxi province was 44.23 Mg/ha, far lower than the average level of global FVCD—which proved that the forest in Jiangxi province was dominated by middle-aged and young forests with low carbon density, and also indicated that the potential of forest vegetation carbon storage in Jiangxi province was huge. (2) Except for the carbon densities of shrub and herb, the vegetation carbon densities of other forest layers and total forest in Jiangxi province were significantly different among different forest types. The vegetation carbon densities of arbor, herb, litter, snags and logs, and total forest were significantly related to some or all of the stand structure factors. Among them, the correlation coefficients between the vegetation carbon density of arbor layer and total forest and VPUA were both the largest. Based on this, the carbon density–volume model of the main forest types in Jiangxi province was built to provide methodological support for the study of forest vegetation carbon storage and carbon neutrality in Jiangxi province. (3) The vegetation carbon densities of arbor, snags and logs, and total forest layers were significantly correlated with altitude and slope degree. Except for the vegetation carbon densities of shrub and herb, the vegetation carbon densities of the rest of the forest layers and the total forest were significantly different between slope position gradients and slope aspect gradients, indicating that topography has a significant effect on FVCD in Jiangxi province, mainly by influencing forest distribution and human disturbance intensity.

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