

Postprint: Altitudinal Distribution Characteristics of Carbon Density in Qinghai Spruce Forests on the Southern Slope of the Qilian Mountains

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Abstract

Forest biomass is fundamental to the study of forest primary productivity, and its carbon density serves as a crucial indicator for evaluating forest ecosystem structure and function. To investigate the altitudinal variation characteristics of typical stand density of *Picea crassifolia* in the Amidongso small watershed on the southern slope of the Qilian Mountains, the biomass model calculation method was employed across different elevations. The elevation range of 2900–3200 m was selected to survey and analyze the variation patterns of carbon density in both the arbor layer and soil layer of *Picea crassifolia* along the altitudinal gradient, aiming to provide fundamental data for carbon storage estimation of *Picea crassifolia* forests in the Qilian Mountains. The results showed that the average total biomass in the study area was $135.59 \text{ t} \cdot \text{hm}^{-2}$, exhibiting a decreasing trend with increasing altitude. The average carbon density of the arbor layer was $70.51 \text{ t} \cdot \text{hm}^{-2}$, while the average soil organic carbon density in the 0–50 cm soil layer was $154.01 \text{ t} \cdot \text{hm}^{-2}$. With increasing altitude, the carbon density of the arbor layer displayed a decreasing trend, whereas the soil organic carbon density exhibited a pattern of initial decline followed by subsequent increase. The ecosystem carbon density of *Picea crassifolia* forest across different altitudes in the study area was $224.51 \text{ t} \cdot \text{hm}^{-2}$, with the carbon densities of the arbor layer and soil layer accounting for 30.5% and 69.5% of the total carbon density, respectively, and showing a decreasing trend with rising altitude. The forest soil carbon pool accounts for a substantial proportion, and enhancing forest soil protection constitutes a critical approach for maintaining forest ecological balance.

Full Text

Distribution Characteristics of Carbon Density in Qinghai Spruce Forest on the Southern Slope of Qilian Mountains with Altitude

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Abstract: Forest biomass forms the foundation for studying forest primary productivity, and its carbon density serves as a crucial indicator for evaluating forest ecosystem structure and function. To investigate the variation characteristics of typical Qinghai spruce (*Picea crassifolia*) stand density with altitude in the Amidongso small watershed on the southern slope of Qilian Mountains, we employed biomass model calculations to analyze changes in carbon density of both arbor and soil layers along an altitudinal gradient. The study aimed to provide baseline data for estimating carbon storage in Qinghai spruce forests at elevations of 2900–3200 m in the Qilian Mountains. Results showed that the average total biomass in the study area was $135.59 \text{ t} \cdot \text{hm}^{-2}$, decreasing with increasing altitude. The average carbon density of the arbor layer was $70.51 \text{ t} \cdot \text{hm}^{-2}$, while the average soil organic carbon density in the 0–50 cm layer was $154.01 \text{ t} \cdot \text{hm}^{-2}$. With rising altitude, arbor layer carbon density exhibited a decreasing trend, whereas soil organic carbon density first decreased and then increased. The ecosystem carbon density of Qinghai spruce forest across different altitudes was $224.51 \text{ t} \cdot \text{hm}^{-2}$, with arbor and soil layers accounting for 30.5% and 69.5% of total carbon density, respectively. Both components showed decreasing trends with increasing altitude. The forest soil carbon pool represents a substantial proportion, and strengthening forest soil protection constitutes a powerful direction for maintaining forest ecological balance.

Keywords: southern slope of Qilian Mountains; Qinghai spruce forest; biomass; carbon density

Introduction

Forest ecosystems represent the primary carbon pool in terrestrial ecosystems, occupying 77% of global vegetation carbon pools and 39% of soil carbon pools

[1]. This massive carbon pool plays a decisive role in maintaining global carbon balance, attracting considerable attention from scholars worldwide regarding its dynamic changes [2]. Altitude, as an extremely complex environmental factor, directly or indirectly influences soil physicochemical properties [3] and vegetation distribution [4] by altering hydrothermal conditions, thereby affecting soil organic matter input and decomposition processes and consequently influencing forest carbon density. Furthermore, forest soil organic carbon constitutes an important component of forest ecosystem carbon pools and serves as a key indicator reflecting soil fertility [5]. Research indicates that altitude variation significantly affects forest soil organic carbon accumulation [6], with vegetation organic carbon at high altitudes responding more sensitively to climate change [7].

Numerous scholars have investigated forest vegetation biomass and soil organic carbon content based on natural altitudinal variations. For instance, Xiong et al. [8] examined biomass, carbon storage, and spatial distribution characteristics of different forest vegetation types in Fanjing Mountain, concluding that forest vegetation biomass and carbon storage were mainly distributed in specific elevation ranges. Qin et al. [9] studied vegetation and soil carbon density in the Henan section of the Yellow River Basin, finding that these parameters showed significant spatial differentiation along altitude gradients. Ren et al. [10] investigated forest vegetation carbon storage in Chengdu, revealing an inverted “V” pattern with maximum values in mid-altitude regions. Zhang et al. [11] explored altitudinal gradient patterns of soil organic carbon storage on the northern slope of Taibai Mountain in the Qinling range, demonstrating significant altitude effects on organic carbon density. These findings indicate that altitude gradients substantially influence montane forest vegetation carbon density and soil organic carbon content, though patterns exhibit regional differences [12]. Therefore, utilizing natural altitudinal variations to understand carbon pool composition and dynamic changes in Qinghai spruce forests is crucial for regional carbon balance development.

The Qilian Mountains constitute a major mountain system on the northeastern Tibetan Plateau, making significant contributions to ecological security in northwestern China. With distinct vertical differentiation, this region represents an ideal area for vegetation studies [13]. Qinghai spruce is the dominant constructive tree species in Qilian Mountain forest areas, showing clear altitudinal distribution dependence. For years, Qinghai spruce forests have attracted considerable research attention due to their exceptional water conservation functions. Current research on Qinghai spruce at different altitudes in the Qilian Mountains has primarily focused on litter decomposition, growth process changes, and responses to environmental factors [14,15]. Understanding carbon density variation patterns in both upper and lower layers is essential for accurately assessing forest ecosystem carbon cycles. Studies have shown that Qinghai spruce sapling biomass carbon reaches maximum values within the 2800-3100 m altitude range [16]. The Amidongso small watershed on the southern slope of Qilian Mountains features Qinghai spruce growing precisely within this range (2900-3200 m).

Therefore, investigating carbon density in this region's Qinghai spruce forests facilitates scientific management of this tree species.

1. Materials and Methods

1.1 Study Area Overview The southern slope of Qilian Mountains is located on the northeastern edge of Qinghai Province, geographically positioned between 98°08'13" E and 102°38'16" E and 37°03'17" N and 39°05'56" N, with elevations ranging from 2286 to 5210 m. The study area features weakly alkaline soils. The region enjoys long annual sunshine duration of approximately 2200–2900 hours, with concurrent rainfall and heat, distinct wet and dry seasons, and precipitation concentrated in June–September. Temperature and precipitation show clear horizontal and vertical gradient differences. The Amidongso small watershed, located 13 km southeast of Qilian County, presents an east-west oriented valley with elevations between 2800–4667 m. The area's lithology mainly consists of acidic igneous rocks, conglomerate, and sandstone. The primary constructive forest species is Qinghai spruce, distributed in patches on shady and semi-shady slopes, with occasional *Sabina przewalskii* distribution, mostly forming single-layer pure stands at 2900–3200 m elevations [17].

1.2 Plot Establishment In July 2021, based on the distribution of Qinghai spruce forests on the southern slope of Qilian Mountains and ensuring consistent environmental conditions (such as slope and aspect), sample plots were established at 100 m altitude intervals from 2900 m to 3200 m, comprising four altitude gradients. Each gradient included three sample plots, totaling 12 plots, each measuring 20 m × 20 m. All Qinghai spruce trees with diameter at breast height (DBH) ≥ 3 cm were measured, with survey factors including canopy closure, DBH, and tree height. Plot descriptions are provided in .

1.3 Sample Collection and Determination Within each plot, five sampling points were selected along the slope direction using random sampling methods. Soil samples were collected at 10 cm intervals from 0–50 cm depth using a soil auger with 5 cm diameter, with five replicates per altitude gradient, totaling 60 soil samples. Additionally, ring knife soil samples were collected at each point by layer to determine bulk density. Soil organic carbon content was measured using the potassium dichromate oxidation-external heating method.

1.4 Calculations 1.4.1 Biomass and Carbon Density Calculation

This study employed biomass models using relative growth equations for individual Qinghai spruce organ biomass [18]. Stand total biomass was calculated by summing all individual tree biomasses within the plot. The formulas are as follows:

$$W_T = \sum_{i=1}^n W_{Ti}$$

where W_T represents total biomass of the sample plot ($\text{t} \cdot \text{hm}^{-2}$), W_{T_i} is the biomass of the i -th tree, and n is the number of trees in the plot.

Following Zeng et al. [19], arbor layer carbon density was calculated by multiplying arbor layer biomass per unit area by a conversion coefficient (carbon mass fraction of dry matter, 0.5). Forest ecosystem carbon density was obtained by summing arbor layer carbon density and forest soil layer average carbon density. Since carbon density of shrub-herb and litter layers constitutes a small proportion of total ecosystem carbon density, these components were excluded from calculations.

1.4.2 Soil Carbon Density Calculation

Soil organic carbon density (SOC_D) for different soil layers was calculated using the following formula [20]:

$$SOCD_d = \frac{C_d \times D_d \times E_d \times (1 - G_d)}{100}$$

where $SOCD_d$ is soil organic carbon density of layer d ($\text{kg} \cdot \text{m}^{-2}$), C_d is soil organic carbon content of layer d ($\text{g} \cdot \text{kg}^{-1}$), D_d is bulk density of layer d ($\text{g} \cdot \text{cm}^{-3}$), E_d is thickness of layer d (cm), and G_d is the percentage of gravel content >2 mm in layer d .

1.4.3 Data Processing

SPSS 26 software was used for statistical analysis, with one-way ANOVA for significance testing and multiple comparisons. Origin 2022b was used for figure and table preparation.

2. Results

2.1 Biomass Distribution Patterns and Carbon Density Variation Characteristics of Qinghai Spruce Forest at Different Altitudes

As shown in , the average biomass of stems, leaves, branches, and roots of Qinghai spruce in the study area was 183.76 kg, 28.52 kg, 41.47 kg, and 59.94 kg, respectively, with ranges of 116.48-279.62 kg, 10.47-56.77 kg, 19.4-74.72 kg, and 27.35-108.23 kg. The average total biomass and arbor layer carbon density were $135.59 \text{ t} \cdot \text{hm}^{-2}$ and $70.51 \text{ t} \cdot \text{hm}^{-2}$, respectively, with ranges of 52.94-208.14 $\text{t} \cdot \text{hm}^{-2}$ and 27.35-108.23 $\text{t} \cdot \text{hm}^{-2}$. Total biomass at 3100 m altitude was significantly greater than at 3200 m ($P < 0.05$), and biomass at 2900 m and 3000 m was significantly greater than at 3200 m, showing a decreasing trend with increasing altitude. Arbor layer carbon density also decreased with rising altitude.

In terms of biomass allocation patterns, all altitudes exhibited the hierarchy: stem > root > branch > leaf, with stems, roots, branches, and leaves accounting for 56.46-69.15%, 14.43-28.85%, 9.4-12.93%, and 5.08-9.82% of total biomass,

respectively. Stems constituted the largest proportion, while leaves represented the smallest.

2.2 Soil Organic Carbon Content and Density Variation Characteristics of Qinghai Spruce Forest at Different Altitudes Soil organic carbon content in the study area ranged from 11.37 to 82.49 $\text{g} \cdot \text{kg}^{-1}$, with an average of 46.11 $\text{g} \cdot \text{kg}^{-1}$. With increasing altitude, soil organic carbon content showed fluctuating changes of first increasing, then decreasing, and increasing again, with maximum values at 2900 m and minimum values at 3000 m. Across different altitudes, maximum soil organic carbon content in each soil layer appeared in the 0-10 cm layer, while minimum values occurred in the 40-50 cm layer. At 3100 m, surface soil organic carbon content was significantly higher than in deeper layers ($P < 0.05$), while differences among soil layers at other altitudes were not significant ($P > 0.05$). At 3200 m, soil organic carbon content showed a fluctuating pattern of decreasing, increasing, then decreasing again with soil depth, while at other altitudes it generally decreased with depth.

As shown in , the average soil organic carbon density in the 0-50 cm layer was 154.01 $\text{t} \cdot \text{hm}^{-2}$, ranging from 134.33 to 169.36 $\text{t} \cdot \text{hm}^{-2}$, initially decreasing then increasing with altitude. Maximum values occurred at 2900 m, while minimum values appeared at 3000 m. Within the same soil layer across different altitudes, soil organic carbon density at 3100 m was significantly greater than at 3000 m ($P < 0.05$), while differences among other altitudes within the same layer were not significant ($P > 0.05$). Within the same altitude across different soil layers, surface (0-10 cm) organic carbon density was greater than deeper (40-50 cm) layers. At 2900 m and 3000 m, soil organic carbon density showed fluctuating patterns with depth, while at 3100 m, it first increased then decreased, with the 30-40 cm layer significantly greater than the 40-50 cm layer ($P < 0.05$). At 3200 m, irregular fluctuations occurred with no significant differences among layers ($P > 0.05$).

2.3 Ecosystem Carbon Density Variation Characteristics of Qinghai Spruce Forest at Different Altitudes The ecosystem carbon density of Qinghai spruce forest across different altitudes was 224.51 $\text{t} \cdot \text{hm}^{-2}$, with arbor and soil layers accounting for 30.5% and 69.5% of total carbon density, respectively. Ecosystem carbon density showed a decreasing trend with increasing altitude. As illustrated in [Figure 2: see original paper] and [Figure 3: see original paper], the proportion of soil carbon density increased while arbor layer proportion decreased with rising altitude.

2.4 Correlations Between Altitude and Carbon Density Indicators in Qinghai Spruce Forest Altitude showed extremely significant negative correlations with average DBH and arbor layer carbon density ($P < 0.01$), and a significant negative correlation with canopy closure ($P < 0.05$), but no significant relationship with soil organic carbon density or content . These correlation patterns indicate that temperature constraints increasingly affect Qinghai spruce

growth at higher elevations within the 2900–3200 m range.

3. Discussion

The average total biomass of Qinghai spruce forest in the Amidongso small watershed on the southern slope of Qilian Mountains was $135.59 \text{ t} \cdot \text{hm}^{-2}$ (range: $52.94\text{--}208.14 \text{ t} \cdot \text{hm}^{-2}$), similar to results from Zhang et al. [21] in the Qilian Mountains. Macroscopically, stand quality differences significantly affect total arbor biomass [22], and environmental heterogeneity at sampling sites influences tree growth, though such differences typically remain within certain ranges. Organ biomass allocation across all altitudes followed the pattern stem > root > branch > leaf, consistent with numerous studies [23,24]. This allocation pattern is closely related to tree size and growth environment (climate, soil texture, etc.), with well-developed root systems being essential for survival in relatively harsh environments.

Total biomass showed a decreasing trend with altitude, consistent with findings by Zhang and Ji [25] in the Qilian Mountains. Scholars generally agree that altitude differences in the Qilian Mountains create substantial spatial heterogeneity in hydrothermal conditions [26,27]. While precipitation increases with altitude within certain ranges [28], low temperatures become another constraining factor for Qinghai spruce regeneration and distribution, limiting carbohydrate formation [29]. Our results show extremely significant negative correlations between altitude and both average DBH and arbor layer carbon density, as well as a significant negative correlation with canopy closure, confirming these temperature constraints.

Forest soil carbon primarily originates from litter accumulation and decomposition [30]. The average soil organic carbon density of Qinghai spruce forest in this study was $154.01 \text{ t} \cdot \text{hm}^{-2}$, similar to results from Zeng et al. [19] in the Qilian Mountains Xishui forest area ($115.83 \text{ t} \cdot \text{hm}^{-2}$) and slightly lower than the Qilian Mountains average ($169.8 \text{ t} \cdot \text{hm}^{-2}$) [31]. Soil organic carbon content and density are jointly constrained by altitude-induced climate differences and site conditions, exhibiting high spatial heterogeneity [32]. The fluctuating patterns of soil organic carbon content and density with altitude, similar to previous findings [27,33], result from comprehensive effects of altitude-induced changes in climate, temperature, rainfall, and biological factors.

Ecosystem carbon density of Qinghai spruce forest in the study area was $224.51 \text{ t} \cdot \text{hm}^{-2}$, with arbor and soil layers comprising 30.5% and 69.5% of total carbon density, respectively. These proportions are remarkably similar to results from Wang et al. [34] using harvest methods (30.39% and 69.61%), confirming that soil carbon storage remains the most important component of forest ecosystem carbon pools. Strengthening forest soil carbon protection is beneficial for forest carbon pool conservation.

4. Conclusion

Based on investigation of Qinghai spruce stand density variation with altitude in the Amidongso small watershed on the southern slope of Qilian Mountains, we conclude:

- 1) The average total biomass of Qinghai spruce plots was $135.59 \text{ t} \cdot \text{hm}^{-2}$, decreasing with increasing altitude. Organ biomass allocation at all altitudes followed the pattern: stem > root > branch > leaf.
- 2) The average vegetation carbon density was $70.51 \text{ t} \cdot \text{hm}^{-2}$, and the average soil organic carbon density in the 0-50 cm layer was $154.01 \text{ t} \cdot \text{hm}^{-2}$. Ecosystem carbon density was $224.51 \text{ t} \cdot \text{hm}^{-2}$, with arbor and soil layers accounting for 30.5% and 69.5% of total carbon density, respectively. Soil carbon density proportion increased while arbor layer proportion decreased with rising altitude.
- 3) The soil carbon pool remains the most important component of forest ecosystem carbon pools. Strengthening forest soil protection is crucial for maintaining forest carbon storage.

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