Forest Biomass Carbon Distribution Along an Elevation Gradient in Qinghai Spruce Forests Based on the FAREAST Model Zhang Wei[1], Li Minghua[2], Wang Dong[1], Chen Xiaoyan[3] [1]Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Resea···

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Abstract

To predict the future distribution range of Qinghai spruce (*Picea crassifolia*) across different altitude gradients, the FAREAST model was used to simulate the altitudinal distribution characteristics of biomass carbon in middle-young aged forests (0–60 years) of Qinghai spruce at three sites in the western, central, and eastern Qilian Mountains. The results show that: (1) At the same site, biomass carbon of Qinghai spruce seedlings and saplings was most abundant at middle altitudes, concentrated between 2,800–3,100 m; beyond this range, biomass carbon decreased accordingly. (2) Comparing different sites, the average biomass carbon of Qinghai spruce seedlings and saplings was highest in the central Qilian Mountains, reaching 27.48 ± 5.51 t • C • hm^{-2}, followed by 24.56 ± 3.50 t • C • hm^{-2} in the eastern region and 23.80 ± 2.07 t • C • hm^{-2} in the western region. (3) The altitudinal distribution range of Qinghai spruce seedlings and saplings was approximately 2,500–3,400 m, but varied among different sites. The simulations indicate that there exists an optimal altitude interval of 2,800–3,100 m for biomass carbon distribution of Qinghai spruce seedlings and saplings in the Qilian Mountains; above or below this interval, the growth and regeneration processes of Qinghai spruce will be constrained. The higher biomass carbon of Qinghai spruce seedlings and saplings in the central Qilian Mountains compared to the eastern and western regions indicates that the central region is the optimal area for growth and potential distribution of Qinghai spruce. The reasons for poor regeneration in the eastern and western regions may be that

the eastern region is more frequently affected by human activities, while the western mountainous region may be more susceptible to drought stress.

Full Text

Simulating the Biomass Carbon Distribution of Young-and-Middle-Aged Picea crassifolia Forests Based on the FAREAST Model Along Altitude Gradients

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Abstract

To predict the future distribution range of *Picea crassifolia* along different altitude gradients, this study simulated the elevational distribution characteristics of biomass carbon in young-and-middle-aged *Picea crassifolia* forests across three sites in the western, central, and eastern Qilian Mountains using the FAREAST model. The results indicate that: (1) At any given site, biomass carbon of *Picea crassifolia* seedlings and saplings is highest at intermediate elevations, concentrated between 2,800–3,100 m, and decreases beyond this range. (2) Comparing different sites, the average biomass carbon of *Picea crassifolia* seedlings and saplings is highest in the central Qilian Mountains, reaching 27.48 ± 5.51 $\mathrm{t \cdot C \cdot hm^{-2}}$, followed by the eastern region at 24.56 ± 3.50 $\mathrm{t \cdot C \cdot hm^{-2}}$, and lowest in the western region at 23.80 ± 2.07 $\mathrm{t \cdot C \cdot hm^{-2}}$. (3) The elevational distribution range of *Picea crassifolia* seedlings and saplings varies among sites, approximately spanning 2,500–3,400 m. Simulations reveal that biomass carbon distribution of *Picea crassifolia* seedlings and saplings in the Qilian Mountains exhibits an optimal elevation interval; growth and regeneration processes are constrained when elevations are above or below this interval. The higher biomass carbon in the central Qilian Mountains compared to the eastern and western regions indicates that the central area represents the optimal zone for *Picea crassifolia* growth and potential distribution. The poorer regeneration in eastern and western areas may result from more frequent human disturbance in the east and greater susceptibility to drought stress in the western mountains.

Keywords: Qilian Mountains; *Picea crassifolia* seedlings and saplings; FAREAST model; biomass carbon; elevational distribution characteristics

Introduction

Forests represent a crucial terrestrial ecosystem type and constitute one of the largest carbon pools on land, playing a vital mediating role in the global carbon cycle. Research demonstrates that over 80% of aboveground carbon storage and 40% of belowground carbon are sequestered in forest ecosystems. Consequently, predicting forest carbon storage and analyzing the spatiotemporal distribution patterns of forest biomass are essential for understanding climate change impacts and have significant practical implications. Forest carbon storage is typically measured by forest biomass quantity, which is converted to carbon storage using biomass conversion and expansion factors (BCEF) through carbon accounting parameters, thereby assessing the carbon sequestration capacity of forest systems. Moreover, predicting forest biomass carbon and analyzing the spatial and temporal distribution patterns of forest biomass are also crucial for developing forest regeneration and management strategies.

The FAREAST model is a forest gap model widely applied to forest succession and carbon storage prediction. Developed based on the KOPIDE and NEWCOP models with added soil succession functional modules and validated accordingly, FAREAST has demonstrated good performance in simulating forest dynamics and carbon storage characteristics. The model simulated the succession characteristics of mixed coniferous-broadleaf forests in the Changbai Mountains, showing that *Acer mono* stand volume reached its maximum of approximately 200 $\mathrm{t \cdot hm^{-2}}$ during primary succession at year 500. Another simulation of different forest types in the Xiaoxing' anling region revealed that adult spruce reaches optimal growth at approximately 800 m elevation. However, these two models were only applied and validated in northeastern China and had not been tested in other regions. To expand the application of gap models to broader areas, researchers developed the FAREAST model for forest succession and biomass carbon distribution prediction in the Far East subcontinent, which has shown good simulation results at the Eurasian subcontinental scale. Recently, the FAREAST model has also been applied to simulate the impacts of climate change on forest tree species composition and carbon storage in the Altai Mountains of Xinjiang, demonstrating its suitability for simulating forest succession and biomass carbon distribution in northwestern China.

The Qilian Mountains, located in China' s northwestern interior, feature harsh environments and fragile ecosystems. *Picea crassifolia*, as the dominant tree species in this region, provides irreplaceable ecosystem services including carbon sequestration, oxygen release, water conservation, climate regulation, and biodiversity maintenance. However, in recent decades, unreasonable land use has led to shrinking *Picea crassifolia* forest areas. Therefore, investigating the distribution characteristics of biomass carbon in *Picea crassifolia* seedlings and saplings can provide valuable references for forest regeneration and restoration. This study selected three sites in the western, central, and eastern Qilian Mountains to apply the FAREAST model in simulating the elevational distribution characteristics of biomass carbon in young-and-middle-aged *Picea crassifolia* forests. The research explores three key questions: (1) How does biomass carbon of *Picea crassifolia* seedlings and saplings change with stand age? (2) What are the elevational distribution characteristics of biomass carbon along altitude gradients at individual sites? (3) How do these distribution characteristics differ among the three simulation sites? The findings will not only enhance understanding of biomass carbon distribution patterns along elevation gradients but also provide theoretical and practical guidance for natural regeneration and artificial restoration of *Picea crassifolia* populations.

1.1 Study Area Overview

The Qilian Mountains are located in northwestern China' s interior, between Qinghai and Gansu provinces, featuring complex terrain and variable climate. Vegetation shows distinct zonal distribution: mountainous steppe zones at low elevations transition to forest-steppe zones and alpine shrub-meadow zones with increasing altitude, culminating in alpine cushion vegetation and bare rock at the highest elevations. The southern slope of the Qilian Mountains is gentle, while the northern slope is steep, resulting in dense, shade-loving *Picea crassifolia* forests on the north slope and sparse *Sabina przewalskii* forests on sunny slopes. Soil types include alpine steppe soil, forest gray-cinnamon soil, and sierozem. At the Tianlaochi catchment in the central Qilian Mountains, the average July temperature is 9.47°C, the average January temperature is -16.86°C, and mean annual precipitation is 437 mm. Snow cover duration is long, with *Picea crassifolia* typically reaching reproductive maturity at approximately 130 years, though at higher elevations with harsh conditions, reproductive maturity may be delayed to 160 years.

[Figure 1: see original paper]

1.2 FAREAST Model Description

The FAREAST model simulates forest carbon storage by modeling the regeneration, growth, and mortality processes of individual trees on each patch (approximately 0.05 hm^2). The model comprises five sub-models: an eco-climate sub-model, a canopy sub-model, a growth sub-model, a regeneration sub-model, and a mortality sub-model. The model structure is illustrated in Figure 2. Input driving parameters include climate and soil variables, which drive the simulation of complete tree growth processes within patches through iterative calculations.

The growth sub-model simulates tree diameter at breast height (DBH) and crown base height. DBH and crown base height are calculated using formulas from the FORSKA model. Tree growth is also influenced by light utilization by canopy structure, soil nutrient conditions, and environmental temperature, which are obtained through the Lambert-Beer law for light interception, effective accumulated temperature (ZEILG), and environmental temperature thresholds, respectively. The regeneration sub-model simulates seedling bank size (seedling number per hm^2) by calculating the sum of local and invading seedlings minus natural mortality. The mortality sub-model calculates leaf and fine root turnover, branch litterfall, and individual tree mortality probability, which is approximately 1% annually. The eco-climate sub-model simulates bio-climate conditions, soil moisture, and available soil nutrients. FAREAST uses monthly climate data to calculate daily temperature, soil water content, soil CO_2 content, and available soil nutrients.

[Figure 2: see original paper]

1.3 Biological and Environmental Parameters Required for Model Operation

The FAREAST model can simulate 35 tree species from boreal forests, including the spruce species simulated in this study. We first selected *Picea crassifolia* forests at the Tianlaochi site in the central Qilian Mountains as the simulation object. The initial biological parameters for *Picea crassifolia* are presented in Table 1. Required environmental parameters include soil and climate variables. Soil physical parameters comprise field capacity and permanent wilting point, with the permanent wilting point set at 12.5 cm soil depth. Additionally, 12 initial soil parameters are needed, including nitrogen and carbon content in litter, humus, and soil layers (Table 2). Required climate parameters include monthly precipitation and monthly maximum and minimum average temperatures, obtained from the nearest national meteorological stations to each simulation site (http://data.cma.cn/).

1.4 Conversion Between *Picea crassifolia* Age and Biomass Carbon

Picea crassifolia is a cold-resistant species with slow growth. Young forest stands typically include both seedlings/saplings and some adult small trees, collectively forming young-and-middle-aged forests. To establish the relationship between stand age and biomass carbon, we first constructed an age (y)-DBH (x) relationship model: $y = -0.0179x^2 + 2.3829x + 40.24$, where y represents age (years) and x represents DBH (cm). Using this formula, *Picea crassifolia* with DBH < 8 cm corresponds to age ≤ 60 years. Based on measured tree height and DBH in sample plots and reference to two-way volume tables, individual tree volumes were obtained. Combining plot area and tree counts yielded stand volume per plot, which was then converted to biomass using the *Picea crassifolia* biomass expansion factor. The biomass-to-carbon conversion coefficient for *Picea crassifolia* typically ranges between 0.45–0.55. Reported values indicate an average biomass-to-carbon conversion coefficient of 0.509 across all organs (stem, branch, leaf, root). Therefore, this study adopts 0.509 as the conversion coefficient for *Picea crassifolia* biomass to carbon.

1.5 Simulation Methods

The simulation process consists of two phases. Phase one simulates 1,000 years of primary succession (starting from bare ground) at the Tianlaochi catchment in the central Qilian Mountains using 0.05 hm^2 plots. Phase two uses the year 60 simulation results as initial conditions to simulate biomass carbon distribution of *Picea crassifolia* seedlings and saplings along altitude gradients at three sites (western, central, and eastern) in the Qilian Mountains. The western site is Qifeng station in the Qilian Mountains National Nature Reserve, driven by meteorological data from the nearest Jiuquan National Meteorological Station (39.46°N, 98.29°E, 1,477 m). The central site is Tianlaochi station, using data from Yeniugou National Meteorological Station (38.25°N, 98.35°E, 3,200 m). The eastern site is Wushaoling station, using data from Wushaoling National Meteorological Station (37.12°N, 102.52°E, 3,045 m). All simulations run for 60 years.

1.6 Model Validation

To validate the model, 25 plots (25 m × 25 m each) were established in the Tianlaochi catchment in the central Qilian Mountains (Figure 1). Individual tree measurements were conducted to calculate stand age and biomass of *Picea crassifolia* with DBH $\leq$ 8 cm and age $\leq$ 60 years. Individual tree biomass carbon was calculated using the formula: $y = 75.18A + 451.9$, where y represents individual tree biomass, A represents plot area, and V represents volume obtained from two-way volume tables. Plot-level biomass carbon was then compared with simulated results through regression analysis, yielding a significant linear relationship between observed and simulated values ($p < 0.01$).

[Figure 3: see original paper]

Results

2.1 Biomass Carbon of *Picea crassifolia* Seedlings and Saplings at Different Sites in the Qilian Mountains

Simulation results show that at the western Qifeng site, biomass carbon of *Picea crassifolia* seedlings and saplings increases significantly over time ($p < 0.01$). The elevational distribution range is 2,600-3,400 m, with no simulations yielding biomass carbon outside this range. Biomass carbon exhibits a hump-shaped trend along the altitude gradient, increasing initially then decreasing. The maximum slope occurs at 3,000 m ($34.14\ t \cdot C \cdot hm^{-2}$), while the minimum slope occurs at 3,400 m ($11.9\ t \cdot C \cdot hm^{-2}$). This indicates that both high and low elevations are unsuitable for regeneration, with mid-elevations representing optimal habitat.

At the central Tianlaochi site, the elevational distribution range is 2,500-3,400 m, extending 100 m lower than the western site. Biomass carbon shows a significant linear positive correlation with time ($p < 0.01$) within the 2,500-

3,400 m range. Maximum and minimum slopes appear at 3,100 m (37.49 t • C • hm^{-2}) and 3,400 m (19.27 t • C • hm^{-2}), respectively.

At the eastern Wushaoling site, the elevational distribution range is 2,500–3,300 m, the narrowest among the three sites. Similar to the other sites, biomass carbon shows a significant linear positive correlation with time ($p < 0.01$). The highest biomass carbon occurs at 2,500 m (29.66 t • C • hm^{-2}), while the lowest appears at 3,400 m (8.62 t • C • hm^{-2}). Maximum and minimum slopes occur at 3,100 m and 3,000 m, respectively.

[Figure 4: see original paper]
[Figure 5: see original paper]
[Figure 6: see original paper]

2.2 Comparison of Biomass Carbon at Year 60 Across Western, Central, and Eastern Sites

Across the three simulation sites, biomass carbon of *Picea crassifolia* seedlings and saplings shows a significant quadratic polynomial relationship with elevation ($p < 0.01$), increasing initially then decreasing with altitude at each site. The goodness-of-fit decreases from west (Qifeng) to central (Tianlaochi) to east (Wushaoling). The highest average biomass carbon occurs at the central Tianlaochi site (27.48 ± 5.51 t • C • hm^{-2}), followed by the eastern Wushaoling site (24.56 ± 3.50 t • C • hm^{-2}), and lowest at the western Qifeng site (23.80 ± 2.07 t • C • hm^{-2}).

[Figure 7: see original paper]

Discussion

3.1 Site-Scale Distribution Characteristics of Biomass Carbon

Using the FAREAST model to simulate biomass carbon of *Picea crassifolia* seedlings and saplings, we found the model accurately captures elevational distribution patterns. At individual sites, biomass carbon exhibits a hump-shaped trend with elevation, peaking at mid-elevations. This aligns with Zhang et al.' s findings in the Xishui Forest Farm of the central Qilian Mountains, though with some differences. Their study identified 2,900 m as the optimal elevation and 3,300 m as the least suitable, differing from our Tianlaochi simulation results. These discrepancies may arise from: (1) Different site locations—Xishui Forest Farm lies near the northern edge in shallow mountainous areas, while Tianlaochi is in deep mountainous terrain with distinct topographic and climate patterns. (2) Different growth stages—Zhang et al. surveyed mature stable populations, whereas this study simulated seedlings and saplings.

Picea crassifolia prefers shady, moist conditions and cold tolerance, determining its specific elevational distribution in the Qilian Mountains. Our results show maximum biomass carbon at 3,100 m, with the model unable to simulate *Picea crassifolia* above 3,400 m. This elevation- and topography-controlled distribution is fundamentally driven by climate dependence. In northwestern mountainous regions, low elevations may impose drought stress due to scarce precipitation, limiting regeneration. At high elevations, although precipitation increases, low temperature becomes the primary limiting factor. Therefore, mid-elevations with optimal water-heat combinations constitute the best habitat for *Picea crassifolia* distribution and regeneration.

3.2 Landscape-Scale Distribution Characteristics

Simulation results show that all three sites can simulate biomass carbon of *Picea crassifolia* seedlings and saplings during 60 years of primary succession from bare ground, but the achievable upper and lower elevation limits differ. The central Tianlaochi site shows the widest elevational range, likely because its location in deep mountainous terrain creates substantial orographic precipitation from southwest warm, moist air currents. Additionally, rich soil organic matter and good permeability create favorable habitat conditions, making Tianlaochi the site with the broadest and highest biomass carbon distribution.

The western Qifeng site shows the lowest biomass carbon, primarily because its proximity to the Badain Jaran Desert creates arid climate conditions with large temperature fluctuations that severely restrict growth and regeneration. The eastern Wushaoling site shows intermediate biomass carbon, possibly due to frequent human activity and severe logging in the 1990s at this eastern edge location of the Qilian Mountains, which has impacted tree growth and regeneration. In summary, two key factors influence biomass carbon distribution: environmental stress and human disturbance. Only by understanding species' successional and distribution response strategies to environmental changes can theory be integrated into practice to guide natural regeneration and restoration of *Picea crassifolia* in the Qilian Mountains.

Conclusions

Based on biological and environmental parameters for *Picea crassifolia*, this study applied the FAREAST model to simulate biomass carbon distribution patterns along altitude gradients for seedlings and saplings ($ $60 years) at three sites: Qifeng (west), Tianlaochi (central), and Wushaoling (east). The main conclusions are:

1) At any elevation within the suitable habitat range across the three sites, simulated biomass carbon of *Picea crassifolia* seedlings and saplings shows a significant linear increasing trend over time. At year 60, the central Tianlaochi site exhibits the highest average biomass carbon (27.48 ± 5.51 $\mathrm{t \cdot C \cdot hm^{-2}}$), followed by the eastern Wushaoling site (24.56 ± 3.50 $\mathrm{t \cdot C \cdot hm^{-2}}$) and the western Qifeng site (23.80 ± 2.07 $\mathrm{t \cdot C \cdot hm^{-2}}$).

2) At each simulation site, biomass carbon shows a significant quadratic polynomial relationship with elevation, increasing then decreasing with

altitude. This indicates an optimal elevation interval for *Picea crassifolia* regeneration, with constraints outside this range.

3) The upper and lower elevation limits for biomass carbon distribution differ among sites. The maximum elevation reaches 3,400 m in the west and central sites but only 3,300 m in the east. The minimum elevation is 2,600 m in the west and 2,500 m in the central and eastern sites. This distribution is closely related to climate variables, soil conditions, topography, and human activity impacts at each site.

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