Response of Qinghai Spruce Forest Regeneration Characteristics to Topographic Factors in the Pailugou Watershed of the Qilian Mountains (Postprint)

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Abstract

To investigate the influence of microtopography on natural regeneration seedlings in Qinghai spruce forests of the Qilian Mountains, this study selected Qinghai spruce in the Pailugou watershed as the research object. Using C-means fuzzy clustering analysis, topographic parameters (elevation, convexity, slope) from 15 fixed sample plots were classified into four distinct microtopographic habitats, and the effects of these habitats on regeneration characteristics (seedling density, mean crown width, mean basal diameter, and mean height) were examined. The results showed: (1) The 15 fixed sample plots were classified into four microtopographic habitat types: high-elevation steep slope, high-elevation gentle slope, low-elevation convex site, and low-elevation concave site. (2) Under different microtopographic conditions, seedling density and mean height decreased in the order: low-elevation concave site > low-elevation convex site > high-elevation gentle slope > high-elevation steep slope; mean crown width and mean basal diameter decreased in the order: low-elevation convex site > high-elevation gentle slope > low-elevation concave site > high-elevation steep slope; regarding mean height, high-elevation steep slope was significantly lower than the other three microtopographies. Elevation, slope, aspect, and slope position significantly affected seedling survival and growth processes. (3) Seedlings exhibited clumped distribution patterns in most microtopographies, with aggregation intensity decreasing in the order: high-elevation steep slope > low-elevation convex site > low-elevation concave site > high-elevation gentle slope. (4) Correlation analysis revealed significant relationships between elevation, slope, slope position and regeneration seedlings ($P<0.05$). In summary, natural regeneration of Qinghai spruce forests was significantly influenced by microtopographic habitats ($P<0.05$), with low-elevation

convex and concave sites being more suitable for seedling establishment and growth.

Full Text

Response of Picea crassifolia Forest Regeneration Characteristics to Topographic Factors in the Pailugou Watershed of Qilian Mountains

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Abstract: To explore the influence of microtopography on natural regeneration of *Picea crassifolia* seedlings in the Qilian Mountains, we selected *Picea crassifolia* forests distributed in the Pailugou watershed as our research object. Using C-means fuzzy clustering analysis, we classified topographic parameters (altitude, convexity, and slope) from 15 fixed plots in the watershed into four distinct microtopographic habitats, and investigated how these microtopographic habitats affected regeneration characteristics (seedling density, mean crown width, mean base diameter, and mean plant height). The results showed that: (1) The 15 fixed plots were classified into four microtopographic habitat types through cluster analysis: high-altitude steep slope, high-altitude gentle slope, low-altitude convex land, and low-altitude concave land. (2) Seedling density and mean plant height under different microtopographic conditions decreased in the order: low-altitude concave land > low-altitude convex land > high-altitude gentle slope > high-altitude steep slope. Mean crown width and mean base diameter decreased in the order: low-altitude convex land > high-altitude gentle slope > low-altitude concave land > high-altitude steep slope. Mean plant height on high-altitude steep slopes was significantly lower than in the other three microtopographies. (3) Different altitudes, slopes, aspects, and slope positions significantly affected seedling survival rates and growth processes. (4) Most regeneration seedlings exhibited aggregated distributions under different microtopographies, with aggregation intensity decreasing in the order: high-altitude steep slope > low-altitude concave land > low-altitude convex land > high-altitude gentle slope. (5) Correlation analysis revealed significant correlations between altitude, slope, slope position, and regeneration seedlings ($P<0.05$). In summary, natural regeneration of *Picea crassifolia* forests was significantly influenced by microtopographic habitat (P<0.05), with seedlings being more suitable for establishment and growth in low-altitude convex land and low-altitude concave land.

Keywords: *Picea crassifolia* forest regeneration seedlings; microtopography; spatial distribution pattern; elevation; Qilian Mountains

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Natural regeneration plays a crucial role in protecting forest ecosystem biodiversity, maintaining forest community stability, and driving succession processes. The seedling stage represents the most vulnerable phase in a plant' s life cycle, being highly sensitive to environmental changes and experiencing the greatest fluctuations in individual numbers. Seedlings are long-term affected by indirect factors including genetic conditions, plant physiological and ecological characteristics, and intrinsic natural environmental aspects, all of which relate to topographic factors, stand structure, biological factors within stands, and natural disturbances caused by human activities. Among these, topographic factors are the most important elements affecting natural regeneration, critically influencing seedling establishment and growth, thereby impacting forest regeneration quality.

Topography decisively mediates the secondary distribution of light, water, temperature, and nutrients. Elevation, slope position, convexity, aspect, and slope gradient constitute important components within this multidimensional variable set. Microtopographic formation significantly influences species within forest communities. Research on the Barro Colorado Island plot in Panama found that topographically induced gradients in moisture content and litter layer thickness affected tree emergence and mortality rates, providing effective conditions for species coexistence. Studies have shown that topographic factors, phylogenetic distance, and neighbor density all play important roles in seedling survival and growth at Badagong Mountain. Zhao et al. found that microtopography significantly affected sapling regeneration of *Tsuga chinensis* var. *tchekiangensis* in the Wuyi Mountains of Jiangxi. Zhao et al. also reported significant effects of topography on seedling survival and mortality in typical broadleaf-Korean pine forests. As a complex and comprehensive environmental factor, topography creates different conditions of moisture, light, and ground cover that lead to varying growth and development status of regeneration seedlings across different landforms. Studies have found that different altitudes and aspects significantly affect natural seedling regeneration, though research on topographic effects on *Picea crassifolia* seedlings remains limited in China. Investigating the response of *Picea crassifolia* natural regeneration to microtopography is therefore essential for the healthy stability and sustainable development of forest ecosystems in the Qilian Mountains.

The Qilian Mountains constitute a major mountain range in western China, located at the intersection of three major plateaus. *Picea crassifolia*, the dominant constructive species of montane forests in the Qilian Mountains, is a unique tree species growing on the northeastern edge of the Qinghai-Tibet Plateau. Its distribution area accounts for 75.72% of the water conservation forest area and 24.74% of the arbor forest area in the Qilian Mountains. In recent years, environmental protection departments have attached great importance to ecological issues emerging in the Qilian Mountains, with local governments implementing a series of measures to restore the ecological environment. This study therefore selected *Picea crassifolia* forests in the Pailugou watershed of the Qilian Mountains as the research object, investigating topographic factors and regeneration seedlings in fixed plots to provide scientific theoretical support for the protection and maintenance of forest ecosystem stability.

1.1 Study Area Overview

The study area is located in the Pailugou watershed of the Xishui forest region in the middle Qilian Mountains (38°24 N, 100°17 E), with a total area of 2.85 km^2 and a longitudinal slope gradient of 1:4.2. The watershed elevation ranges from 2600 to 3800 m, with an average annual precipitation of 433.6 mm, average annual evaporation of 1081.7 mm, mean annual relative humidity of 60%, mean annual temperature between -0.6 and 2.0°C, and average annual sunshine duration of 1893 h. The climate is classified as alpine semi-arid montane forest-steppe. The constructive species *Picea crassifolia* is distributed in patches or strips on shady and semi-shady slopes between 2600 and 3300 m. Dominant shrub species include *Caragana jubata*, *Salix gilashanica*, and *Potentilla fruticosa*, while major herbaceous plants are *Carex atrata*, *Stipa capillata*, and *Polygonum viviparum*.

1.2 Sample Plot Establishment

Within the 2700–3300 m elevation range in the Pailugou watershed of the Qilian Mountains, we selected typical *Picea crassifolia* forest stands with good growth conditions and minimal human disturbance. Based on site conditions and stand structure, we established 15 typical *Picea crassifolia* forest fixed plots (Table 1). Because the arbor forest was relatively sparse, we set larger plot sizes of 20 m × 36 m (instead of the standard 20 m × 20 m). We used a total station to divide each 20 m × 36 m plot into 5 m × 5 m subplots, totaling 432 subplots, and conducted topographic measurements and regeneration seedling surveys. Following the "Z" pattern, we measured every *Picea crassifolia* tree in each plot, recording tags, relative coordinates (x, y), base diameter, height, crown width, and height under branches. Following Tuo et al.' s method for *Picea crassifolia* diameter class division, individuals with base diameter <1.0 cm were classified as seedlings, and those with base diameter of 1.0–5.0 cm as saplings. Within each regeneration seedling subplot, we established a 1 m × 1 m grid to survey herbaceous species, quantity, mean height, mean coverage, and total subplot coverage.

1.3 Spatial Distribution Pattern Analysis

We selected the univariate pair correlation function from spatial point pattern analysis methods to analyze the spatial distribution patterns of regeneration seedlings in different microtopographic habitats. Assuming that only topographic factors were operating, we used the complete spatial randomness model as the null model and employed Monte Carlo simulation to verify whether distribution patterns of regeneration seedlings differed among microtopographic habitats. From the univariate results, we could determine that if the univariate pair correlation function values fell within the upper and lower envelope lines, the pattern was random; if values were above the upper envelope line, the pattern was aggregated; and if values were below the lower envelope line, the pattern was uniform.

1.4 Data Analysis

Microtopographic data were processed using Microsoft Excel 2010 and SPSS 26.0 software for clustering analysis to classify different habitats. We selected four regeneration characteristics of *Picea crassifolia* seedlings (seedling density, mean crown width, mean base diameter, mean plant height) for ANOVA, followed by correlation analysis to examine the effects of different habitat characteristics on seedling features. Data plotting was completed using gin 2021 software, and spatial distribution patterns were analyzed using Programita Manual Enero 2014 software.

2.1 Microtopographic Habitat Classification

The 15 fixed *Picea crassifolia* forest plots were divided into four different habitat types through C-means fuzzy clustering analysis: high-altitude steep slope, high-altitude gentle slope, low-altitude convex land, and low-altitude concave land. Table 2 shows that elevation decreased in the order: high-altitude steep slope > high-altitude gentle slope > low-altitude convex land > low-altitude concave land. Convexity decreased in the order: low-altitude convex land > high-altitude steep slope > high-altitude gentle slope > low-altitude concave land. High-altitude steep slope, high-altitude gentle slope, and low-altitude convex land showed significant differences in convexity ($P<0.05$), while no significant difference existed between high-altitude gentle slope and low-altitude concave land ($P>0.05$). Slope gradient decreased in the order: high-altitude steep slope > low-altitude concave land > high-altitude gentle slope > low-altitude convex land. No significant difference in slope gradient was found between low-altitude convex land and low-altitude concave land ($P>0.05$), while other slope gradients differed significantly ($P<0.05$).

2.2 Regeneration Density and Distribution Characteristics of *Picea crassifolia* Under Different Microtopographic Conditions

Table 3 presents the number of subplots, seedling and sapling quantities, and regeneration densities across topographic parameters. Elevation analysis revealed that at 2718 m, seedling and sapling regeneration densities were highest at 2,375,600 and 1,190,400 individuals · hm^{-2}, respectively. At 2925 m elevation, seedling and sapling quantities were lowest at 1,400 and 1,800 individuals, respectively, with relatively small regeneration densities. Seedling and sapling regeneration densities differed significantly among elevations ($P<0.05$).

Slope position analysis showed that mid-slope positions had the most subplots (n=162) with 2,624,400 seedlings and 1,268,800 saplings, achieving regeneration densities of 1,620,000 and 783,000 individuals · hm^{-2}, respectively, indicating strong regeneration capacity. Lower slope positions contained substantial saplings (n=1,268,800) with a regeneration density of 783,000 individuals · hm^{-2}. Upper slope positions had the fewest seedlings and saplings (n=302,500 and 94,400, respectively), with regeneration densities of 265,625 and 101,750 individuals · hm^{-2}. Significant differences in seedlings and saplings existed among slope positions, with mid-slope seedlings and lower-slope saplings being most abundant and showing relatively strong regeneration capacity, while upper-slope seedlings and saplings were least abundant, indicating poor regeneration capacity.

Within slope gradients, the 26°–35° range had the most subplots (n=144), seedlings (n=2,934,000), and saplings (n=1,584,000), with regeneration densities of 2,043,750 and 1,100,000 individuals · hm^{-2}, respectively. The 6°–15° slope had the fewest seedlings and saplings and the lowest regeneration densities. This indicates that *Picea crassifolia* seedlings and saplings grew best in the 6°–15° slope gradient.

Picea crassifolia forests are generally distributed on shady and semi-shady slopes as shade-tolerant species. Among aspects, the north direction had the most subplots (n=162) with seedling and sapling quantities of 2,624,400 and 1,268,800, respectively, and regeneration densities of 1,620,000 and 783,000 individuals · hm^{-2}. The northeast direction was second, while the northwest direction had the fewest subplots. Seedling and sapling quantities and regeneration densities gradually decreased from north to northwest, with regeneration capacity weakening accordingly.

When convexity >0, the landform is convex, indicating the subplot elevation is higher than surrounding areas, and vice versa for concave landforms. In convexity ranges of 0–0.5 and 0.5–1.0, subplot numbers totaled 390, accounting for 90.24% of total subplots, with the most seedlings and saplings (n=2,624,400 and 1,268,800, respectively) and regeneration densities of 1,620,000 and 783,000 individuals · hm^{-2}. The fewest seedlings and regeneration densities occurred in convexity ranges <0.5. In convexity ranges of 0–0.5, sapling quantities and regeneration densities were minimal.

2.3 Regeneration Seedling Characteristics of *Picea crassifolia* Under Different Microtopographic Habitats

As shown in Figure 1, low-altitude concave land had significantly higher seedling density than other microtopographies, with a density of 2,375,600 individuals · hm^{-2}. Low-altitude convex land, high-altitude gentle slope, and low-altitude concave land followed, with strong regeneration capacity. High-altitude steep slope had the lowest seedling density at 1,400 individuals · hm^{-2}, showing the weakest regeneration capacity. Seedling density differed significantly between low-altitude concave land and high-altitude steep slope, high-altitude gentle slope, and low-altitude convex land ($P<0.05$).

For mean crown width, low-altitude convex land exceeded other microtopographies, while low-altitude concave land exceeded high-altitude gentle slope, and high-altitude steep slope was lowest. High-altitude steep slope differed significantly from high-altitude gentle slope, low-altitude convex land, and low-altitude concave land ($P<0.05$).

Regarding mean base diameter, habitats ranked from largest to smallest as: low-altitude convex land > high-altitude gentle slope > low-altitude concave land > high-altitude steep slope. High-altitude steep slope was significantly lower than the other three microtopographies.

For mean plant height, high-altitude steep slope was significantly lower than other microtopographies, with significant differences between high-altitude steep slope and low-altitude convex land and low-altitude concave land ($P<0.05$), but no significant difference between high-altitude steep slope and high-altitude gentle slope ($P>0.05$).

2.4 Spatial Distribution Patterns of *Picea crassifolia* Regeneration Seedlings Under Different Microtopographic Habitats

Univariate pair correlation function analysis results (Figure 2) showed that in low-altitude convex land habitats, regeneration seedlings exhibited aggregated distribution at 0–12.5 m and 14.5-15.5 m scales, random distribution at 12.5-13.5 m, and uniform distribution at 13.5-14.5 m. In high-altitude steep slopes, seedlings showed aggregated distribution at 0–6.5 m and 10.5-15.5 m, random distribution at 6.5-7.5 m, and uniform distribution at 7.5-10.5 m. In high-altitude gentle slopes, seedlings displayed aggregated distribution at 0–8.5 m, random distribution at 8.5-10.5 m, and aggregated distribution again at 10.5-15.5 m. In low-altitude concave land, seedlings showed aggregated distribution at 0–15.5 m.

High-altitude steep slopes and high-altitude gentle slopes showed random distributions of regeneration seedlings (Figure 3), while low-altitude convex land and low-altitude concave land exhibited aggregated distributions.

2.5 Correlation Between Regeneration Characteristics and Topographic Factors Under Different Microtopographic Habitats

No correlation existed between regeneration characteristics and aspect (P>0.05), but some regeneration characteristics correlated with altitude, convexity, slope, and slope position (Table 4). Under high-altitude steep slope microtopography, convexity showed significant positive correlation with seedling density (P<0.05), while mean crown width, mean base diameter, and mean plant height showed no significant correlation with altitude, slope, aspect, or slope position (P>0.05).

In high-altitude gentle slope habitats, mean plant height showed significant negative correlation with altitude (P<0.05), while other regeneration characteristics showed no significant correlation with topographic factors (P>0.05). Under low-altitude convex land conditions, mean base diameter correlated significantly with slope (P>0.05), while seedling density, mean crown width, and mean plant height showed no correlation with altitude, convexity, slope, aspect, or slope position (P>0.05). In low-altitude concave land habitats, mean base diameter correlated significantly with slope position (P<0.05), while other regeneration characteristics showed no significant correlation with topographic factors (P>0.05).

3.1 Analysis of Regeneration Density and Distribution Characteristics Under Different Microtopographic Habitats

This study found that altitude is an important ecological factor affecting natural regeneration of *Picea crassifolia* forests, with seedling density gradually decreasing as elevation increases, consistent with Zhang et al.' s findings. However, seedling density was smallest within the 2925 m altitude gradient. Field surveys revealed that this altitude range contained many mature *Picea crassifolia* individuals with intense intra- and interspecific competition, where required light, water, and other factors were occupied by adult trees, squeezing the survival space for seedlings and reducing their numbers.

Gentle slopes facilitate soil water storage and typically have higher stand density and canopy closure. Ding et al. found that these factors also limit seed germination. Conversely, as slope steepness increases, stand density gradually decreases, providing survival space for seedling growth and development, with good light conditions and strong soil permeability. These improved microenvironments help seedlings resist natural disasters. North-facing slopes had the highest seedling density, followed by northeast-facing slopes, with northwest-facing slopes being lowest. On semi-shady slopes with shorter sunshine duration, *Picea crassifolia* forests have thick litter and moss layers, adequate soil moisture reserves, and favorable conditions for seedling growth. South-facing and semi-sunny slopes have longer sunshine duration, stronger radiation, and easier water evaporation, leading to lower soil moisture content that is unfavorable for seedling growth and development.

The study found that low-altitude concave land had significantly higher seedling density than other microtopographies. The large seedling density in low-altitude concave land indicates abundant seedlings that can compensate for individual losses caused by intense intra- and interspecific competition, maintaining population stability and showing growth trends. However, low-lying areas with abundant water are prone to stream erosion in valley zones, causing soil layer loss that inhibits plant growth. Analysis of four different habitats showed that high-altitude steep slopes had lower seedling density, mean crown width, mean base diameter, and mean plant height than other habitats. Lower canopy closure easily creates forest gaps, which provide adequate light and growth space to meet seedling needs. However, high-altitude steep slopes have greater gradients, prone to soil erosion, which is unfavorable for growth and development. Therefore, to maintain stable population numbers and prevent structural damage, artificial protection, monitoring, and environmental improvement for seedlings and saplings should be strengthened.

3.2 Analysis of Regeneration Characteristics Under Different Microtopographic Habitats

Differences in *Picea crassifolia* regeneration characteristics among different microtopographic habitats were analyzed. Generally, small-scale population distribution patterns are constrained by population ecological processes (such as seed dispersal limitations, seedling recruitment processes, and intra- and interspecific competition), while large-scale patterns are significantly constrained by environmental heterogeneity (such as light, water, temperature, and soil conditions). Plant growth and distribution patterns are often linked to various biological or abiotic factors. This study found that the farther seeds were from parent trees, the fewer seeds were present, and newly emerged individual populations were distributed in aggregated patterns. *Picea crassifolia* seedling numbers decreased with increasing scale. Seedlings first formed aggregated distributions at smaller scales, then gradually transitioned to random distributions at larger scales. Aggregated distribution benefits individual growth by helping populations resist various harsh external conditions and improving individual survival rates.

Picea crassifolia is a shade-tolerant species generally distributed on shady and semi-shady slopes. Soil water retention is crucial for plant growth and development. However, in similar microenvironments, *Picea crassifolia* forests respond differently to environmental changes at different growth stages. In high-altitude gentle slope habitats, altitude correlated with regeneration characteristics, indicating that as altitude gradually increased, hydrothermal conditions became limiting factors for plant growth and development, with individual seedling numbers gradually decreasing, consistent with Huang et al.' s findings. In low-altitude convex land, slope correlated with regeneration characteristics. As slope increased, *Picea crassifolia* adult tree growth was limited by terrain and environmental factors, creating more forest gaps and larger survival space that benefited plant growth. In high-altitude steep slopes, seedling density positively correlated with convexity. Concave landforms generally present concave shapes with relatively low soil temperatures favorable for seed storage, but seeds require certain temperature conditions for germination. Therefore, seedling density in concave land was slightly lower than in other microtopographies. When soil moisture conditions meet seedling growth requirements, light conditions and survival space become limiting factors for *Picea crassifolia* natural regeneration.

3.3 Spatial Distribution Patterns and Correlations Between Regeneration Characteristics and Microtopographic Habitats

This study found that the diameter structure of *Picea crassifolia* forest regeneration seedlings showed an approximate inverted "J" shape, indicating a growing distribution state and good growth conditions. This plays a very important role in research on water conservation and biodiversity protection and maintenance in the Qilian Mountains. Future efforts should strengthen seedling protection to form healthy forest ecosystems and provide scientific decision-making for coordinated ecological development.

4 Conclusion

Microtopography affects seedling distribution and growth through secondary redistribution of light, water, and soil nutrients. This study classified *Picea crassifolia* forest fixed plots in the Pailugou watershed into four different microtopographic habitats and investigated regeneration characteristics under different microtopographic influences, drawing the following main conclusions: (1) Individual seedling numbers in *Picea crassifolia* forests first increased then decreased with increasing altitude. Topographic factors including convexity, slope, aspect, and slope position affected natural regeneration to varying degrees, indicating that low-altitude convex land and low-altitude concave land were more suitable for seedling establishment and growth.

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Note: Figure translations are in progress. See original paper for figures.