Analysis of Factors Influencing Natural Regeneration of Picea schrenkiana across Different Aspects: Postprint

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Abstract

To understand the effects of different slope aspect environmental factors on the natural regeneration of Picea schrenkiana forests, a series of quadrats were established on shady, semi-shady, semi-sunny, and sunny slopes of Picea schrenkiana forests at the same altitude in the middle section of the northern slope of the Tianshan Mountains to conduct investigations, structural equation models of slope aspect environmental factors-regeneration index were constructed, and the relationship between spruce seedling survival status and environmental factors was analyzed based on the environmental characteristics of each slope aspect. The results showed that: (1) Semi-shady and semi-sunny slopes were more suitable for seedling survival and growth, with their regeneration indices (0.065, 0.057) being significantly higher than those of shady and sunny slopes; (2) Litter had a dual effect on Picea schrenkiana regeneration: an overly thick undecomposed litter layer was detrimental to regeneration, while abundant organic matter could promote the formation of a high-nitrogen soil environment, which was beneficial for understory seedling regeneration; (3) The intensity of effects of different slope aspect environmental factors on the regeneration index was in the following order: total nitrogen content (0.60) > adult tree density (0.46) > semi-decomposed litter layer (0.37) > total potassium content (0.24) > organic matter content (0.23) > total phosphorus content (-0.16) > available phosphorus content (-0.32) > undecomposed litter layer thickness (-0.34). In summary, Picea schrenkiana seedlings in this region regenerated better on semi-shady and semi-sunny slopes with a canopy density of approximately 0.6, litter thickness of approximately 2.5 cm, and higher soil total nitrogen and total potassium contents.

Full Text

Analysis of Factors Influencing Natural Regeneration of Picea schrenkiana on Different Slope Aspects

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Abstract

To understand how environmental factors on different slope aspects affect the natural regeneration of Picea schrenkiana forests, we established a series of sample plots on shady, semi-shady, semi-sunny, and sunny slopes at the same altitude on the middle northern slope of the Tianshan Mountains. We constructed structural equation models of environmental factors and regeneration indices for different slope aspects, and analyzed the relationship between seedling survival status and environmental factors based on the characteristics of each slope aspect. The results showed that: (1) Semi-shady and semi-sunny slopes were more suitable for seedling survival and growth, with their regeneration indices (0.065 and 0.057) being significantly higher than those of shady and sunny slopes; (2) Litter had a dual effect on Picea schrenkiana regeneration—an overly thick undecomposed litter layer was detrimental to regeneration, while abundant organic matter could promote the formation of a high-nitrogen soil environment that favored understory seedling regeneration; (3) The intensity of environmental factors' effects on the regeneration index was ranked as: total nitrogen content (0.60) > adult tree density (0.46) > half-decomposed litter layer (0.37) > total potassium content (0.24) > organic matter content (0.23) > total phosphorus content (-0.16) > available phosphorus content (-0.32) > undecomposed litter layer thickness (-0.34). Overall, Picea schrenkiana seedlings in this region regenerated best on semi-shady and semi-sunny slopes with a canopy density of approximately 0.6, litter thickness of about 2.5 cm, and higher soil total nitrogen and total potassium contents.

Keywords: Picea schrenkiana; natural regeneration; slope aspect; environmental factors; structural equation model; northern slope of Tianshan Mountains

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Forest natural regeneration is a crucial ecological process involving multiple stages of the plant life cycle, with the seedling stage being most sensitive to environmental conditions and experiencing high mortality rates. Seedlings, as forest reserve resources, play a vital role in community development and are influenced by soil nutrients, litter, light and temperature, and canopy density during growth. Environmental factors affect forest regeneration through complex relationships, where their independent and interactive effects directly influence seedling survival rates and consequently alter stand structure. Since environmental factors vary with slope aspect, studying the relationship between environmental factors and forest regeneration across different slope aspects helps clarify mechanisms and predict future forest development trends.

Picea schrenkiana is the dominant species in Tianshan forests, accounting for approximately 60% of the forest area in the Tianshan region and forming the main component of the forest ecosystem in the Tianshan Mountains and even Xinjiang as a whole, playing a crucial role in the formation and maintenance of forest ecosystem functions. In recent years, Picea schrenkiana on the middle northern slope of the Tianshan Mountains has generally exhibited poor natural regeneration and seedling survival difficulties. Field investigations revealed that Picea schrenkiana seedlings on different slope aspects show distinct distribution characteristics and age structures. Previous studies have shown that even short distances between mountain slopes with different aspects can significantly affect seedling establishment due to changes in slope aspect. As an important topographic factor, slope aspect can influence soil nutrients, intra- and interspecific competition, and consequently interfere with plant growth. Moreover, slope aspect effects on microclimate conditions can lead to obvious differences in vegetation growth and diversity across aspects. The future development of forest communities largely depends on environmental conditions, and slope aspects with poor seedling regeneration status will disrupt the overall community structure in the region. Therefore, investigating key factors that promote or constrain regeneration on different slope aspects can help improve forest regeneration success rates in the area.

This study focused on Picea schrenkiana seedlings on different slope aspects at the same altitude gradient on the middle northern slope of the Tianshan Mountains, investigating their distribution, growth status, and age structure. We evaluated natural conditions on different slope aspects and analyzed the effects of canopy density, litter thickness, and soil physicochemical properties on seedling regeneration, aiming to identify key factors influencing natural regeneration of Picea schrenkiana on the middle northern slope of the Tianshan Mountains and provide theoretical basis for improving natural regeneration and developing reasonable forest management plans.

1.1 Study Area Overview

The study area is located in Banfanggou Forest Farm, Urumqi County, Xinjiang (43°25 ~43°26 N, 87°27 ~87°29 E), at an altitude of 1500-2800 m. The region has a temperate continental climate with an average annual temperature of 2-3°C, historical maximum temperature of 30.2°C, and minimum of -30.5°C. Annual precipitation is 544.0 mm, evaporation is 1134.1 mm, and average relative humidity is 65%. Maximum snow depth is 30.5 cm. The forest is a temperate coniferous forest dominated by Tianshan Picea schrenkiana, with sparse understory shrubs. The average diameter at breast height (DBH) of trees is approximately 14.0 cm, average height is about 36.2 m, and canopy density ranges from 0.6 to 0.8. The forest soil is gray-brown forest soil with high development degree, obvious profile differentiation, and a thick humus layer.

1.2 Sample Plot Setup and Investigation

Based on comprehensive surveys, sample plots were established in 2021 on shady, semi-shady, semi-sunny, and sunny slopes at the same altitude gradient with minimal human disturbance and similar slope positions and gradients. The maximum horizontal distance between plots did not exceed 4 km. On each slope aspect, we established 20 m × 20 m sample plots, with 4 plots per aspect, totaling 16 plots. We used GPS to measure plot latitude, longitude, altitude, slope aspect, and gradient, and recorded herbaceous layer coverage. Due to sparse shrubs in the plots, shrub data were not recorded. We conducted measurements of all trees in each plot, recording the distribution status (number of seedlings per unit area), growth condition (average seedling height), and age structure of the regeneration layer. Picea schrenkiana individuals with height (H) < 20 cm were classified as seedlings, those with 20 cm $\leq$ H $<$ 1.3 m as saplings, and those with H $\geq$ 1.3 m as adult trees. We measured heights of regeneration seedlings, saplings, and adult trees, and DBH of adult trees. Basic plot information is shown in .

1.3 Sample Collection and Measurement

In each sample plot, we established a diagonal line and set 5 soil sampling points along it. At each point, the soil profile was divided into three layers (0-20 cm, 20-40 cm, and 40-60 cm). Soil water content was measured using the ring method for each layer. Soils from the same layer within a plot were uniformly mixed, brought back to the laboratory, air-dried, and sampled using the quartering method for grinding and sieving to determine soil physicochemical properties, including total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, available potassium, slowly available potassium, nitrite nitrogen, and organic matter. Soil water content was determined by the drying method; total nitrogen by the Kjeldahl method; total phosphorus by the molybdenum-antimony anti-colorimetric method; total potassium, available potassium, and slowly available potassium by flame photometry; available nitrogen by the alkali diffusion method; nitrite nitrogen by spectrophotometry; organic matter by the potassium dichromate oxidation method; and available phosphorus by the sodium bicarbonate extraction method. Near each sampling point, we established a 50 cm × 50 cm litter layer quadrat to measure the thickness of undecomposed and half-decomposed litter layers.

Canopy density was obtained through hemispherical photography using a DSLR camera with a fisheye lens. Photos were taken at the four corners and center of each plot, with 3 photos per point. The tripod was positioned at 1.3 m height during photography. Finally, WinSCANOPY plant canopy analysis system was used to analyze forest canopy images and obtain data.

1.4 Data Processing

The regeneration index is an indicator for evaluating forest regeneration quality, with larger values representing better regeneration effects. Based on measured vegetation data from 16 plots, this study used the entropy method to calculate regeneration indices. The entropy method is widely used in resource and environmental protection fields and has high credibility in determining weight values. We constructed regeneration evaluation standards from three indicators: seedling distribution status (percentage of seedlings in total plot individuals), growth condition (average seedling height), and age structure (percentage of saplings in total plot individuals). We performed one-way ANOVA on regeneration indices, soil water content, canopy density, litter thickness, and various soil physicochemical property indicators across different slope aspects using the agricolae package, with significance tested at $\alpha = 0.05$, followed by least significant difference tests.

Original data for each indicator were linearly transformed using the following formula:

$$X_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}}$$

where X_{ij} is the dimensionless data for each indicator; x_{ij} is the i-th sample data for the j-th indicator; and $x_{\min}$ and $x_{\max}$ are the minimum and maximum values for the corresponding indicator.

We then calculated the proportion (p_{ij}) of the j-th indicator:

$$p_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}}$$

and the information entropy (E_j) of the j-th indicator:

$$E_j = -\frac{1}{\ln m} \times \left(\sum_{i=1}^{m} p_{ij} \ln p_{ij} \right)$$

where m is the sample size for each indicator.

The weight (W_j) of the j-th indicator was:

$$W_j = \frac{1 - E_j}{\sum_{j=1}^{n} (1 - E_j)}$$

The regeneration index was calculated as:

$$RC = \sum_{i=1}^{n} W_j \times p_{ij}$$

where n is the number of evaluation indicators.

We conducted correlation analysis among influencing factors using the corrplot package, and constructed structural equation models using the lavaan package. Model fit was evaluated using chi-square to degrees of freedom ratio (χ^2/df), comparative fit index (CFI), incremental fit index (IFI), and root mean square error of approximation (RMSEA). Generally, RMSEA < 0.08 indicates good model fit.

2.1 Regeneration Indices of Picea schrenkiana on Different Slope Aspects

The regeneration index reflects forest regeneration quality. As shown in , regeneration indices differed among slope aspects, showing a trend of first increasing then decreasing from shady to sunny slopes. Specifically: semi-shady slope (0.065) > semi-sunny slope (0.057) > shady slope (0.029) > sunny slope (0.026). Among the four slope aspects, semi-shady slopes showed the best regeneration status, followed by semi-sunny slopes, while shady and sunny slopes had poor regeneration.

2.2 Understory Environmental Characteristics of Picea schrenkiana on Different Slope Aspects

Soil water content showed an overall decreasing trend as slope aspect changed from shady to sunny ([Figure 1: see original paper]). Shady slope soil water content was significantly higher than sunny slope, while semi-shady and semi-sunny slopes had similar water content. Canopy density also generally decreased from shady to sunny slopes, with shady slope canopy density significantly higher than other aspects, and semi-shady and semi-sunny slopes significantly higher than sunny slope. Litter thickness on sunny slopes was slightly lower than other aspects, but no significant differences existed among the four aspects.

Soil physicochemical properties of Picea schrenkiana stands responded to slope aspect changes (). Soil organic matter, total nitrogen, and total potassium contents showed a trend of first increasing then decreasing from shady to sunny slopes, with the first two being significantly higher on semi-shady and semi-sunny slopes than on shady and sunny slopes. Total phosphorus, available phosphorus, and available potassium contents showed the opposite trend—first decreasing then increasing. Total phosphorus and available phosphorus contents on semi-shady and semi-sunny slopes were significantly lower than on sunny slopes. Available potassium was significantly higher on shady and sunny slopes than on the other two aspects. Nitrite nitrogen and slowly available potassium contents on shady slopes were significantly higher than other aspects, decreasing gradually from shady to sunny slopes. Available nitrogen content was similar across all four aspects, indicating it was not affected by total nitrogen content.

2.3 Effects of Environmental Factors on Regeneration Indices of Picea schrenkiana

Environmental factors on different slope aspects showed certain correlations with regeneration indices ([Figure 2: see original paper]). Among 36 variable pairs, 15 showed significant correlations, with 9 positive and 6 negative relationships. Undecomposed litter layer thickness was extremely significantly negatively correlated with regeneration index ($P < 0.001$), while half-decomposed litter thickness and adult tree basal area were significantly positively correlated ($P < 0.05$). Adult tree density was extremely significantly positively correlated with regeneration index ($P < 0.001$). Regarding soil physicochemical properties, organic matter and total nitrogen contents were extremely significantly positively correlated with regeneration index ($P < 0.001$), total phosphorus content was extremely significantly negatively correlated ($P < 0.001$), and total potassium content was significantly positively correlated ($P < 0.05$).

2.4 Structural Equation Model Construction

Based on correlation analysis results ([Figure 2: see original paper]) and previous studies on environmental factors affecting forest regeneration, we selected 10 indicators with significant coupling relationships for model construction: adult tree density, canopy density, undecomposed litter layer thickness, half-decomposed litter layer thickness, and soil organic matter, total nitrogen, total phosphorus, total potassium, and available phosphorus contents ([Figure 3: see original paper]).

Since our data followed a multivariate normal distribution, we used maximum likelihood estimation for analysis. Model fit was good (^{2}/df = 19.864, RMSEA = 0.064, CFI = 0.95, IFI = 0.95). For factors influencing Picea schrenkiana regeneration index, adult tree density, soil organic matter content, half-decomposed litter layer thickness, and soil available phosphorus content showed mediating effects, except for soil total nitrogen, total phosphorus, total potassium contents and undecomposed litter layer thickness ().

Among promoting factors, soil total nitrogen content had the greatest total effect on regeneration index (0.60), followed by adult tree density (0.46), half-decomposed litter layer thickness (0.37), total potassium content (0.24), and organic matter content (0.23). Inhibiting factors included total phosphorus content (-0.16), available phosphorus content (-0.32), and undecomposed litter layer thickness (-0.34). Results showed that under conditions with sufficient adult trees providing seed sources, environments with moderate half-decomposed litter thickness and high soil total nitrogen, total potassium, and organic matter contents were more suitable for Picea schrenkiana seedling survival and growth, while overly thick undecomposed litter layers and excessively high total phosphorus and available phosphorus contents inhibited regeneration processes.

3 Discussion

Water-heat conditions and soil nutrient contents differed significantly among slope aspects in the same region, with slope aspect indirectly affecting Picea schrenkiana seedling survival and growth by altering environmental factors. Regeneration index results showed that regeneration status on semi-shady and semi-sunny slopes was better than on shady and sunny slopes (), which may be closely related to canopy density. Wei et al. found that moderate stand density was more conducive to forest regeneration. In this study, seedlings occurred most frequently at canopy densities around 0.6, indicating that canopy densities on semi-shady and semi-sunny slopes were more suitable for seedling growth.

Shady slopes had higher stand density, increased litter input, and thickness greater than other aspects. Due to shorter light duration, litter decomposition slowed, particularly for the more recalcitrant lignin components. Litter accumulation hindered nutrient dissolution and cycling, thereby inhibiting seedling growth. Sunny slopes had longer light duration and lower canopy density, with substantial water loss through evapotranspiration that could not meet seedling water requirements. Additionally, sunny slopes had the smallest litter thickness among the four aspects, and the half-decomposed layer that primarily stores water and nutrients would be decomposed by light, reducing water and nutrients and limiting regeneration.

Semi-shady and semi-sunny slopes had more moderate canopy densities compared to the other two aspects. With sufficient seed sources, these slopes could provide both required water-heat conditions and soil nutrients, helping improve seedling survival rates and regeneration status. Picea schrenkiana is a shade-tolerant species, and its seedlings are sensitive to light response. Sunny slopes had low canopy density (0.54 ± 0.01) with intense light; excessive light did not promote seedling survival and growth. Instead, longer light duration led to insufficient soil moisture and fertility on sunny slopes, with lower contents of total nitrogen and total potassium required for seedling growth, which may also be factors inhibiting seedling growth.

During sampling, we found that even on semi-shady and semi-sunny slopes, plots with excessively high density still had few seedlings, while more seedlings occurred under forest gaps. Drobyshev's research also indicated that canopy gaps were important factors promoting spruce regeneration, suggesting that adult tree density and regeneration index do not always maintain a positive correlation. However, [Figure 2: see original paper] shows that adult tree density and regeneration index remained positively correlated, possibly because our sample plots were established in areas with moderate adult tree density but good regeneration, where adult trees had not yet strongly inhibited seedling growth and mainly served as seed sources.

Although litter thickness showed no significant differences among the four slope aspects, correlation analysis and structural equation model results revealed that the undecomposed litter layer inhibited seedling regeneration, while the half-decomposed litter layer promoted it. On one hand, overly thick litter layers may block seed-soil contact and release excessive allelochemicals, preventing seed germination. On the other hand, litter decomposition can produce organic matter and provide water needed for seedling growth. Therefore, litter has a dual effect on seedling regeneration. Based on these findings, when litter thickness is moderate, it can both shelter seedlings during early growth stages and prevent excessive thickness from blocking light, consistent with Chang et al.'s conclusion that overly thick or thin litter layers inhibit seedling growth.

Soil organic matter and nitrogen-phosphorus-potassium elements showed regular patterns across slope aspects. The uneven distribution of soil nutrient contents indicated differences in soil fertility among slope aspects, directly affecting stand regeneration. Among the four aspects, semi-shady and semi-sunny slopes with better regeneration had significantly higher total nitrogen content than shady and sunny slopes, suggesting that soil total nitrogen content may be the main factor limiting Picea schrenkiana growth. Structural equation model results showed that soil total nitrogen content was the most important factor affecting Picea schrenkiana regeneration. Nitrogen can improve seedling photosynthetic efficiency, and shows that soil nitrogen content on semi-shady and semi-sunny slopes in the study area was significantly higher than on shady and sunny slopes, more conducive to promoting forest regeneration.

Soil organic matter promoted seedling establishment. On one hand, soil organic matter contains many small pores that can form soil aggregates to improve water retention, ensuring water needed for seedling growth. Increased soil moisture can enhance root oxygen solubility, facilitating organic matter mineralization and increasing soil nitrogen content. Organic matter can also reduce soil phosphorus content through adsorption, creating a low-phosphorus environment favorable for seedling growth. In this study, phosphorus content in soils of shady and sunny slopes was higher than on semi-shady and semi-sunny slopes, with excessive phosphorus content negatively affecting forest regeneration. High phosphorus environments inhibit plant root growth; studies have shown that excessive phosphorus can cause stomatal closure, affect photosynthesis, inhibit absorption of other nutrients, disrupt nutrient balance, and lead to plant death. Potassium promotes seedling growth, mainly playing an osmotic regulation role. Seedlings have high potassium demand in early stages, but due to potassium excretion and other phenomena, their demand for potassium becomes lower than for nitrogen in later stages.

4 Conclusion

This study focused on Picea schrenkiana on four different slope aspects in Banfanggou Forest Farm in the middle Tianshan Mountains, using structural equation models to quantify the effects of various environmental variables on seedling regeneration across slope aspects. Results showed that seedling regeneration on semi-shady and semi-sunny slopes was superior to other aspects, indicating that the water-heat ratio on these slopes was more favorable for spruce growth. The stands achieved suitable canopy density for seedling regeneration, and the annually accumulated moderate litter layer regulated soil nutrient content and ratios, providing favorable microhabitats for seedling growth. Therefore, on shady slopes with excessive canopy density, thinning measures can be implemented to reduce stand density and improve understory ventilation and light conditions, with appropriate removal of overly thick litter to facilitate seedling root growth. On some slope aspects lacking nitrogen, phosphorus, and other nutrient elements, artificial fertilization can supplement nutrients required by seedlings. This study identified key factors influencing Picea schrenkiana regeneration on different slope aspects in the middle Tianshan Mountains, helping guide appropriate management practices to improve stand regeneration capacity based on actual stand conditions in the study area.

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