The potential factors promoting the *Larix principis-rupprechtii* natural regeneration in North China

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Natural regeneration plays an important role in determining species diversity and evolution. Exploring causes of variation in regeneration dynamics can provide key insights into the factors affecting regeneration. However, the relationship between the regeneration of *Larix principis-rupprechtii* and environmental factors is not clear in north China. Primarily, the three extents of regenerated *L. principis-rupprechtii* were selected in Shanxi Province. Then, the redundancy analysis revealed the environmental factors (topography, stand structure, soil property, and litter) that affected natural regeneration. The structural equation modeling identified the most importance of direct and indirect factors that affecting *L. principis-rupprechtii* natural regeneration. Litter thickness, canopy density, and adult tree diameter at breast height were positively correlated with natural regeneration. Aspect and total volume of nitrogen were negatively associated with natural regeneration. In addition, there was no significant correlation between natural regeneration and other environmental factors (altitude, slope, adult tree height, stand density, soil water content, soil organic content, total P, available N, available P, and soil enzyme). Further artificial intervention measures should be considered to promote plantation regeneration. This finding provides an effective base for land managers to conduct forest restoration and sustainable management.

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Abstract

Natural regeneration plays an important role in determining species diversity and evolution. Exploring causes of variation in regeneration dynamics can provide key insights into the factors affecting regeneration. However, the relationship between the regeneration of *Larix principis-rupprechtii* and environmental factors is not clear in north China. Primarily, the three extents of regenerated *L. principis-rupprechtii* were selected in Shanxi Province. Then, the redundancy analysis revealed the environmental factors (topography, stand structure, soil property, and litter) that affected natural regeneration. The structural equation modeling identified the most importance of direct and indirect factors that affecting *L. principis-rupprechtii* natural regeneration. Litter thickness, canopy density, and adult tree diameter at breast height were positively correlated with natural regeneration. Aspect and total volume of nitrogen were negatively associated with natural regeneration. In addition, there was no significant correlation between natural regeneration and other environmental factors (altitude, slope, adult tree height, stand density, soil water content, soil organic content, total P, available N, available P, and soil enzyme). Further artificial intervention measures should be considered to promote plantation regeneration. This finding provides an effective base for land managers to conduct forest restoration and sustainable management.

Keywords Natural regeneration, Environmental factors, Plantations, Management implication, Litter layers, Guandi Mountain

Introduction

Natural regeneration is crucial in forest ecosystems for providing the next generation with canopy trees (*Lombaerde et al., 2019*). It is a tendency for tree regeneration to achieve close-to-nature management (*Elisa et al., 2021*). The regeneration of overstorey trees can make the forest ecological system retain a higher biomass diversity and ecological quality (*Puhlick et al., 2012*). Natural regeneration is replacing artificial planting in most places in a dominant manner (*Christian et al., 2018; Puettmann et al., 2015*). Compared with traditional regeneration, natural regeneration is the cost-effective time-saving renewal of a stand by its seeds. It can achieve higher seedlings density by making full use of the soil-plant composite system and adapting complex habitats (*Kolo et al., 2017a; Srinivasan et al., 2015*).

It has been challenging to promote the natural regeneration of *Larix principis-rupprechtii*, one of the main tree species of typical natural secondary forest in the mountains area of North China. Many research found that the regeneration of *L. principis-rupprechtii* endured difficult periods with the shifting from seeds to seedlings (*Gao et al., 2020; Hernandez-Barrios et al., 2015*). The priority target is to identify the factors controlling the natural regeneration of trees. The seedling establishment of *L. principis-rupprechtii* in natural regeneration is more easily affected by abiotic and biotic factors, such as moisture, elevation, soil properties, and temperature (*Liu et al., 2012; Terwei et al., 2013*). Hence, a better understanding of the basic characteristics of trees regeneration is a prerequisite for effective management implications.

Previous studies have shown that regeneration significantly affects stand density, canopy density, herb, shrub, and litter layers (*Nakhoul et al., 2020; Royo & Carson, 2008*). Stand density and canopy density can influence herb and shrub cover. As herbs and shrubs grew, the productions of litter were increasing, affecting the solar radiation. For instance, low understory light levels limit seedlings' survival, while light availability exerts pressure in shade-tolerant trees (*Sangsupan et al., 2021*). Litter impacts the composition of species communities by changing the micro-climate needed for seeds to germinate (*Hu et al., 2016*). In turn, litter decomposition affects nutrient recycling. In addition, topography affects runoff, soil drainage, and soil property variation, thus adjusting the regenerated condition (*Wang et al., 2001*). Strong ties exist between topographic position, soil nutrient, and plantation regeneration (*Dessalegn et al., 2014*). Previous studies analyzed the relations between topographic, soil, shrub, and herb to explore the main determinants of regenerated seedlings through traditional multivariate analysis (*Wang et al., 2016*). Although some studies discussed several factors affecting the regeneration, few had comprehensively assessed the relevance of potential factors affecting the *L. principis-rupprechtii* regeneration (*Caquet et al., 2010; Ibáñez et al., 2015; O'Brien et al., 2007; Zhang et al., 2011*).

This study focused on all the potential environmental factors influencing the regeneration of *L. principis-rupprechtii* which were selected in few areas in North China. A region of *L. principis-rupprechtii* natural regeneration in Shanxi Province was selected to identify the control factors. Three plantations regenerated degree were classified: (1) regeneration density ≤ 3000 tree/ha (2) 3000 < regeneration density ≤ 5000 tree/ha (3) regeneration density > 5000 tree/ha. This study was designed to (ⅰ) assess the all-potential factors affecting *L. principis-rupprechtii* regeneration, (ⅱ) identify the main influencing factors affecting natural regeneration, and (ⅲ) propose some management implications to promote the level of *L. principis-rupprechtii* natural regeneration. The results are expected to provide some ideal guidance for the managing *L. principis-rupprechtii* natural regeneration and further understanding to achieve sustainable development of forest regeneration.

Material & methods

Study site

This study was conducted in Chailugou of Guandi Mountain, Jiaocheng County, Shanxi Province (111°28′–111°33′E, 37°48′–37°51′N) (Fig. 1) (*Yang et al., 2017*). The annual average temperature is 4.3 ℃, with the minimum and maximum temperatures being –11.9 ℃ and 30.7 ℃, respectively. The climate belongs to the temperate continental monsoon climate. The average atmospheric pressure is 934.2 hPa, with the minimum and maximum pressure being 920.3 hPa and 948.4 hPa, respectively. The average water vapor pressure is 2.5 hPa, the annual average precipitation and evaporation are 822 mm and 1268 mm, respectively, and the elevation is 1500-2831 m (*Zhao et al., 2021*). The main soil types are mountain cinnamon soil, cinnamon soil and brown soil (*Yang et al., 2017*).

The dominant plant species were forests (*L. principis-rupprechtii*, *Pinus tabuliformis*, *Picea wilsonii*, *Picea meyeri*, *Picea asperata* and *Populus simonii*), shrubs (*Acer tataricum subsp. ginnala*, *Rosa multiflora*, *Spiraea salicifolia*, *Clematis florida*, and *Berberis amurensis*), and grasses (*Fragaria orientalis*, *Geranium wilfordii*, *Chquuuujrysanthemum chanetii*, *Lathyrus humilis*, *Rubia cordifolia*, *Bupleurum smithii*, and *Thalictrum aquilegiifolium*).

Experimental design

In the summer of July to August 2022, an area of 1 hm^2 in the artificial forest (no thinned or managed in recent years) in Guandi Mountain was investigated to find *L. principis-rupprechtii* natural regeneration, including 14 sampling plots (20 m×20 m). Then the trees within the plot wood were seized feet to record height, diameter at breast height (DBH), canopy cover, species and numbers. Meanwhile, all trees were classified into three types in each plot (regenerated plants of seedlings: height ≤ 1 m, saplings: height > 1 m, DBH ≤ 5 cm; adult trees: DBH > 5 cm), and also classified according to regeneration degree (high: > 5000 tree/ha; medium: 3000-5000 tree/ha; low: < 3000 tree/ha). Each plot was set with a GPS to measure longitude, latitude, and elevation. Meanwhile, growth cores were used to determine the age of adult trees, while a compass was used to record the aspect and slope (Table 1).

Data collection

The research site was located in the rocky mountain area, too dry below 60 cm soil depth near the bedrock. Five soil sampling plots were collected with an X-shaped collection scheme at soil depth 0–20 cm, 20–40 cm, and 40–60 cm in each plot by using a soil auger after three days without rainfall event, and replicated three times. These three soil layers were mixed and placed in an aluminum box as composite soil samples and brought back to the laboratory for drying and weighting (105℃, 24h) to calculated soil water content (SWC). Meanwhile, the dried soil samples were crushed and sieved with a 1.5 mm screen to remove rocks and roots. Soil organic content (SOC) was measured by using the H_2SO_4-K_2CrO_7, total nitrogen (TN) was determined by the Kjeldahl methods, total phosphorus (TP) were determined by the colorimetric method after digestion with $HClO_4$-H_2SO_4, and available nitrogen (AN) was measured with the method of *Li et* *al. (2018)*. Furthermore, soil enzymes (sucrase, phosphatase, and urease) were measured with the method of *Xiangping et al. (2021)*.

After sampling soil, five herb quadrats (1 m×1 m) and five shrub quadrats (5 m×5 m) with an X shape sampling method were established in these sampling plots. At each quadrat, the species, numbers, height, and coverage were conducted. The five litter samples were also collected near herb and shrub sample plots with an X-shape pattern to record the thickness of , then bagged and weighed. The collected litter was taken to the laboratory for drying and weighting (85℃, 24h) then calculated the accumulation of litter (*A et al., 2021*).

Data analysis

The natural regeneration data (regenerated numbers, trees DBH, and trees height per plot) could not be normalized although through various methods. Therefore, the effects of treatments via nonparametric tests (Kruskal-Wallis ANOVA) were analyzed. The raw data was ranked to test the interaction between multiple factors. Then the environmental gradients were identified through sorting analysis by using CANOCO (version 5.0). Preliminary detrended correspondence analysis of the all-regenerated sampling plots demonstrated that the gradient lengths were < 3.0, indicating that the regeneration plots showed linear responses to latent environmental variation, evidence of the reasonability of linear multivariate methods (*Li et al., 2018*). Therefore, the redundancy analysis (RDA) was carried out in the CANOCO 5.0 software to determine the community's predominant environmental factors. The scale of the sort centered on correlations among the species. Monte Carlo simulations with a significance level of 99% were used to test the statistical significance based on random permutations (*Chen & Cao, 2014*). The regeneration data was transformed through logarithmic transformation to reduce the influence of extreme values (*Gazer, 2011*).

The number, diameter at breast height and height of regenerated plants were used to represent the species. Environmental factors were divided into four categories: topographic factors (altitude, slope, and aspect), stand structure (stand density, adult tree average diameter at breast height, adult trees height, and canopy density), soil properties (soil water content, soil organic content, total nitrogen, total phosphorus, available phosphorus, available potassium, ammonia nitrogen, urease, sucrase, and phosphatase), and litter (thickness and accumulation). All values for these factors were square-root transformed to ensure the uniformity of variance before conducted statistical analysis. All values after logarithmic transformation were analyzed using the ANOVA method; meanwhile, Duncan's test ($p < 0.01$ or $p < 0.05$) was used to compare the differences in environmental factors. Pearson correlation coefficients were determined to test the relationships between environmental factors and regeneration. Statistical parameters and tests were conducted in SPSS 22.0 (Chicago, USA) and drafted in Origin 2023 (Northampton, MA, USA).

Structural equation modeling (SEM) was established to test all potential effects of environmental factors on regeneration by transforming the data sets into a path relation network (*Malik et al., 2018*). A confirmatory approach was used to measure the maximum likelihood of data fitting the hypothesized path model, deducing environmental factor influences natural regeneration. The fitting of the path model and the relationship between structure and data were verified by using the Lavan R (version 4.2.1) package (*Rosseel, 2012; Team, 2015*). The fittest model was identified by high comparative fit index (CFI > 0.9), high goodness of fit index (GFI > 0.9), low root mean square error of approximation index (RMSER ≤ 0.08), and low standardized root mean square residual index (SRMR < 0.08).

Results

Characters of natural regeneration

Natural regeneration was better in the study area (Fig. 2, Table 2) after field investigation. A great number of regenerated saplings were recorded, especially the maximum plot 4 (552 trees) and the minimum plot 14 (N = 26); however, the number of regenerated seedlings was low except plot 1 (N = 62), plot 3 (N = 17), and plot 10 (N = 19) (Fig. 2). In addition, there also had a low number of adult trees (number from 1 to 10). The population of regenerated saplings made up more than 80% except plot 1 (59%), while regenerated seedlings and adult trees were less occupied in each sample plot (Fig. 2). However, there were no regenerated seedlings recorded in plots 8 and 11. Sampling plot 9 (density = 2200 tree/ha), 11 (density = 2775 tree/ha), and 14 (density = 1125 tree/ha) were recorded medium regeneration degree. Other sample plots with a great regeneration degree of *L. principis-rupprechtii* were recorded greater than 3000 tree/ha.

Environmental factors for RDA analysis

Based on statistical theory, the best predictors of *L. principis-rupprechtii* regeneration were determined. RDA could distinguish the relative contributions of topographic factor, stand structure, soil properties, and litter variables to *L. principis-rupprechtii* regeneration; meanwhile, the correlation between variables and multivariable data was evaluated. Fig. 3 shows the RDA ordination diagram. The correlation between the corresponding variables is represented by the cosine values of the environment variables in the graph; the sine cosine value represents the positive correlation between the variable, while the negative cosine value represents the negative correlation.

The results show a strong correlation between regeneration and environmental factors as the variation in the regeneration of 94.2% is shown on axis 1 (Fig. 3). Fig. 3-B shows all biplots of the RDA analysis. Litter thickness, litter accumulation, stand density, and canopy density positively correlates with the regenerated number, while altitude, soil water content, and total P have a weak correlation with the regenerated number (Fig. 3-A). Litter thickness and altitude are respectively the strongest and weakest effects. The variable of total N, available P, aspect, adult tree height, and adult tree diameter at breast height negatively correlate with the regenerated number; the negative effect of aspect is the largest. Regenerated height strongly positively correlates with the aspect. It negatively correlates with litter accumulation, litter thickness, stand density, canopy density, total P, soil water content, and altitude (strongly negative correlation), while adult height, adult tree DBH, total N, available P, and available N have a weak effect. Regenerated tree DBH positively correlates with aspect and available N, the latter being the strongest; meanwhile, it negatively correlates with other environmental factors, with altitude having the strongest negative effect. Sample plots (2, 3, 4, 6, 7, 12) show the same patterns expect plot 5, while plots (1, 8, 9, 10, 11, 13, 14) show the same patterns, representing the largest degrees of natural regeneration, with sample plot 4 showing the highest (Fig. 3-B).

In the RDA analysis, litter thickness and canopy density contribute more than 10% (Table 3). The RDA1 axis positively correlates with total P, soil water content, altitude, stand density, canopy density, litter thickness, and litter accumulation; available N, available P, total N, aspect, average adult tree diameter at breast height, and adult tree height show a negative correlation (Table 4). Litter thickness has a greater positive correlation coefficient with RDA1 (0.696), while available N has the lowest negative correlation coefficient with RDA1 (-0.134). The aspect most highly correlates with RDA2 (0.522) followed by available N (0.055). Other variables show negative correlations.

Regeneration correlation with environmental factors

According to RDA analysis, thirteen environmental factors were selected. Fig. 4 shows the correlation between stand structure, soil properties, litter variables and topographic factors. The number of regenerated trees positively correlates with stand density (0.62) and canopy density (0.55), and significantly positive correlates with litter thickness (0.70). The extent of regeneration (include number, diameter at breast height, and height) positively correlates with litter thickness (0.70, 0.69, and 0.55, respectively). Soil water content (-0.72) and altitude (-0.85) significantly negatively correlate with tree regeneration height. Soil water content notably negatively correlates with aspect (-0.81) but significantly positively correlates with stand density (0.68) and positively correlates with altitude (0.66). Total N is greatly positive with available N (0.67). Litter thickness is negatively correlated with aspect (-0.64) but positively correlated with stand density (0.57) and litter accumulation (0.61). Adult tree diameter at breast height is negatively correlated with litter thickness (-0.60).

Structural equation model (SEM)

Based on maximum likelihood estimation, eight environmental factors are selected to form the SEM. All indexes are high in this model which has a great degree of fit (χ^2/df = 0.446, P = 0.874). The comparative fit index (CFI) and goodness of fit index (GFI) are 0.999 and 0.991, respectively. The parsimony goodness of fit index (PGFI) and parsimony normed fit index (PNFI) are 0.505 and 0.552, respectively. The standardized root means square residual (SRMR) and the root mean square error of approximation (RMSEA) are 0.027 and 0.002, respectively.

Litter thickness and regeneration are positively associated, with the path coefficient being 0.87. Regeneration positively correlates with canopy density, with the path coefficient being 0.63. Altitude positively correlates with litter thickness, canopy density, and soil water content, the path coefficient of which are 0.25, 0.71, and 0.31, respectively. Aspect positively correlates with litter accumulation, with the path coefficient being 0.31. Total N positively correlates with litter thickness, with the path coefficient being 0.23. Aspect and canopy density is positively correlated, having a path coefficient of 0.30. Meanwhile, litter accumulation is positively associated with litter thickness, with the path coefficient being 0.81. Regeneration is negatively associated with litter accumulation, total N, and aspect, the path coefficients of which are -0.08, -0.17, and -0.18, respectively. Total N and litter accumulation are negatively correlated, with the path coefficient of -0.47. The aspect is negatively associated with litter thickness and soil water content, the path coefficient of which are -0.40 and -0.53, respectively.

Discussion

According to a series of analyses, litter thickness, altitude, aspect, canopy density, adult tree DBH and total N are selected factors that affected the *L. principis-rupprechtii* natural regeneration.

Effect of topography on regeneration

Soil serves as the essential part affecting the growth and distribution of vegetation. Soil and vegetation are affected by topography (*Liu et al., 2012; Parker, 2013*). Topographic factors can adjust seeds, water, and nutrient redistribution. For instance, aspect has a significant effect on plant community structure and extents of natural regeneration (*Fu et al., 2004; Ma et al., 2010; Wang et al., 2016*). The ordination results indicated that the aspect and altitude were the major topographic factors affecting regeneration. However, SEM analysis indicated altitude did not influence regeneration. In this study, the difference between high and low elevations in sampling plots was 88 m. Many studies indicated a little effect on the development of vegetation and regeneration when the elevation change was < 300 m (*Liu et al., 2012; Wang et al., 2006*), which may not be enough to cause variations in water conditions. Therefore, the elevation variable was not chosen as the element affecting regeneration. The aspect was positively related to the activity of aboveground organisms and the distribution of herbs and negatively correlated with regeneration (*Scowcroft et al., 2010; Vitousek et al., 1994*). There were two kinds of aspects (Northwest and West) recorded in our study site, which determined the amount of solar radiation accepted (*Sariyildiz et al., 2005*). The seedlings of *L. principis-rupprechtii* need enough light to grow at early-stage from seeds to seedlings then saplings. The Northwest aspect could receive more solar radiation than the West aspect. A great regeneration density was recorded in the Northwest aspect in this study. Soil temperature and soil water availability are controlled by aspect, which in turn affect seedlings' establishment and growth (*Mcnab, 1992; Xue et al., 2012*). Topography can affect the soil depth and profile development and the accumulation of soil nutrients, indirectly influencing the distribution of plants and species composition (*Dessalegn et al., 2014; Liang & Wei, 2020; Sariyildiz et al., 2005*). In this study, regeneration was negatively correlated with aspect (-0.18), suggesting that it is easier for seeds to accumulate and grow in the aspect of the Northwest with more solar radiation.

Effect of stand structure on regeneration

Stand structure factors greatly influence the level of regenerated seedlings and plants restoration, which can affect seedlings' richness and density (*Liu et al., 2020*). This study conducted the effect of stand structure on natural regeneration. The change of different factors depended on the life stages of regenerated seedlings. As one of the structure factors, canopy density affects stand structural composition, litter cover, species richness, and composition (*Chen & Cao, 2014; Takahashi & Mikami, 2008*). Regenerated seedlings need light to grow, which is important for regeneration to increase light capture. So, seedlings need to reduce self-shading to accept more efficient light in the forest understory (*Takahashi & Mikami, 2008*). The SEM analysis suggested that adult tree's DBH positively correlated with natural regeneration. Mother trees with greater DBH typically obtained more soil water, light, and other resources to support seedlings' growth, occupying a dominant position in the forest (*Li et al., 2005*). Many seeds produced by strong mother trees were higher in quantity and quality, which might explain the high regeneration density in the study area. There was a positive correlation between canopy density and regeneration, consistent with that of *A et al. (2019)* and *Mou et al. (2012)*. Meanwhile, the strength of this correlation was higher than that of adult trees DBH. The regenerated period of light requirements for growth increased with the increasing canopy density. The shortage of light supplements could cause poor growth and even death (*Gaudio et al., 2011; Wang et al., 2017*). Some studies have also indicated the light is one of the most important environmental factors influencing the development of natural regeneration; direct light transmission is more conducive to seed germination and seedlings' growth, conducting to its natural regeneration (*Canham et al., 1990; Kneeshaw et al., 2006*). In general, the relationship between canopy density, and adult tree DBH effect on *L. principis-rupprechtii* regeneration in this study was highly consistent with the findings of other studies (*A et al., 2019; Ares et al., 2010; Koorem & Moora, 2010; Liang & Wei, 2020*).

Effect of litter on regeneration

Understory shrubs, herbs, and litter play an important role in maintaining the biodiversity in local forest ecosystems and affecting natural forest regeneration (*Li et al., 2018*). Because with the increasing of shrubs height and herb coverage, more light is intercepted, and more litter is accumulated. In turn, the growth space availability decreases (*Caccia & Ballaré, 1998; Facelli & Pickett, 1991; O'Brien et al., 2007*). Shrubs were minor and less distributed in sampling plots, indicating no effect on regeneration. In addition, *L. principis-rupprechtii* is shade tolerance species, so the herb lacks a clear effect on regenerated seedlings (*Kolo et al., 2017b; Lombaerde et al., 2019; Vayreda et al., 2013*). However, some studies have suggested that limitation on the understory vegetation can promote natural regeneration since the herb can provide a shady environment to support the growth of seedlings. In turn, seedlings restrain the growth of herbs, explaining the existence of a few understories' vegetation (*Bose et al., 2012; Émilie et al., 2015; Simon et al., 2017; Skay et al., 2021*).

RDA analysis suggested that litter thickness could explain 60.4% for regeneration. SEM analysis showed that it had a path coefficient of 0.87 for regeneration. So, the litter thickness was closely correlated with regeneration. Generally speaking, the seeds of *L. principis-rupprechtii* majorly scatter in soil layers for their length above 2 mm (*Liang & Wei, 2020*). With the thickness of litter layers increasing, the water holding capacity was increased. Stable temperature and better water holding capacity provide suitable growth conditions for germination while limiting soil water evaporation (*Boydak, 2004; Petrou & Milios, 2020; Spanos et al., 2000*). Instead, some studies have indicated that the seeds do not grow and even die in litter layers since the radicles fail to reach the soil layers to attain adequate nutrients. Additionally, the litter has an auto-toxic effect on seeds' germination and seedlings' growth (*Pardos et al., 2007; Willis et al., 2021*). Nevertheless, litter thickness has positive correlations with regeneration in this study (Fig. 5) since the adequate litter thickness and stable decomposition rate of litter can reduce a mechanical and physiological battier to promote natural regeneration, helping seeds find favorable conditions to germinate (*Baker & Murray, 2010; Eckstein & Donath, 2005*). So, the thickness of litter was in an ideal state in this area, which can be adjusted in further management to achieve the optimal regeneration density.

Effect of soil properties on regeneration

Soil nutrient circulation is an important factor affecting natural forest regeneration (*Chen & Cao, 2014*). Seeds germination and seedlings' growth need soil resources, such as soil organic content, soil water content, total nitrogen, and total phosphatase (*Will et al., 2005*). SEM analysis showed that total nitrogen greatly contributed to explaining natural regeneration compared with other soil properties. Since numerous litters were accumulated and decomposed in the surface soil layer at extensive management forest, increasing total nitrogen content. Total nitrogen was positively correlated with canopy density and negatively correlated with regeneration, while litter thickness was positively correlated with total nitrogen. Hence, species were deduced to increase total nitrogen, which was in agreement with that of *Baker & Murray (2010)* and *Li et al. (2015)*. In addition, total N is one of the most important variables impacting species richness and plant distribution (*Zuo et al., 2012*). Meanwhile, more nutrients were released from inputted litter with forest regeneration (*Deng et al., 2013*). Nevertheless, as the total nitrogen content decreased, the number of species increased (*Liu et al., 2011; Rhoades et al., 2009*). Through observation, the richness (number) and quantity (height and diameter at breast height) of species varied in the RDA, indicating insufficient regeneration quality in the study site. Though high total nitrogen volume can restrict natural regeneration, a great proportion of total N consumption is needed for regenerated seedlings (*Xu et al., 2018*). So, artificial restoration is a necessary for in the later stage.

Management implications

Environmental factors (aspect, canopy density, adult tree DBH, litter thickness, and total nitrogen) and regeneration of *L. principis-rupprechtii* were mutually related and restricted. Therefore, to improve the regeneration and soil quality, the coevolution of regeneration and soil quality should be considered. Effective implications should be considered, like appropriate removal of litter to decrease thickness to promote seeds germination. Scattered seedlings and dead trees should be removed to enlarge the distance between seedlings and adult trees and allow more light available to *L. principis-rupprechtii*.

Conclusions

Great understandings of the environmental factors affecting seedlings' growth were needed to achieve *L. principis-rupprechtii* regeneration. Based on RDA and SEM analysis, litter thickness was the most important variable affecting natural regeneration, followed by canopy density, adult tree DBH, aspect, and total N. Hence, intervention measures of the above should be adopted in forest management, such as reducing the thickness in the thicker area and removing dead trees to increase the forest gap. Some aggregate regenerated seedlings near the adult trees were properly removed to the Northwest aspect. Further, the results may contribute to formulate scientific and flexible regeneration management implications and achieve sustainability for forest plantation of the mountain area in north China.

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Figure 1

The study site location in Jiaocheng County (A). (B) Sampling plots (1-14) in Guandi Mountain, gray boxes indicate the fourteen sampling areas.

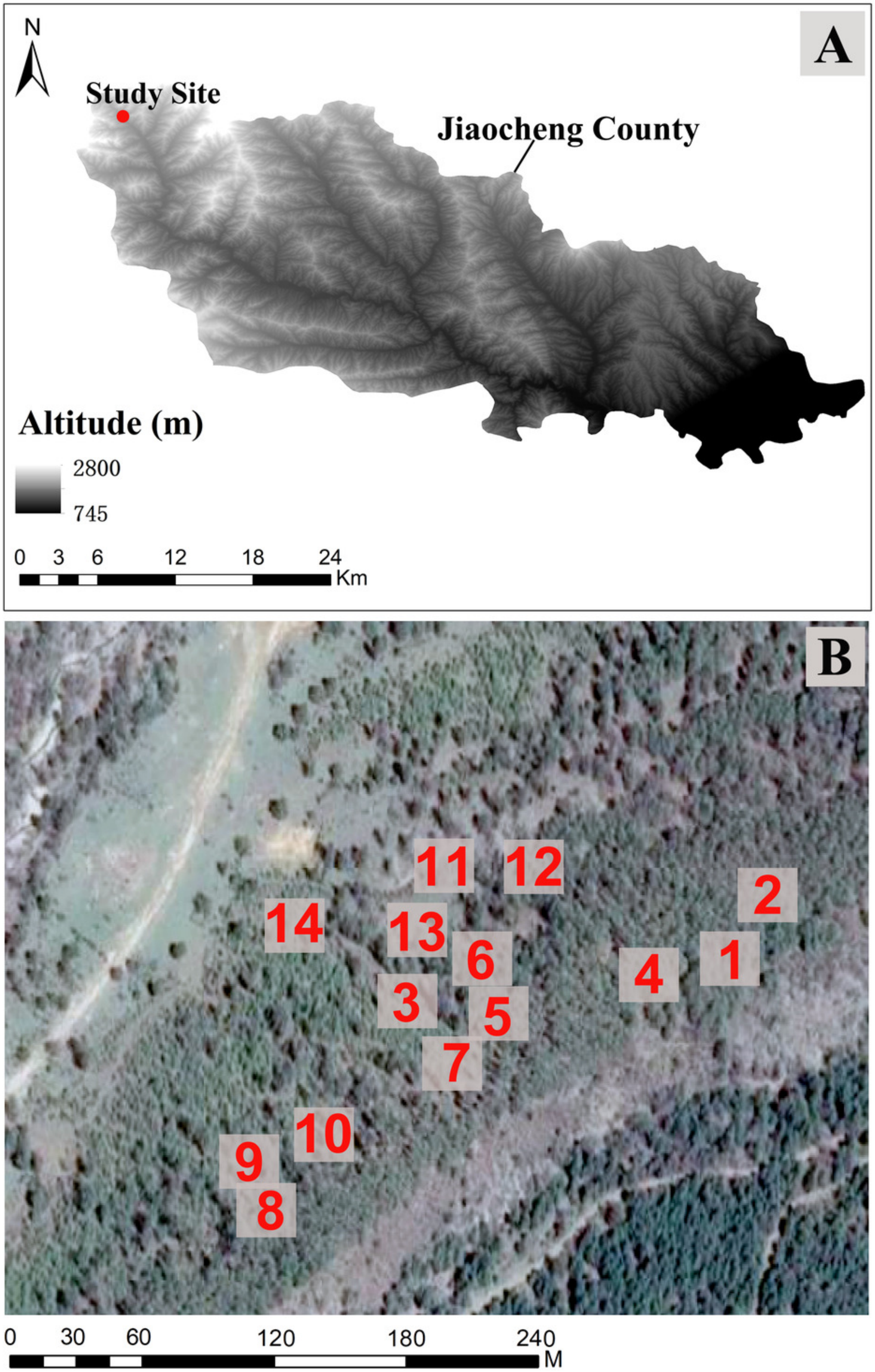
A
N
Study Site
Jiaocheng County
Altitude (m)
2800
745
0 3 6 12 18 24
Km
B
11
12
2
14
13
6
1
4
3
5
7
10
9
8
0 30 60 120 180 240
M

Figure 2

Regenerated tree number and distribution of different sample plots in height and diameter at breast height (DBH) class.

Note: Seedlings: height < 0.5 m; Saplings: height ≥ 0.5 m, DBH ≤ 0.5 m; Adult trees: DBH > 2 m).

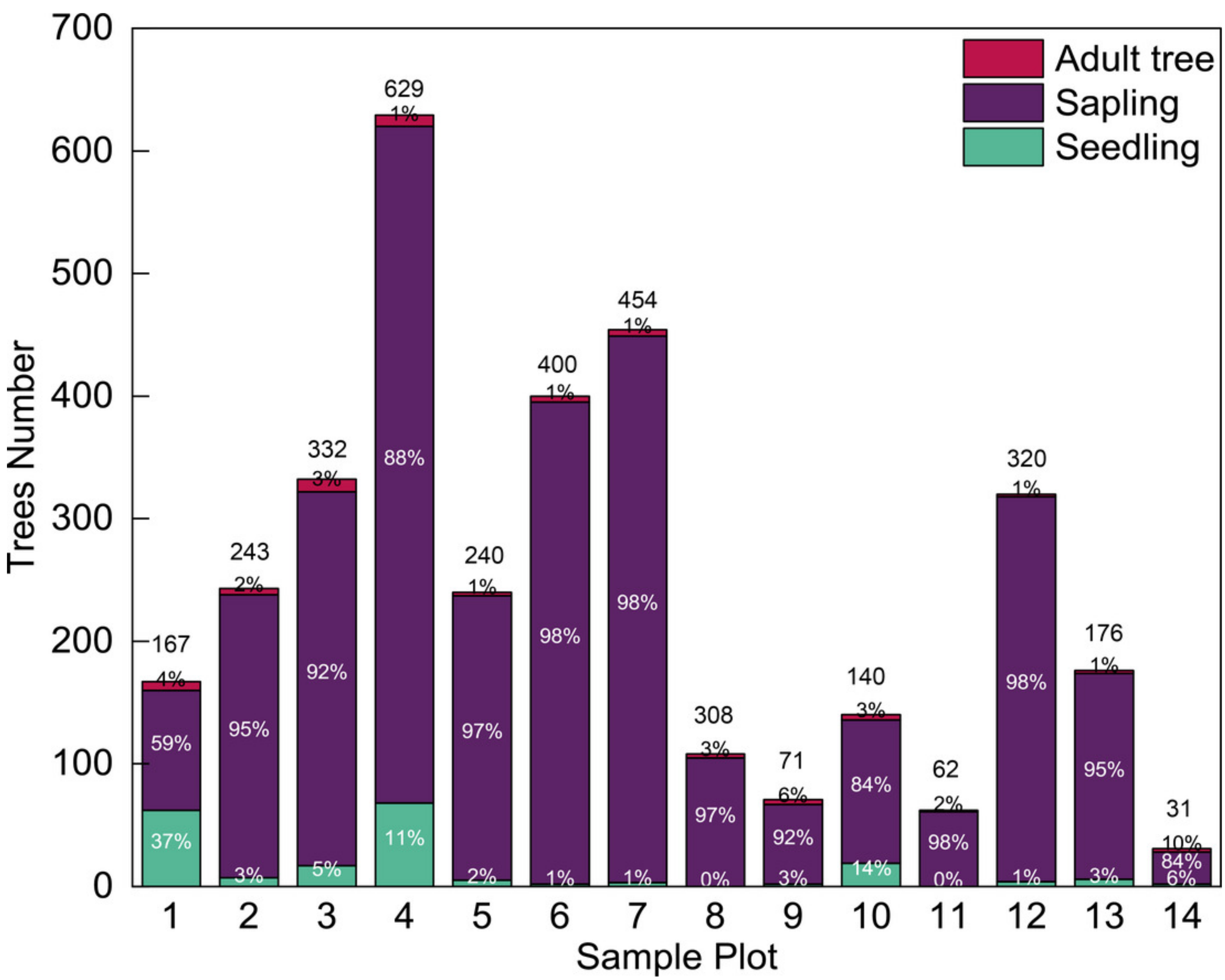

Figure 3

Ordination diagram of the redundancy analysis (RDA) results of topographic factors, stand structure, soil properties, and litter in sample plots.

(A) The relationship between the number (Re-Number), DBH (Re-DBH), height (Re-Height), and impact factors of regenerated trees; (B) the relationship between sample plots distribution and impact factors. The direction of the arrows corresponds to the correlation (positive or negative) among the environmental factors with the axis. The lengths of the arrows indicate the extent of correlation to which a factor impacts regeneration and longer lines indicate further correlations. Abbreviations of stand structure, soil properties, and litter variables in figures are as follow: StaD, stand density; Adt-DBH, adult tree average diameter at breast height; Adt-Height, adult tree height; CanD, canopy density; SWC, soil water content; TP, total phosphorus; TN, total nitrogen; AN, ammonia nitrogen; AP, available phosphorus; LitT, litter thickness, and LitA, litter accumulation.

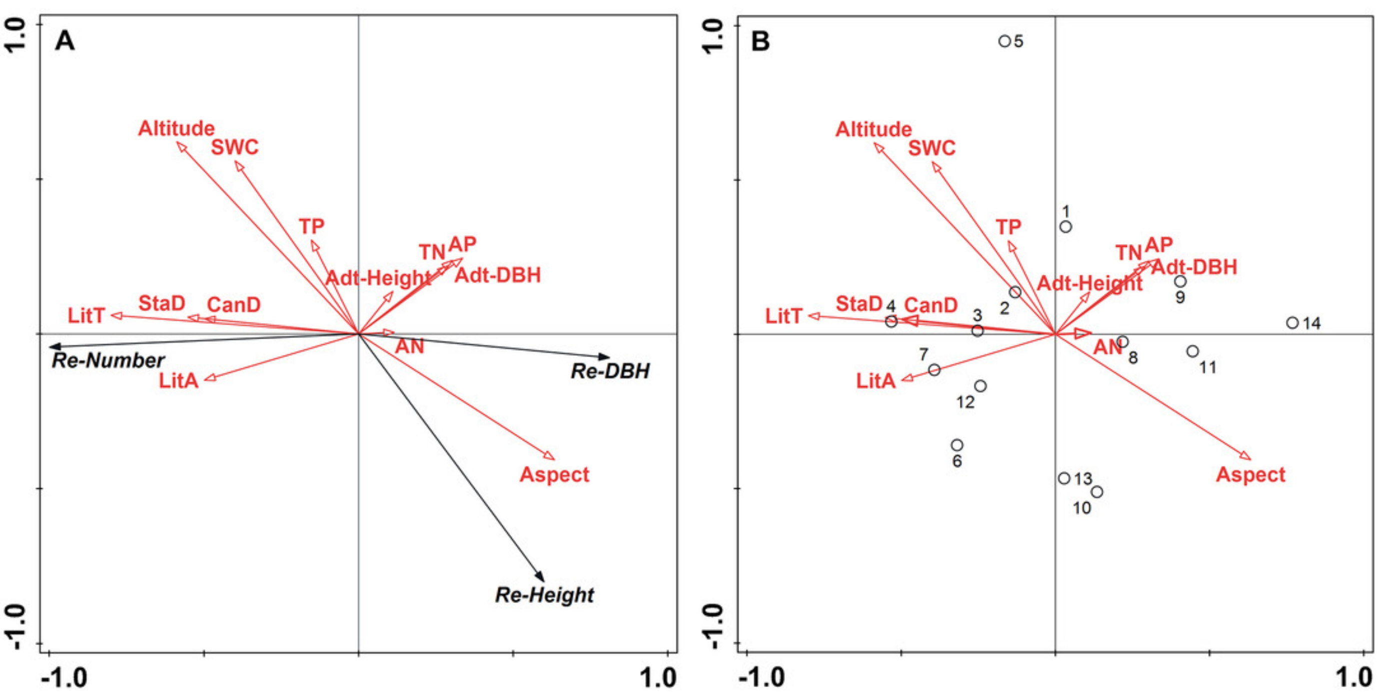

Figure 4

Correlation analysis of environmental factors.

Re-number, regenerated tree number; Re-DBH, regenerated tree diameter at breast height; Regenerated-Height, regenerated height; TP, total P; AN, available N; TN, total N; SWC, soil water content; StaD, stand density; CanD, canopy density; LitT, litter thickness; LitA, litter accumulation; Adt-DBH, adult tree diameter at breast height; Adt-Height, adult tree height.

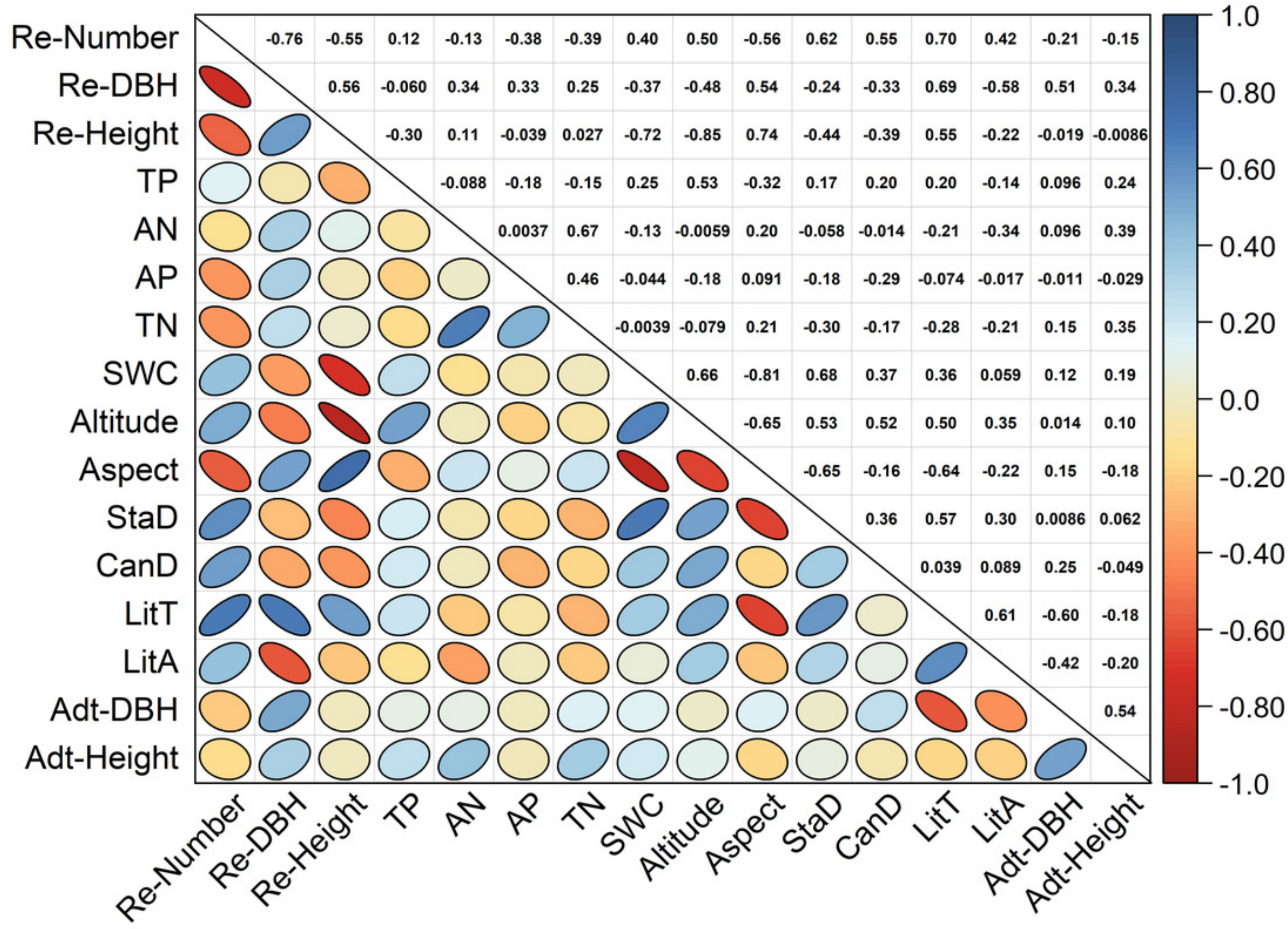

Figure 5

Corrected structural equation model with standardized path coefficients between influence factors and regeneration. Figures on the arrows indicate standardized path coefficients.

Red arrows indicate negative affect, while blue arrows indicate positive association.

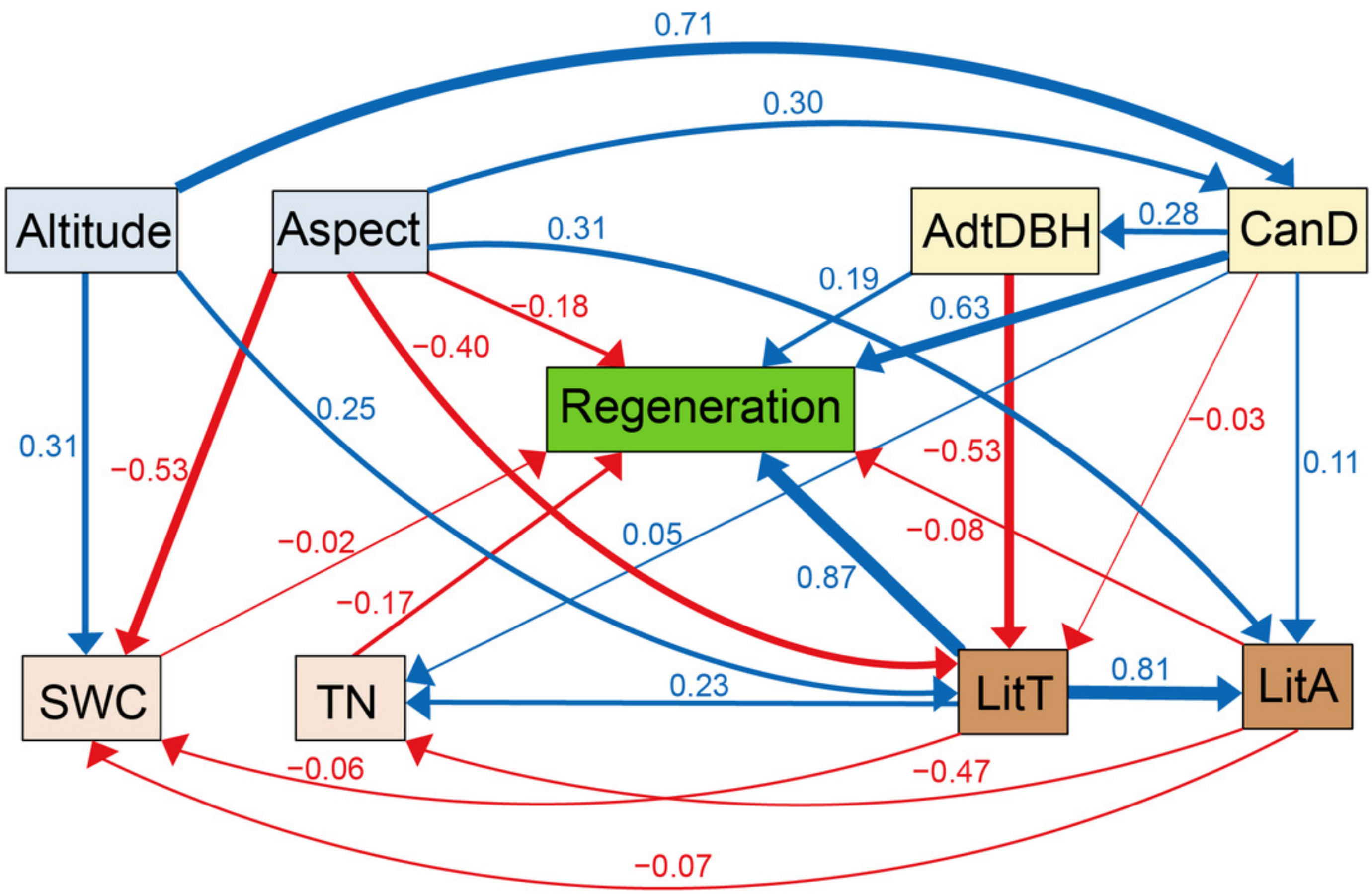

Table 1(on next page)

Summary of the stand characteristics in sample plots

Table 1

Plot	Basal area ($m^2 \cdot ha^{-1}$)	Altitude (m)	Longitude	Latitude	Stand density ($Tree \cdot ha^{-1}$)	Aspect	Slope (º)	DBH (cm)	Height (m)	Age (a)
1	3.89	2063	111º32′32″	37º51′21″	175	N-W	19.4	44.5	21.13	56
2	2.50	2066	111º32′33″	37º51′21″	125	N-W	13	35.7	23.9	59
3	1.95	2060	111º32′28″	37º51′19″	250	N-W	23	31.49	17.81	50
4	2.39	2070	111º32′31″	37º51′20″	225	N-W	15.7	34.87	20.87	64
5	1.94	2078	111º32′26″	37º51′17″	75	N-W	17	31.47	21.73	64
6	1.14	2029	111º32′25″	37º51′17″	175	N-W	25	24.14	19.84	62
7	2.07	2018	111º32′24″	37º51′15″	125	N-W	22	32.48	16.54	64
8	1.75	2002	111º32′19″	37º51′14″	75	N-W	24	29.87	21.8	55
9	3.51	2007	111º32′18″	37º51′15″	100	W	22	42.3	21.1	82
10	1.64	1990	111º32′19″	37º51′15″	100	W	32	28.88	21	70
11	0.75	2022	111º32′25″	37º51′20″	50	W	15	19.6	12.3	19
12	2.36	2025	111º32′26″	37º51′20″	50	W	18	34.7	14.5	65
13	2.83	2023	111º32′24″	37º51′20″	50	W	21	37.95	24	19
14	4.67	2000	111º32′23″	37º51′21″	75	W	8	48.77	22.7	59

Note: N-W is the northwest aspect of each plot, and W is the west aspect of each plot.

Table 2(on next page)

Total *L. principis-rupprechtii* regeneration density in study plots

1 Table 2

	Study site													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Density (Tree·ha^{-1})	4025	6000	8175	15500	6075	10725	11225	3100	2200	3800	2775	9325	5500	1125

2

Table 3(on next page)

Percent variance of environmental factors affecting the regeneration

Abbreviations of stand structure, soil properties, and litter variables in figures are as follow: LitT, litter thickness; CanD, canopy density; AP, available phosphorus; SWC, soil water content; TN, total nitrogen; Adt-DBH, adult tree average diameter at breast height; Adt-Height, adult tree height; StaD, stand density; TP, total phosphorus; LitA, litter accumulation; AN, ammonia nitrogen.

Table 3

Factor	Explains (%)	Pseudo-F	*P*
LitT	60.4	18.3	0.004
CanD	20.5	11.9	0.004
Altitude	3.7	2.4	0.12
AP	2.5	1.7	0.182
Aspect	1.3	0.9	0.402
SWC	2.8	2.3	0.14
TN	2.7	2.7	0.126
Adt-DBH	1.2	1.2	0.324
Adt-Height	2.1	2.1	0.138
StaD	1.2	2.1	0.164
TP	0.9	2.8	0.17
LitA	0.6	5	0.122
AN	0.1	< 0.1	1

Table 4(on next page)

Coefficients for environmental factors for RDA1 and RDA2

Table 4

Environmental factor	RDA1	RDA2
Total P	0.120	–0.278
Available N	–0.134	0.055
Available P	–0.382	–0.292
Total N	–0.394	–0.226
Soil water content	0.401	–0.592
Altitude	0.496	–0.692
Aspect	–0.561	0.522
Stand density	0.616	–0.114
Canopy density	0.547	–0.108
Litter thickness	0.696	–0.203
Litter accumulation	0.416	–0.008
Average adult tree diameter at breast height	–0.215	–0.144
Average adult tree height	–0.150	–0.096