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Spatial patterns in natural *Picea crassifolia* forests of northwestern China, as basis for close-to-nature forestry

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Abstract: Close-to-nature forest management has been proposed as an effective method for improving the quality of plantation forests. Knowledge of spatial distribution patterns, structure, and succession trajectories in natural forests can provide guidelines for the establishment of close-to-nature forest plantations. Such knowledge is lacking in natural spruce (*Picea crassifolia*) forests in the Qilian Mountains of China, impeding the establishment of production forests. We conducted a case study in the Qilian Mountains to analyze the relationships between the naturally-formed forest patches and terrain factors, spatial heterogeneity of stand characteristics, and stand structure following harvesting disturbance. Our results suggested that spruce plantations will be effective on the N, NE, and NW slopes, at elevations between 2700 and 3300 m, and on slopes ranging from 15° to 45°. Further, planted forest patches should occupy 64% of the slope area on semi-shady slopes (NE, NW). Spatial patterns in the studied forest exhibited a strong scale-effect, and an area of 0.25 ha could be used as the most efficient plot scale for the management of spruce plantations. Partial logging is an effective method for the conversion of spruce planted forests into near-natural forests, and the intensity of partial logging can be determined from the negative exponential function relationship between stand density and DBH. Our results provided critical information for the development of spruce plantations and conversion of existing plantations.

Keywords: *Picea crassifolia;* spruce; Close-to-nature forestry; Spatial patterns; Qilian Mountains

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Introduction

Reforestation played a significant role in ecological restoration and economic development in China. Today, plantations cover about 70 million hectares and account for more than 30% of the total forested area in the country. The emphasis in plantation forestry was placed on short-term productivity and on the pursuit of economic interests, while site conditions were often ignored during the selection of tree species. Divergence from the processes of ecological succession in planted forests resulted in poor forest health across the continuously-increasing afforestation area. Soil degradation, increase in forest pests, decline in biodiversity, and low ecological and economic benefits were often observed in afforested areas (Nagaike et al. 2012; Wingfield et al. 2013). Finding solutions to these problems and implementing sustainable management in plantations comprise the current focus in forestry research in China. Domestic and international research and management practices have shown that close-to-nature forest management is an effective method for improving the quality and ecological benefits of planted forests (von Oheimb et al. 2005; Zeng 2009; Roessiger et al. 2011; Schou et al. 2012).

The model of close-to-nature forest management originated in Central Europe in an attempt to maintain sustainable productivity and economic interests, and adapted the "natural automation" theory (e.g. self-regulation and self-regeneration) (Schütz 1999; Pommerening and Murphy 2004). Close-to-nature forest management is based on analyses of stability, biodiversity, multi-functionality, and resilience of a forest ecosystem. The main goals are development of quality of individual stems and reliance on natural regeneration. The desired characteristics of forest structure include multiple tree species, multi-story, and uneven-aged forest, while those of productivity incorporate permanent forest cover and high quality of products (Nagaike et al. 2010).

Recently, the concept of close-to-nature forestry has been adopted in other European countries, as well as in North America and Japan. The pioneering work for close-to-nature forest management in China was led by the Beijing International Forestry Project Management Office in 1998 (Zeng 2009). Subsequently, the Chinese Academy of Forestry established five demonstration areas for close-to-nature forest management in Beijing, Hainan, Yunnan, Sichuan, and Shaanxi. Currently, an increasing number of Chinese scientists and forest managers are involved in research on close-to-nature forestry (Lin and Huang 2001; Lu 2009).

In China, reforestation with native tree species has grown rapidly in an effort to restore vegetation in mountainous areas. Differences in climatic and geographical conditions of various mountain ranges resulted in variable habitat conditions, and diversity of native tree species and their genetic make-up. However, surveys of native vegetation and habitat assessments are lacking. Additionally, knowledge of the distribution patterns and composition structure in natural forests is limited. The spatial distribution of trees is a result of many ecological processes, and plays a key role in determining regeneration, survival, growth, mortality, understory development, rate of spread of diseases, impact area of disturbances, and other ecological characteristics, which can be manipulated by forest management (e.g., thinning, harvesting, planting, etc.) (Chen and Bradshaw 1999). Understanding of the spatial pattern of natural forests may provide significant insights into processes and mechanisms that maintain stand stability (Jia et al. 2016). Such information can be used in the planning of close-to-nature plantations.

In the Qilian Mountains, forest cover decreased due to deforestation from 22.4% in 1949 to 12.4% in the 1990s (Wang and Cheng 1999). Since 1991, efforts to restore mountain vegetation have intensified. The most widely planted species in the region is the Qinghai spruce (*Picea crassifolia Kom.*) (Wang et al. 1997). This species is shade tolerant, and found at locations with annual precipitation of approximately 400-700 mm. It is endemic and widespread in the Qilian Mountains, where it accounts for 75.7% of the total forest area (Chen et al. 2015; Yu et al. 2015). However，due to generally high stand densities and unreasonable distribution patterns, water deficits, low forest productivity, and poor stability of the ecosystem are common problems in spruce plantation forests in most locations except on shady and semi-shady slopes (Zhu et al. 2015). This has severely restricted the growth and sustainable development of these forests. Therefore, a quantitative understanding of the spatial distribution patterns, the structure and the succession trajectory of natural forests can inform about key theoretical thresholds for the establishment of close-to-nature plantation ecosystems.

In our study, we focused on the natural and secondary spruce forest. Using LiDAR and ground-survey data, we analyzed spatial heterogeneity, in particular, the relationships between patchy distribution and topographic factors, and the distribution patterns and changes in stand structure at different scales. The objective of our study was to provide guidelines for the establishment, conversion, and management of close-to-nature plantations. Specifically, we wanted to determine: 1) how to design plantation patches in different terrain conditions (including slope, slope area, aspect, and altitude), 2) what plot size and spatial pattern that could be used for the management of planted forests, and 3) what stand structure (e.g. stand density) of plantation that should be maintained in different successional stages.

1 Materials and Methods

1.1 Study area

Two experimental sites were chosen, one in Dayekou, and one in Sidalong forest protection zones in the middle of the Qilian Mountains (Figure 1). The two sites are 60 km apart, with similar climatic conditions characterized by a semiarid climate. Mean annual temperature (MAT) is about 2.0°C and mean annual precipitation (MAP) ranges from 374 to 407 mm at an elevation of 2700 m, about 65% of which falls between July and September. The MAT decreases with elevation at a rate of 0.58°C per 100m, whereas MAP increases with elevation by about 4.3% per 100 m. Annual evaporation ranges from 1050 to 1100 mm, and relative humidity from 60 to 65% (He et al. 2010).

Vegetation patterns in the area are closely related to topography. Spruce is the dominant tree species, mostly found on shady (north-facing) and semi-shady (northeast- or northwest-facing) slopes. *Polygonum viviparum*, *Saussurea humilis*, *Carex scabriostris*, *Thuidium delicatulum* and *Hypnum cupressiforme* are the dominant understory species.

Grey cinnamon soil, present on shaded slopes, and chestnut soil, developed on sunny slopes, are the two most typical soils in the catchment (Chen et al. 2016). The main parent material is calcareous rock, which is overlaid by a relatively thin soil layer (less than 1 m) with coarse texture.

1.1.1 Image data and terrain parameters

To retrieve accurate topographic information, low-density LiDAR was used to generate a digital elevation model (DEM). The LiDAR data were collected on 23 June 2008 by an airborne laser-scanning (ALS) system, covering an area of about 56 km^2 in the Dayekou catchment. The raw data were further processed and released by the “Heihe Plan Science Data Center” (HPSDC) (http://westdc.westgis.ac.cn/). The DEM, a raster surface at a spatial resolution of 1 m, was produced by interpolating the height of ground laser hits. Topographic information, including elevation, slope, and aspect, was extracted from the DEM using ArcGIS 9.0 software (Diamond and Ross 2016). A detailed vegetation map for our study developed in 2001, also provided by the HPSDC, was used to identify the dominant forest type of spruce. We then modified the map with the use of high-resolution color-charged coupled device (CCD) carried in the airborne image.

We determined the spatial distribution of spruce forests by overlapping the layer of DEM. Moreover, we calculated the area of individual

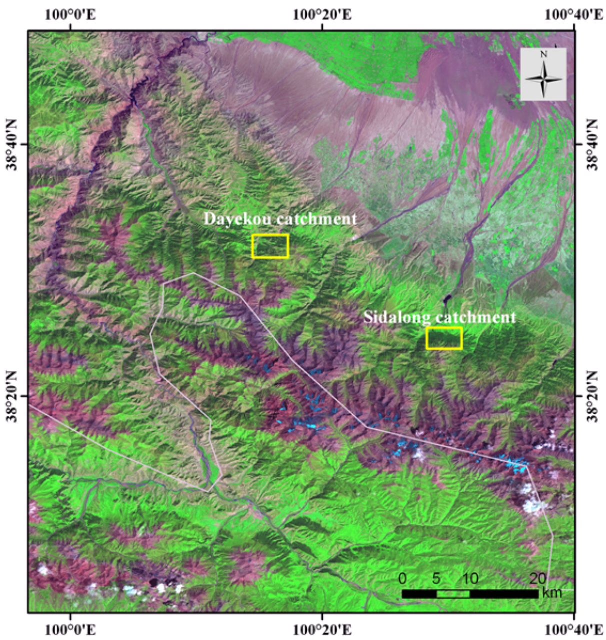

Figure 1 Location of the Dayekou and Sidalong catchments in the Qilian Mountains, northwestern China.

forest patches and their corresponding slopes to identify the proportion of suitable planting ranges.

1.1.2 Sample plot survey

We conducted four vegetation surveys (Table 1; plots located in the Dayekou catchment were included in Figure 2). For the first survey in August 2006, we selected three plots (30 m × 30 m) each in the Dayekou and Sidalong catchments. For the second survey in August 2007, we investigated more than 10 plots (30 m × 30 m) in the same study areas. For the third survey in August 2012, we investigated 21 plots (each 30 m× 30 m) along an elevation gradient in the Dayekou catchment. In the final survey in July 2013, we chose 9 large plots (100 m× 100 m) in the Dayekou catchment. Within each plot for each survey, the relative position, DBH, stand density, and age of each tree were recorded. To ensure an accurate and efficient sampling of stem coordinates (x, y), each plot was subdivided into a grid of 10 m × 10 m cells. The location of each measured tree was determined using a coordinate system established in each plot, and the age of each tree was determined both directly and indirectly, after He et al. 2010. Briefly, all older trees (DBH >10 cm) were cored as close to the ground as possible, and the ages were determined in the laboratory by counting the rings using a stereomicroscope; for younger trees (DBH >10 cm and taller than 1m), the ages were determined by counting the annual nodes; when the number of annual nodes could not be used to identify the age, the age was determined using annual ring counts. The ages of seedlings shorter than 1m were estimated based on the relationship ($y=8.1x+1.6$, $r^2 = 0.93$, $p < 0.01$) between age (y, years) and height (x, m) (He et al. 2010). Average annual soil moisture at a depth of 20 cm of the typical slopes in the Dayekou catchment was measured by ECH_2O sensors coupled in a 5TM system (Decagon Devices Inc., Pullman, WA, USA).

1.2 Spatial pattern analysis

Spatial heterogeneity is a common characteristic of natural forests (Wehenkel et al 2015). For forest managers, the appropriate scale of observation is that unit of area from which useful ecological information can be obtained; that includes the size, shape, and the separation distance between plots, and sampling margin (Král et al. 2014). Different stand structure characteristics can be obtained depending on the size of the sampling area. Therefore, we divided our large plots (100 m × 100 m) into different-sized areas (10m × 10m, 20m × 20m, 30m × 30m, 40m × 40m, 50m × 50m, 70m × 70m), and calculated the coefficients of variation (calculated as the ratio of the standard deviation to the mean) for DBH and density at the different scales. Based on the relationship between plot size and the corresponding coefficient of variation, we determined the smallest plot size that could be used to represent stand characteristics; this method can provide the basis of scale for forest spatial point-pattern analysis, and the theoretical basis for selecting the optimal size of a sampling unit for the layout and conversion to nearly-natural plantations. In addition, a t-test was used to detect the differences in average DBH and stand density between small plots (10 m × 10 m, 20 m × 20 m, 30 m × 30 m, 40 m × 40 m, 50 m × 50 m, 70 m × 70 m) and large plots (100 m × 100 m).

We analyzed the spatial distribution pattern of trees by adopting the method of point-pattern analysis (Ripley 1977; Haase 1995; Pommerening and Stoyan 2008; Jia et al. 2016). Point-pattern analysis takes into account the distance between an individual and other individuals in a population, rather than the distance to the nearest neighbor.

Table 1 Plot survey information for spruce forests.

Survey site	Time	Time of logging	Harvest type	Plot number	Plot area (m^2)	Stand density (trees ha^{-1})(Mean ± SD)	Mean age(yr) (Mean ± SD)
Sidalong	August 2006-2007	1970s	60% thinning	5	30 × 30	16153 ± 691	9 ± 2
Dayekou	August 2006-2007	1930s	60% thinning	5	30 × 30	1652 ± 112	61 ± 2
Sidalong	August 2006-2007	No logging	—	3	30 × 30	562 ± 71	107 ± 7
Dayekou	August 2012	Early 1900s	Clearcut	21	30 × 30	2376 ± 287	65 ± 5
Dayekou	July-August 2013	Early 1900s	Clearcut	9	100 × 100	1953 ± 239	62 ± 3

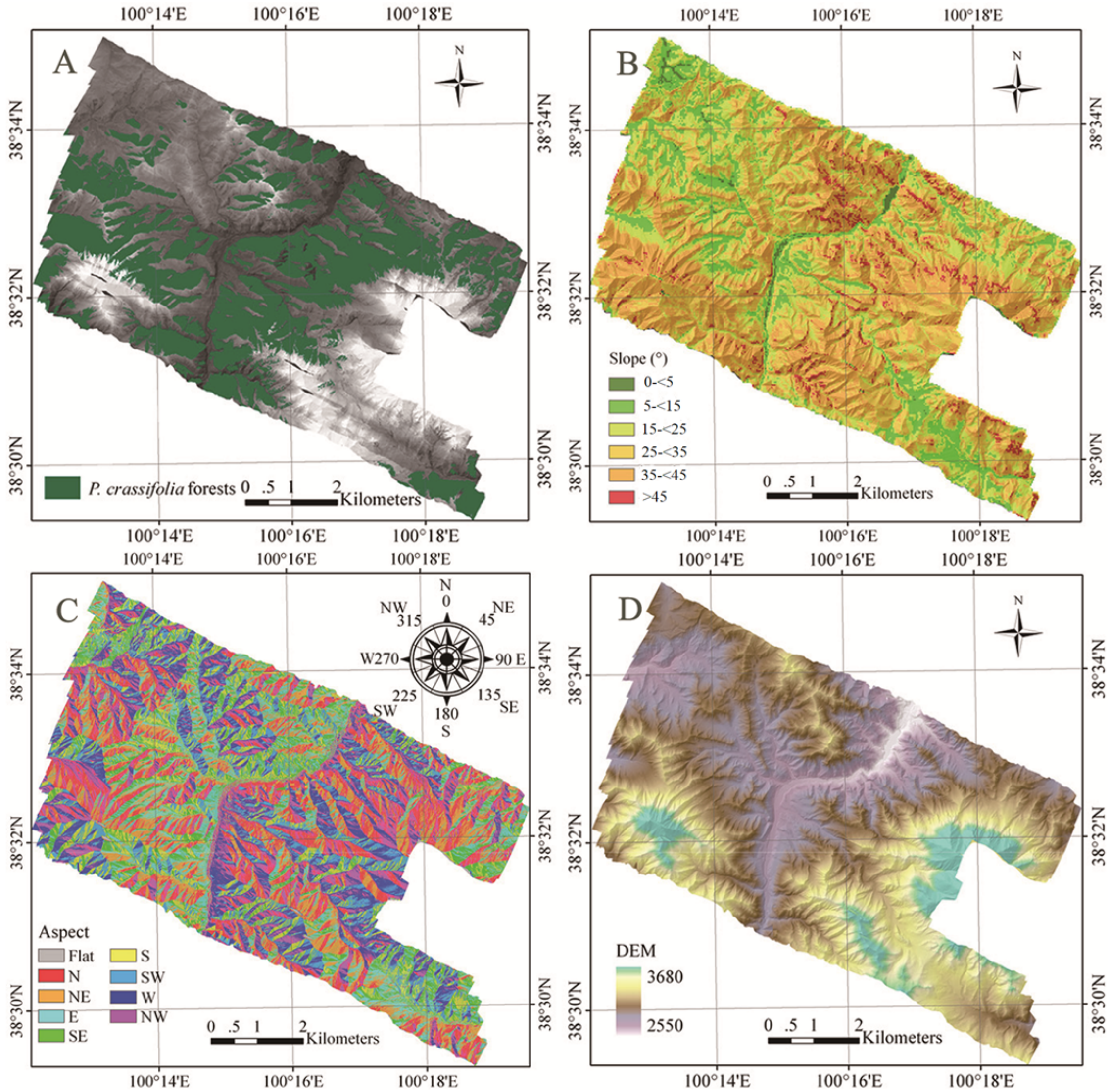

Figure 2 The spatial distribution (A), slope (B), aspect(C), and the DEM (D) in spruce patches in the Dayekou catchment.

We defined Ripley's K function as a random sample of individuals from a population that fell in a fixed point at the center of a circle, with r as the expectation within the radius of the circle. The calculation method of Ripley's K and the correction method for the edge effect can be found in Ripley (1977), Haase (1995), and Jia et al. (2016):

$$\hat{K}(r) = An^{-2}\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{I_r(u_{ij})}{w_{ij}} \qquad (1)$$

In the formula, r was the distance between plants, A was the area of the plot in m², n was the total number of plants in the analysed plot, u_{ij} was the distance between plant i and j, and w_{ij} is a weighting factor to correct for edge effects. When $u \leq r$, then $I_r(u)$ was 1; otherwise, when $u > r$, then $I_r(u)$ was 0. The weighting factor was the proportion of the circumference of the circle centered on point i and passing through point j, which was inside the bounds of the study area. Generally, $L(r)$, a transformed form of $K(r)$, was used to determine whether a particular point pattern deviated from Poisson distribution (Besag 1977):

$$L(r) = \sqrt{\hat{K}(r)/\pi} - t \qquad (2)$$

$L(r) = 0$ indicated random distribution; $L(r) < 0$ indicated uniform distribution, and $L(r) > 0$, aggregated distribution.

We obtained the simulation envelopes of $L(r)$ through Monte Carlo simulations based on a homogenous Poisson process, and calculated *L(r)* values for different spatial scales according to the actual distribution of population data (dot pattern). If *L(r)* value fell in the simulation envelope, the population data were randomly distributed; otherwise, data deviated from random distribution. If the population exhibited aggregated distribution, the value of *L(r)* that exceeded the upper limit of the interval was defined as the degree of aggregation and the corresponding distance was the aggregation distance (Rebertus et al. 1989). The aggregation dimension was defined as the area of a circle with the radius of the aggregation distance (Jia et al. 2016).

2 Results

2.1 Relationships between terrain factors and spatial distribution of spruce patches

We extracted the spatial distribution pattern, slope direction, slope, and the DEM of spruce patches from laser-radar and land-use data available for the study site (Figure 2). We defined 8 aspects, 6 classes of slope, and 5 altitude ranges (Table 2) in the study area, and determined their total area, and the corresponding distribution area of forest patches. Spruce patches on the N, NE, and NW aspects accounted for 73.35% of the forest area. Forest patches found on slopes ranging from 15° to 45° accounted for 81.38% of the total forest area, and those at altitudes from 2700 to 3300 m accounted for 97.53% of the total forest area. These results reflected the link between terrain parameters and the spatial distribution of spruce. Further, these results indicated terrain-associated thresholds beyond which the success of plantations would be uncertain; these thresholds can be used as guidelines in conversion efforts to near-natural spruce plantations

Some typical semi-shady slopes were not entirely covered by *spruce* patches (Figure 3), and lower moisture contents were detected on these slopes than shady slopes (Figure 3). We analyzed the proportion of the area of forest patches to semi-shady slopes for 39 slopes using laser-radar images and artificially-measured topographic data. We found that, for the NE and NW aspects, the proportion of forest patch-to-slope area ranged from 45% to 80%, with an average of 64%. Figure 4 shows spatial patterns of a spruce plantation, and illustrates that planting the entire slope may be an inefficient use of effort and financial resources.

2.2 Spatial heterogeneity of spruce forest structural characteristics

Spatial patterns in the natural forest exhibited a strong scale-effect. With our approach of dividing a large (100m × 100m) natural forest plot into progressively smaller plots, we found that with an increase in plot area, the coefficient of variation decreased for average DBH and density of spruce, and both relationships were characterized by a power function (Figure 5). When the plot area was > 0.25 ha (50m × 50m), the coefficient of variation for average DBH and average density of spruce tended to stabilize (Figure 5); this indicated that a plot with an area of 0.25 ha could be used as representative of the smallest plot scales, as this scale captured the heterogeneity and the distribution pattern of spruce. In addition, when plot area was > 0.25 ha, no significant differences were detected in average DBH and density between small and large plots (Table 3).

After we divided 9 large plots into 36 small

Table 2 The proportions of forest area to total area in different aspects, slopes, and altitudes at the study site.

Aspect	Area (km^2)			Slope (°)	Area(km^2)			Altitude (m)	Area(km^2)		
	Total	forest	%		Total	Forest	%		Total	Forest	%
Flat	0.12	0.00	0.02	0-5	1.23	0.09	0.45	<2700	4.07	0.02	0.12
N	16.65	6.10	31.58	5-15	7.79	1.77	9.14	2700-2900	11.13	2.15	11.12
NE	15.48	4.67	24.15	15-25	11.31	4.31	22.30	2900-3100	20.72	10.45	54.03
E	11.60	1.56	8.09	25-35	16.12	5.79	29.97	3100-3300	18.64	6.26	32.38
S	8.43	0.40	2.05	35-45	15.89	5.71	29.56	>3300	1.82	0.46	2.35
S	10.04	0.39	2.01	>45	3.99	1.66	8.58	-	-	-	-
SE	12.22	0.55	2.86	-	-	-	-	-	-	-	-
W	12.49	1.86	9.62	-	-	-	-	-	-	-	-
NW	12.95	3.79	19.62	-	-	-	-	-	-	-	-

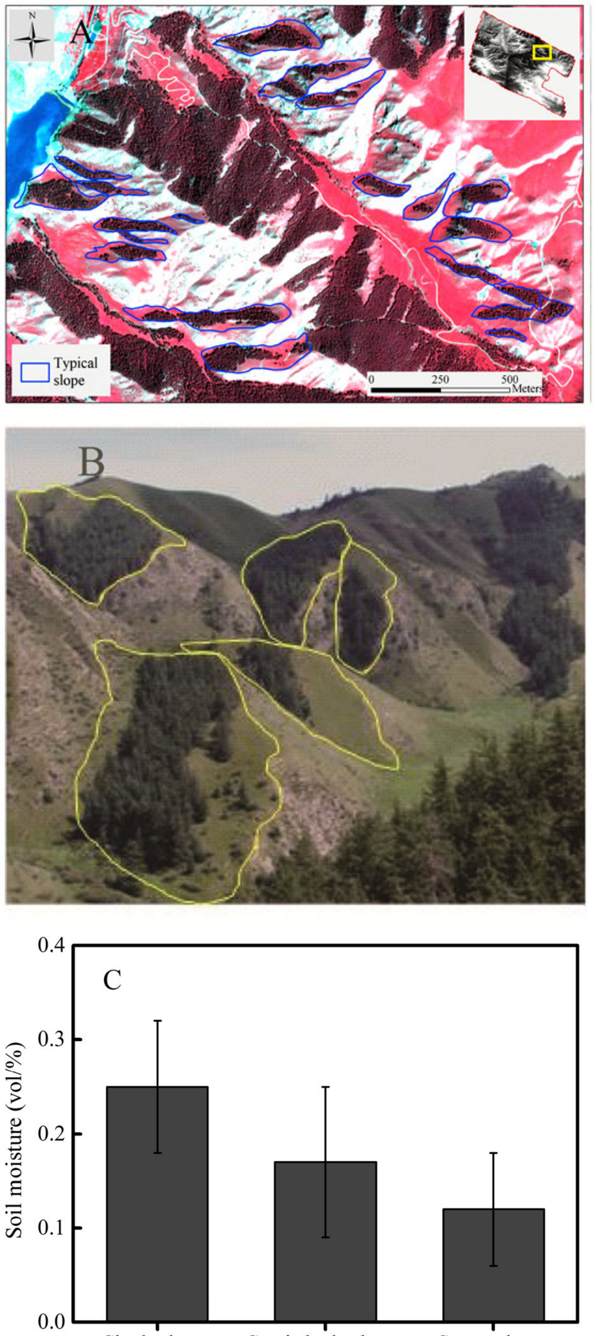

Figure 3 Distribution of spruce natural forest patches on semi-shady slopes. Blue boundaries in A and yellow boundaries around the forested areas in B indicate the boundaries of the typical semi-shady slopes in the Dayekou catchment. C: average annual soil moisture at a depth of 20 cm of the typical slopes in the Dayekou catchment.

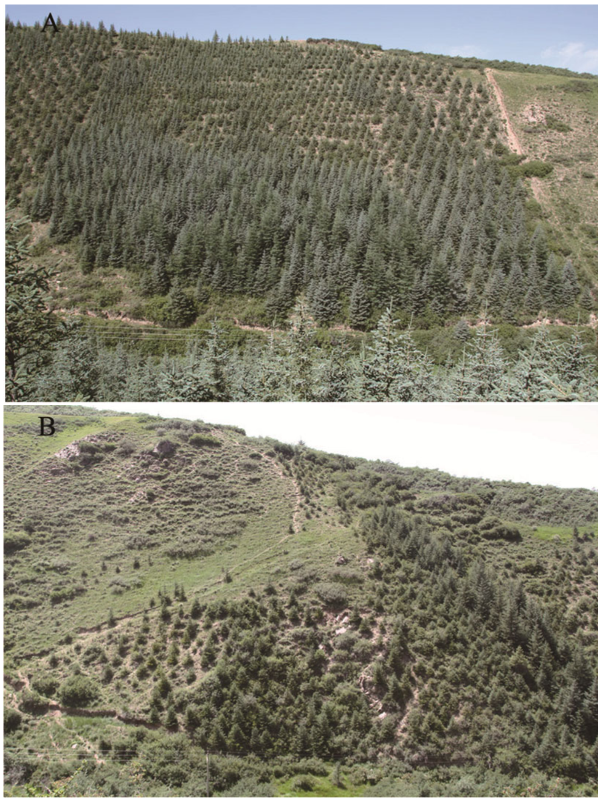

Figure 4 Variation in growth and distribution of spruce plantations on semi-shady slopes. A: a spruce plantation patch in the Dayekou catchment; B: a spruce plantation patch in the Sidalong catchment.

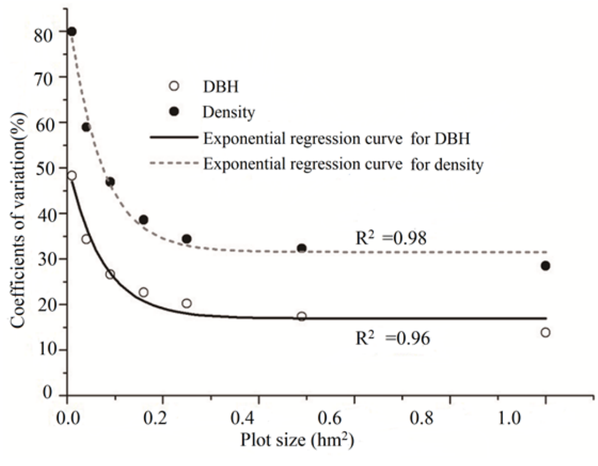

Figure 5 Change of the coefficients of variation with plot size for spruce average DBH and density.

plots, each with an area of 0.25 ha, and used point-pattern analysis at patch scale, the *L(r)* values exhibited large spatial variability, with a coefficient of variation of 60%. However, we could determine the spatial distribution of spruce based on the average *L(r)* value (Figure 6). We found that spruce trees exhibited an aggregated distribution pattern at a distance ≤ 23 m. When trees in a sample area were separated into two size-classes according to their DBH (saplings at DBH ≤ 10 cm and trees at DBH > 10 cm), saplings exhibited clustered

Table 3 Significance test of spruce density and DBH between small plots (10m × 10m, 20m × 20m, 30m × 30m, 40m × 40m, 50m × 50m, 70m × 70m) and large plots (100m × 100m).

Sample size (m^2)	Mean DBH (Mean ± SD)	*t*	*df*	*p*	Mean density (Mean ±SD)	*t*	*df*	*p*
10 × 10	12.6 ± 6.1	14.195	899	0.000	1913 ± 1561	0.013	899	0.990
20 × 20	11.5 ± 3.9	6.581	224	0.000	1963 ± 1151	0.009	224	0.993
30 × 30	11.0 ± 2.9	4.055	99	0.000	1956 ± 918	0.041	99	0.967
40 × 40	10.9 ± 2.5	2.969	48	0.004	1926 ± 742	-0.269	48	0.789
50 × 50	10.6 ± 2.1	1.990	35	0.054	1973 ± 737	0.165	35	0.870
70 × 70	10.8 ± 2.0	1.694	15	0.111	1955 ± 622	-0.177	15	0.862
100 × 100	10.3 ± 1.9	0.695	8	0.506	1953 ± 521	0.262	8	0.800

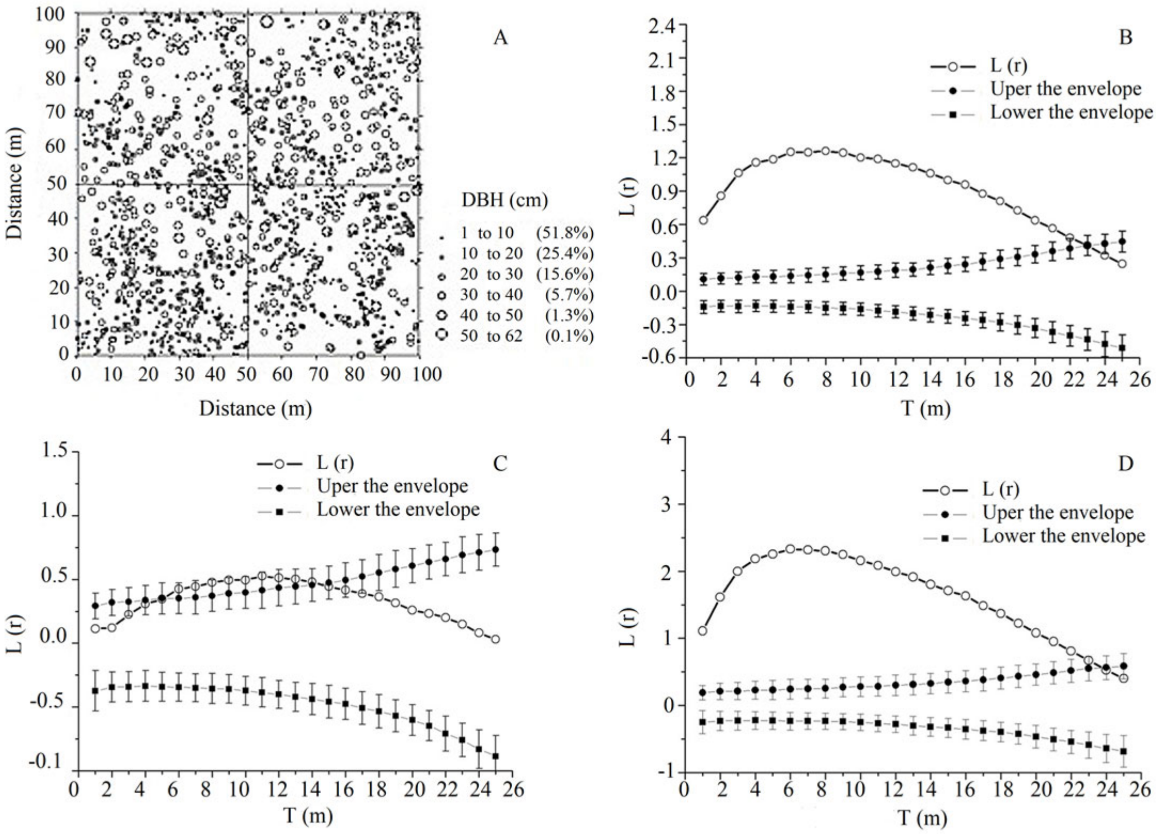

Figure 6 Tree location maps (A) and point-pattern analysis of spruce in a fixed-scale plot (100 m × 100 m). B: Diagram of all trees; C: Diagram of trees with DBH > 10 cm; D: Diagram of trees with DBH≤10cm. L(r) value was used to determine whether a particular point pattern deviated from the Poisson distribution (L(r) = 0 indicated random distribution, L(r) <0 indicated uniform distribution, and L(r)> 0, aggregated distribution); r was the corresponding scale (m).

distribution at a distance ≤ 23 m; trees, however, exhibited an aggregated distribution pattern at distances from 5 to 14 m, and were randomly distributed at other distances.

2.3 Changes in stand structure of spruce forest over time

The average density of spruce trees exhibited an aggregated distribution pattern at a distance ≤ 23 m. When trees in a sample area were separated into two size-classes according to their DBH (saplings at DBH ≤ 10 cm and trees at DBH > 10 cm), saplings exhibit natural forest without logging disturbance was 562 ± 71 trees/ha. With silvicultural thinning to 40%, density reached 16,153 ± 691 trees/ ha 30 years after treatment, and decreased to 1,652 ± 112 trees / ha 70 years after treatment (Table 1). The average age of undisturbed natural forest was 107 ± 7 years, and ages of secondary forests recovering for 30 and 70 years were 9 ± 2 and 61 ± 2 years, respectively

(Table 1). We found that the stand density in natural forests of spruce was negatively correlated with mean DBH, and the relationship was characterized by an exponential function (R^2 = 0.62) (Figure 7).

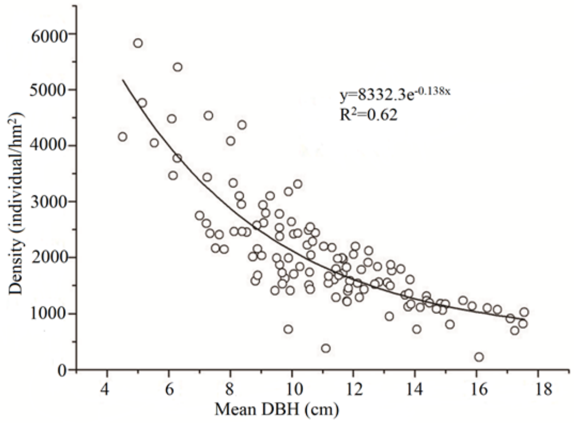

Figure 7 Relationship between spruce density and mean DBH

3 Discussion

As a result of the interacting environmental factors, such as climate, topography, soils, and hydrology, the landscape in the Qilian Mountains exhibited a mosaic of patches of grassland, scrubland, and forest. In our study sites, 97.53% spruce trees were distributed at altitudes ranging from 2700 to 3300 m, where the main control factors were precipitation and temperature (He et al. 2013; Chen et al. 2015). At lower altitudes, mean annual precipitation (MAP) was lower, and mean annual temperature (MAT) higher, resulting in higher evapotranspiration and lower soil moisture than at higher elevations. This had become a major limiting factor for forest patches extending down slopes. However, at higher altitudes, precipitation and soil moisture were not key limiting factors for the distribution of forest patches; instead, mean annual and minimum temperatures determined the distribution of forest patches (He et al. 2013). Spruce patches were found mainly on slopes ranging from 15° to 45°. On gentle slopes (< 5°) at low elevations, forest patches accounted for only 7.3% of the area, mainly due to low soil moisture conditions induced by long-term direct sunlight, and high evapotranspiration. In this arid mountain region, slope aspect was the main factor controlling the spatial distribution pattern of forest patches; different slope aspects exhibited different soil moisture conditions. On shady slopes, spruce patches covered almost the entire slope, and were large. However, on semi-shady slopes, due to limited water conditions compared to shady slopes, forest patches covered only a percentage of the slope area (Figure 3). We concluded that when afforesting semi-shady slopes, 64% of the slope area may be planted; planting the entire slope may be an inefficient use of effort and financial resources.

Forest structure is both, a product of and a factor in ecosystem processes and biological diversity, and information about forest structure provides an essential basis for the analysis of forest ecosystem disturbance (Wehenkel et al. 2015). Due to the high degree of heterogeneity existed in the spatial pattern in the natural forest, the information about forest structure obtained in the field survey was linked to the plot scale (Paluch 2007; Král et al. 2014). It has been widely observed in previous studies that the spatial variability of stand-structural parameters decreased with plot size and then stabilized at a specific range of plot sizes (Paluch 2007; Král et al. 2014); the minimum plot areas that provided a balanced distribution of stand-structural parameters depended on the particular tree species (Wehenkel et al. 2011). Our results confirmed those of previous research to some extent, and a plot area of 0.25 ha can be used as the minimum management plot for spruce forests. When plot area was > 0.25 ha, the acquired stand characteristics of spruce exhibited more accurate spatial representation than did those obtained at smaller scales. A previous modeling study by Du et al. (2015) also reported similar results in a spruce secondary forest. In addition, point-pattern analysis of the 9 large plots indicated that spruce trees also showed a specific distribution pattern within the range of transect lengths < 23 m. Therefore, we speculated that a plot area of 0.25 ha could be used as the most efficient plot scale for the management of spruce plantations. When converting to close-to-nature spruce forests, partial logging and group felling can be conducted at the scale corresponding to the distribution pattern of natural forests. Generally, the spatial variability of stand-structural parameters is related to the size, shape, and the separation distance of sampling plots, and successional stages (Král et al. 2014). Thus, to determine the appropriate scale and spatial pattern for the management of spruce planted forests in the region, long-term studies conducted at different successional stages on the shape and the separation distance of sampling plots are needed.

Forest disturbance is ubiquitous, and it leads to spatial heterogeneity of resources, including light, temperature, nutrients, moisture, and other environmental conditions. Post-disturbance changes in the environment influence to varying degrees the physiological and ecological processes of the dominant species, species composition, and the succession trajectory (Hubbert et al. 2006; Burton et al. 2009; Rozas et al. 2009). In the year following harvesting disturbance in a spruce forest, a large number of seedlings was observed. In the subsequent 30 years, forest density exhibited an exponential increase, then decrease, until it gradually stabilized, probably as a result of intra-specific competition (Table 1). Finally, the forest entered a self-thinning stage and exhibited characteristics of a different age structure, with an increase in size of individual trees (He et al. 2010). For example, in about 30-year-old planted spruce forests, forest gaps could be created to improve the ingrowth rate of understory shrubs and seedlings, and to gradually form a different age structure (He et al. 2010). In addition, we found that the stand density of spruce was negatively correlated with DBH and the relationship was characterized by an exponential function (R^2 = 0.62) (Figure 7). The significance of relationships between density and the size of the average tree (such as diameter, height, biomass or volume) have been demonstrated for a wide spectrum of species under self-thinning conditions (Zeide 2010). There is a considerable diversity of views on the processes causing self-thinning, prediction variables, and analytical forms of models. The most popular models were proposed by Reineke (1933) and Yoda (1963). The results of our study confirmed the models proposed by Yoda, and provided important references for density control and adjustment in spruce plantations. Stand density can be adjusted according to the function of density and DBH in natural forests (Figure 7), thus promoting succession.

4 Conclusions

Based on LiDAR and ground-survey data, we determined critical thresholds for the spatial distribution, structure, and succession trajectory in spruce natural forests in the Qilian Mountains. Our results have several important implications for spruce plantation management: (1) spruce plantations will be effective on the N, NE, and NW slopes, at elevations between 2700 and 3300 m, and on slopes at 15° to 45°. Further, planted forest patches should occupy less than 64% of the slope area on semi-shady slopes (NE, NW); (2) spatial patterns of stand characteristics in spruce forest plots exhibited a strong scale-effect, and a specific distribution pattern could be found within the range of transect lengths less than 23 m; when the plot area was > 0.25 ha, the spatial variability of stand-structural parameters tended to stabilize. Thus, we speculated that a plot area of 0.25 ha could be used as the most efficient plot scale for the management of spruce plantations; (3) during the conversion of planted forests to near-natural plantations, partial logging can be used to create canopy gaps to allow the development of the sapling stage, and gradually form the desired age structure. The intensity of partial logging can be determined from the negative exponential function relationship between spruce stand density and DBH.

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