

## SPATIAL PATTERNS AND CORRELATIONS OF TREES IN A NATURAL SECONDARY FOREST OF WHITE BIRCH WITH UNDER-PLANTING OF QINGHAI SPRUCE IN A HIGH-COLD REGION OF WESTERN CHINA

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### Abstract

We investigated the feasibility of artificially promoting forest succession by planting Qinghai spruce (*Picea crassifolia* Kom.) trees in secondary natural white birch forests (*Betula platyphylla* Suk.). Survey data in a 100 × 100 m sample plot were analyzed using Wiegand-Moloney's *O*-ring function to determine the spatial point patterns and correlations (intraspecific and interspecific) between two *DBH* (diameter at breast height) classes of white birch and Qinghai spruce. Results showed that both the white birch and the Qinghai spruce populations were growing, and that the spatial point patterns of all of the *DBH* classes fit a random distribution. However, the fitted curves of the Qinghai spruce trees in *DBH* classes 2 and 3 were waved and indicated clustered and regular distributions alternately at different scales. The intraspecific correlations changed from negative to positive, and Qinghai spruce showed greater negative correlations than white birch. The interspecific correlations also primarily changed from negative to positive, and strong interspecific competition dominated the two species, with the smaller trees suffering serious stress from the larger trees of the other species. The biological characteristics of the white birch were fast-growing, photophilic, and shade-intolerant, while the Qinghai spruce were slow-growing and shade-tolerant. These characteristics can be considered as key factors behind the current spatial patterns. In addition, impractical planting methods of the Qinghai spruce might be another important cause of the interspecific competition; therefore, ecological thinning of the current forest is advised.

**Key words:** Spatial point pattern; Wiegand-Moloney's *O*-ring function; Forest regeneration; Forest management.

### Introduction

The spatial patterns of species have always been a research focus in ecology (Dale, 1999; Pielou, 1969; Wiegand & Moloney, 2004). Population distribution patterns are the result of long-term adaptations of plants species to environmental conditions (Baack, 2005; Ewela & Mazzarino, 2008; Lejeune & Tlidi, 1999; Niggemann & Bialozyt, 2012), and are known as the configuration status or distribution status of the individuals in horizontal space.

Spatial distribution patterns can illustrate the dynamic changes in the species and community, the biological characteristics of the population (e.g., life history strategies, light, shade), the ecological processes (seed diffusion, intraspecific and interspecific competition, interference), and the relationship between with environmental factors (Dale, 1999; Druckenbrod *et al.*, 2005; Zhang *et al.*, 2015). Thus, the study of spatial patterns can deepen our understanding of community structure, and explore the formation and support mechanisms of biological diversity of plant communities, to correctly evaluate and properly manage forest communities (Getzin *et al.*, 2008; McDonald *et al.*, 2003; Wang *et al.*, 2010).

As such, the close association between spatial patterns and ecological processes, and quantitative analysis of the structure and formation processes, has become the main target of ecologists (McIntire & Fajardo, 2009; Tilman & Kareiva, 2005; Tuda, 2007). There are many methods to study spatial distribution patterns, such as quadrat sampling, point pattern analysis, and fractal theory; however, point pattern analysis is the most important and most commonly used method in plant

ecology researches (Perry *et al.*, 2006; Richard *et al.*, 2009; Wiegand & Moloney 2004).

The theory of point pattern analysis was suggested by Ripley (1977). This method maps all individual plants in the study area (Wiegand *et al.*, 2013), and then quantitatively analyses the characteristics of the pattern to verify the formation processes of the pattern and suggest the potential mechanism of formation. This method makes full use of spatial point information, and can provide comprehensive spatial scale information, and so can describe population spatial patterns and interspecific relationship at any scale.

Ripley's *K*-function (Ripley, 1981), the most widely known method in spatial point pattern analysis (Wiegand *et al.*, 2013), is a second order statistics method that considers the edge effect (Batista & A. Maguire, 1998; Wells & Getis, 1999; Wiegand, 2004; Wiegand & Moloney, 2004). This method uses all of the information within the circle of the radius of a distance (scale) *r*, and produces an accumulative function that contains information over a range of scales. However, this effectively means that the effects over larger scales are confounded with those over shorter distances (Condit *et al.*, 2000; Schurr *et al.*, 2004; Wiegand & Moloney, 2004; Zhang, 2011). Wiegand-Moloney's *O*-ring statistical approach, uses rings with radius *r* and width  $\omega$ , instead of circles, and has the advantage that specific distance classes can be isolated. The accumulative *K*-function can detect an aggregation or regularity up to a given distance *r* and is, therefore, appropriate if the process in question (e.g., the negative effect of competition) only operates at a certain distance. Conversely, the *O*-ring approach can detect aggregation or dispersion at a given distance *r* (Wiegand & Moloney, 2004).

Choosing a correct null hypothesis is crucial for the effective use of the spatial point pattern method. Complete spatial randomness (CSR) is the simplest and most commonly used model (Wiegand & Moloney, 2004). However, because of the complexity of the spatial process, different ecological processes may form the same spatial pattern (Barot *et al.*, 1999; Levin, 1992; Wiegand *et al.*, 2003). Meanwhile, spatial pattern and scale depend on each other, and spatial patterns at specific scales may have specific causes (Wiegand *et al.*, 2007). Therefore, it is difficult to demonstrate a complex ecological process using only the CSR test. More complex null models are needed, such as the Heterogeneous Poisson process (HP), nested double-cluster process, Poisson cluster process, and random labeling method.

Recently, studies are focused on spatial distribution patterns and association analyses of dominant populations (Hanus *et al.*, 1998; Hao *et al.*, 2007; Li *et al.*, 2008). Analyzing the spatial patterns and interspecific associations of individuals of different age classes enables us to better understand spatial and temporal dynamics of plant communities, as well as growth factors of young age class individuals (Li *et al.*, 2008). Although it is impractical to measure the ages of all trees in a forest, generally, trees in the same age class have similar heights and DBH (diameter at breast height) in the same habitat (Frost & Rydin, 2000). Hence, for practical purposes, age distribution is generally replaced by height or DBH distributions (Akhavan *et al.*, 2012; Arévalo, 2013; Pommerening *et al.*, 2011).

In the present study, we analyzed the spatial patterns and correlations within a secondary natural white birch (*Betula platyphylla* Suk.) forest planted with Qinghai spruce (*Picea crassifolia* Kom.). We hypothesized that larger trees affected the growth of smaller trees of two different DBH classes. A univariate *O*-ring function [ $O_{11}(r)$ ] with HP was used to analyze the spatial distribution patterns of different DBH classes for white birch and Qinghai spruce, and a bivariate *O*-ring function [ $O_{12}(r)$ ] was used to analyze intraspecific and interspecific associations between the two species. Our objectives were to: (1) explore the spatial patterns and correlations of the two species among different DBH classes; (2) examine the processes which may have contributed to these patterns; (3) evaluate the rationality of the current planting patterns that plant plenty Qinghai spruce trees under secondary white birch forest to promote artificial forest succession and provide theoretical support with statistical analysis.

Results from this study can help explore the causes of population dynamics and distribution patterns, and support the theoretical basis of population regeneration, dynamic accommodation, self-sustainability, and community succession. This can inform sustainable management, species recovery, and reconstruction of water conservation forests in high-cold regions of western China.

## Material and Method

**Overview of the study area:** The study area Fig. 1 was the Baoku Forest Farm, which has an undulating mountainous terrain comprised of ravines and complicated topography. It is located at the foot of the Daban Mountain, northwest of Datong County, Xining City, Qinghai Province. The

geographic coordinates are 36°55′–37°32′ N and 100°52′–101°39′ E, and the altitude is 2610–4600 m. The main arbor species were white birch (*Betula platyphylla*), Qinghai spruce (*Picea crassifolia*), Cathay poplar (*Populus cathayana*), and China savin (*Sabina chinensis*). The main shrub species were sea buckthorn (*Hippophae rhamnoides*), alpine willow (*Salix oritrepha*), azalea (e.g., *Rhododendron thymifolium*, *Rhododendron anthopogonoides*, *Rhododendron przewalskii*), bush cinquefoil (*Potentilla fruticosa*), and barberry (*Berberis thunbergii*).

The Baoku Forest Farm has an edge zone affected by the southwest monsoon. It has a cold semi-humid climate with significant plateau continental climate characteristics. Due to the terrain and elevation, the general characteristics are long winters and short summers with no obvious dry and wet seasons, an annual average temperature of 2.4°C, 73 dof active accumulated temperature, annual sunshine of 2596.5 h, annual frost-free period of 45–60 d, with no absolute frost-free period, and annual rainfall of 549.9 mm.

**Sample plot study:** In this area, most of the arbor species are on the north of mountains with slope of 20°–30°. The main arbor species in Baoku forest farm before the 1950s was Qinghai spruce, but there was widespread destruction of this species because of overexploitation in the 1950s. As a result, the main arbor species is currently white birch, which has grown in deforested areas. To promote artificial forest succession, 3-year-old Qinghai spruce seedlings were planted along contour lines (row widths of 5–15 m) with three Qinghai spruces planted in one hole (holes were 1.5–2 m apart) under the white birch in 1982. This study was conducted in August 2012 in a 100 m × 100 m sample plot (37°9′47″ N, 101°34′23″ E, with slope of 21° and aspect of 310°) of secondary natural white birch forest. In this plot, For each tree, height, DBH, crown breadth, and the X and Y coordinates (using one angular point of the sample plot as the original point in a Cartesian coordinate system) were measured and recorded Table 1 and Fig.2

**Diameter structures of white birch:** To analyze the species structure dynamics, the DBH structure was used and the two species were classified using the DBH. White birch was classified into four stages according to historical and local forest farm worker reports: B1 (seedling, DBH < 3 cm); B2 (sapling, 3 cm ≤ DBH < 7 cm); B3 (mid-tree, 7 cm ≤ DBH < 15 cm); and B4 (adult tree, DBH ≥ 15 cm).

**Diameter structures of Qinghai spruce:** Qinghai spruce was classified using a similar method as for the white birch; however, as the Qinghai spruce trees were planted in 1982 and produce seeds that require at least 30 years to germinate, no new seedlings were found in these investigation. Therefore, the DBH structure did not represent the age structure; instead, it represented the growth status of Qinghai spruce under white birch forest conditions. According to historical and local forest farm worker reports, the DBH of 30-year-old Qinghai spruce can reach 11 cm under normal conditions. Therefore, the DBH structure of Qinghai spruce was classified into four stages: S1 (severe stress, DBH < 3 cm), S2 (moderate stress, 3 cm ≤ DBH < 7 cm), S3 (light stress, 7 cm ≤ DBH < 11 cm), and S4 (normal, DBH ≥ 11 cm).

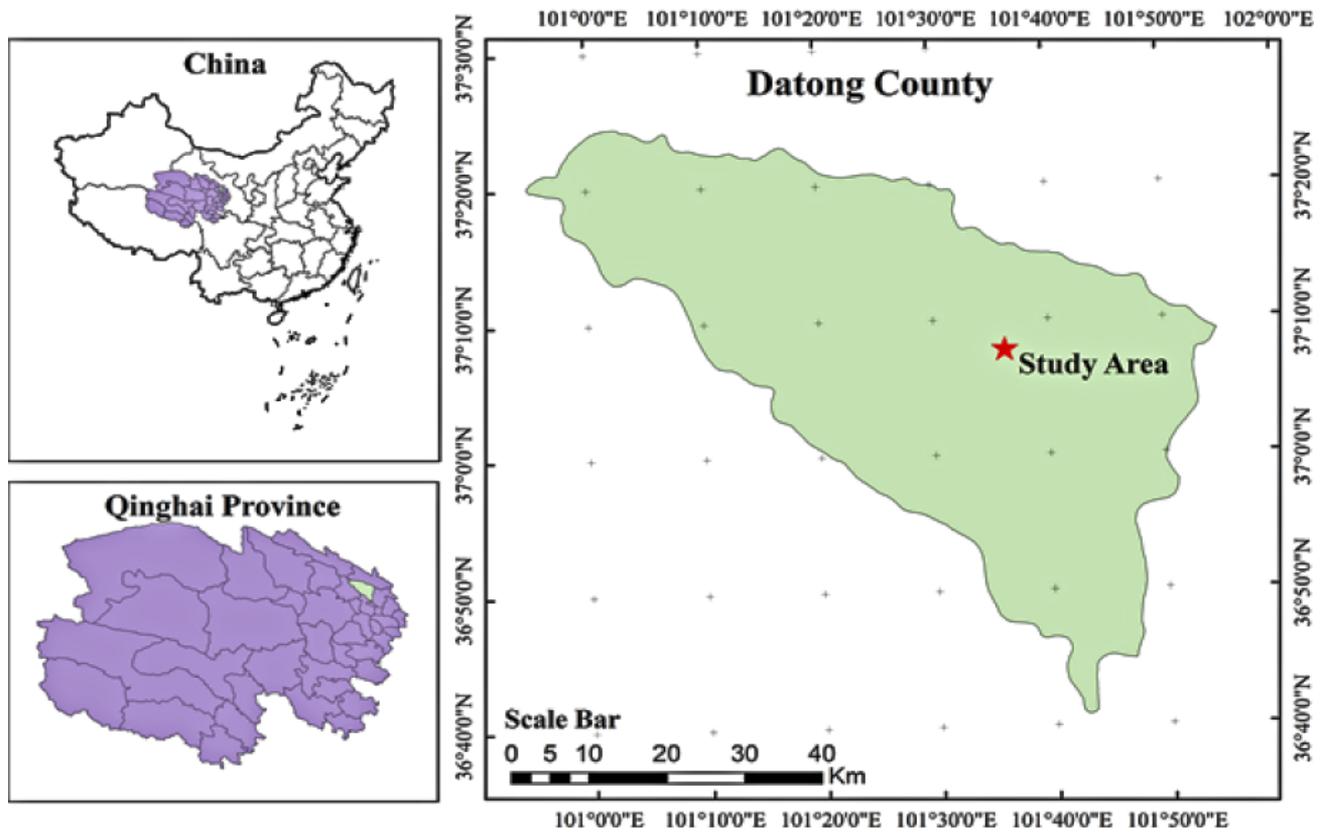


Fig. 1. Location of the study area.

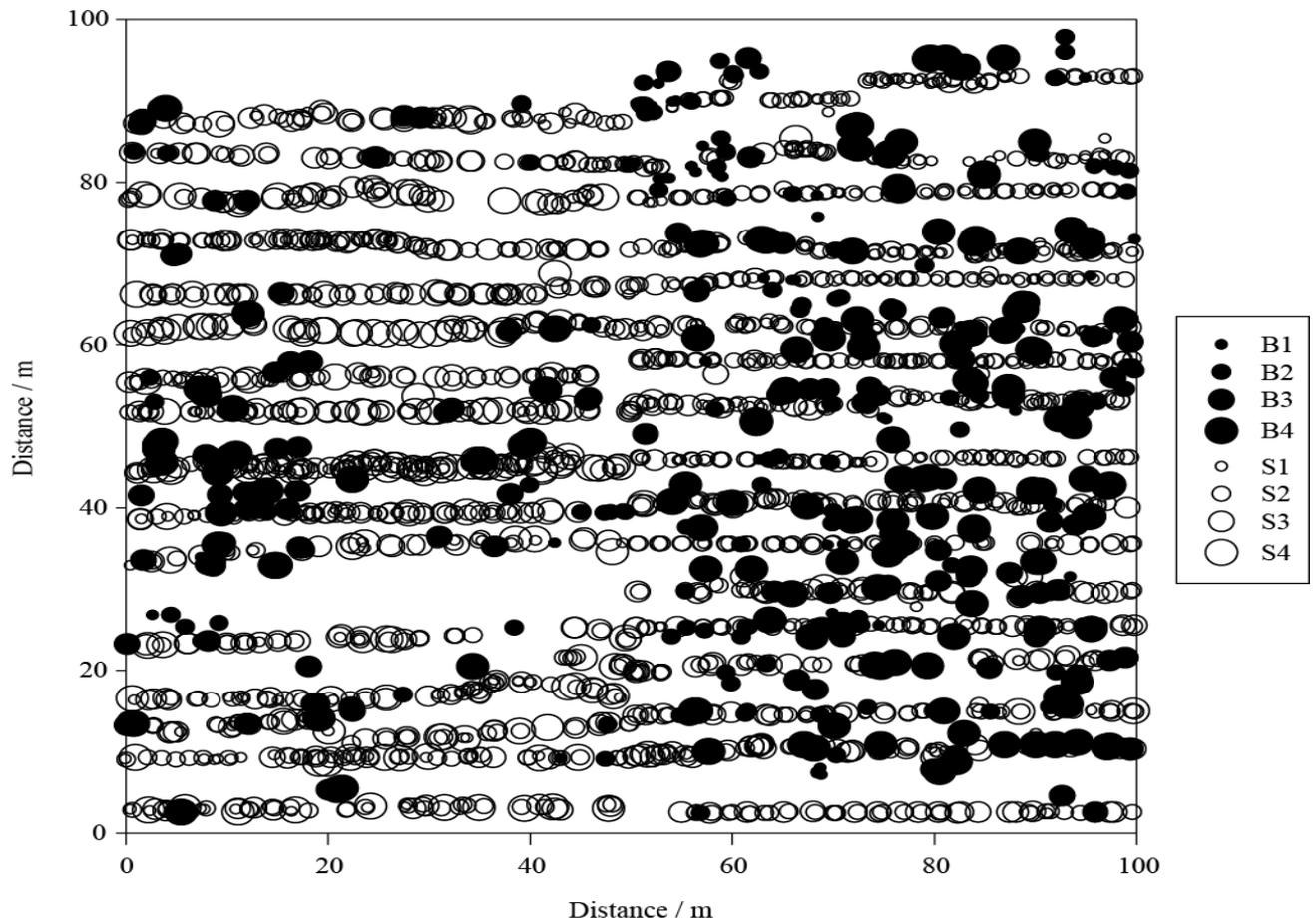


Fig. 2. Coordinates of white birch and Qinghai spruce in the sample plot.

**Table 1. The stand structure of two species in the sample plot. B and S indicate white birch and Qinghai spruce, respectively. Numbers 1, 2, 3, and 4 indicate DBH classes.**

Species	Count	Crown (m)	Height (m)	Diameter (m)	Canopy density
S1	339	1.16 ± 0.41	2.51 ± 0.83	2.1 ± 0.5	0.8
S2	1046	1.9 ± 0.53	4.74 ± 1.37	4.74 ± 1.1	
S3	510	2.56 ± 0.55	6.92 ± 1.52	8.37 ± 1.07	
S4	159	2.95 ± 0.55	8.28 ± 1.82	13.95 ± 3.19	
B1	64	1.29 ± 0.52	2.88 ± 1.08	1.94 ± 0.62	
B2	138	2.04 ± 0.71	4.75 ± 1.44	4.44 ± 1.07	
B3	129	3.21 ± 0.76	8.34 ± 2.04	10.26 ± 2.3	
B4	155	4.1 ± 0.97	12.2 ± 3.06	23.04 ± 6.54	

**Data analysis:** As defined by Wiegand & Moloney (2004), the O-ring statistic  $O_{12}(r) = \lambda_2 g_{12}(r)$  gives the expected number of points in pattern 2 at distance  $r$  from an arbitrary point of pattern 1:

$$O_{12}^w(r) = g(r) \lambda_2 = \frac{1/n_1 \sum_{i=1}^{n_1} \text{points}_2 [R_{1,t}^w(r)]}{1/n_1 \sum_{i=1}^{n_1} \text{Area} [R_{1,t}^w(r)]} \quad (1)$$

where,  $n_1$  is number of points in pattern 1,  $R_{1,t}^w(r)$  is a ring with width  $w$  at distance  $r$  from an arbitrary point of pattern 1,  $\sum_{i=1}^{n_1} \text{points}_2 [R_{1,t}^w(r)]$  is the number of points in pattern 2 in  $R_{1,t}^w(r)$ , and  $\sum_{i=1}^{n_1} \text{Area} [R_{1,t}^w(r)]$  is the area of  $R_{1,t}^w(r)$ .

The univariate O-ring Statistic  $O(r)$  is calculated by setting pattern 2 equal to pattern 1. Specific theories concerning the O-ring functions refer to a related paper (Wiegand & Moloney, 2004).

HP model is on the basis of density function, which can eliminate the influence of large scale environmental heterogeneity, and is mainly used to simulate the relationship between species and its habitat. For the univariate analysis, the HP null hypothesis model was used to eliminate the possible effects of uneven density by moving the window to ensure that the random distribution of spatial points was limited to a radius < 10 m. The null hypothesis was accepted if the function value of the Monte Carlo simulation results was between the upper and lower envelope line, which indicated that the spatial distribution was random. The spatial distribution was considered clustered if the result was above the upper envelope line and regular if it was below the lower envelope line.

For the bivariate analysis, the HP null hypothesis model was used to eliminate possible effects of uneven density. An antecedent condition null hypothesis was then used to conduct the spatial correlation tests under the assumption that larger trees can shelter smaller trees of two different DBH classes. The null hypothesis was accepted if the function value of the Monte Carlo simulation results was between the upper and lower envelope line, which indicated that there was no correlation between the two different DBH classes. A positive correlation was observed if the result was above the upper envelope line and a negative connection if it was below the lower envelope line.

All analyses were conducted using Programita 2010 software (Wiegand, 2004; Wiegand & Moloney, 2004), and 99% confidence intervals were calculated using 99 Monte-Carlo simulations and a ring width of 3 m.

## Results

**Diameter distributions:** As shown in Table 1, numbers of Qinghai spruce in each DBH class were class 2 > class 3 > class 1 > class 4, which was close to a normal distribution and showed that the Qinghai spruce population faced strong competition as all of the Qinghai spruce trees were planted in the same year. In contrast, the order of white birch was class 4 > class 2 > class 3 > class 1, the result showed that greater trees dominate the white birch population and the generation speed was slow down.

The distributions of the two species within the sample plot were also plotted in Fig. 2. The seedlings and samplings of the white birch were close to adult trees, but the Qinghai spruce trees with normal growth status were mainly distributed in the forest gaps of adult white birch trees. This indicated that the adult white birch potentially disturbed the growth of Qinghai spruce, and that large Qinghai spruce trees influenced the spread of white birch seeds.

### Spatial point patterns for different DBH (age) classes:

The spatial pattern analysis of white birch is shown in Fig. 3. All of the DBH classes of white birch followed a random distribution. B1 followed a slightly regular distribution at 11 m and slightly clustered distribution at 37 m; B2 followed a clustered distribution at 1–2 m and slightly regular distribution at 44 m; B3 followed a slightly clustered distribution at 33 m; and B4 followed a slightly regular distribution at 43 m.

Fig. 4 illustrates the spatial pattern analysis of the Qinghai spruce; all of the DBH classes of Qinghai spruce fit a random distribution. S1 only followed a slightly clustered distribution at 11 m; S2 followed a cluster distribution at 6 m, 11 m, 22 m, 27–28 m, 32–33 m, 37–39 m, 43 m, and 48–49 m, and a regular distribution at 2–3 m, 8–9 m, 19 m, 24–25 m, 30 m, 35–36 m, 40–41 m, and 45–46 m; S3 followed a slightly clustered distribution at 6 m, 11 m, 21–22 m, 27–28 m, 32 m, and 43 m, and a slightly regular distribution at 2–3 m, 19 m, 24–25 m, 40–41 m, and 46 m; S4 followed a slightly clustered distribution at 17–18 m and 42–43 m.

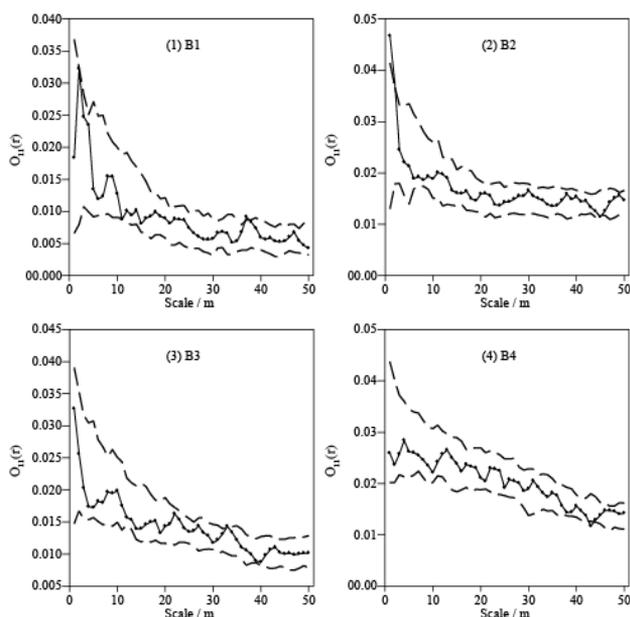


Fig.3. Spatial point patterns of white birch. Solid lines indicate the sample statistic; dashed lines represent confidence intervals.

**Intraspecific correlations between two different DBH (age) classes:**

Fig.5 illustrates the relationships between two different *DBH* (age) classes of white birch. B2 and B1 showed a slightly positive correlation at 1–3 m, but were not correlated at other scales; B3 and B1 showed a negative or no correlation at 1–23 m, no correlation at 24–47 m, and a positive correlation at 48–50 m; B3 and B2 showed a negative correlation at 120 m, no correlation at 21–35 m, and a positive correlation at 36–50 m; B4 and B1 showed a negative correlation at 1–8 m, no correlation at 9–47 m, and a positive correlation at 48–50 m; B4 and B2 showed a negative correlation at 1–19 m, no correlation at 20–39 m, and a positive correlation at 40–50 m; B4 and B3 showed a negative or no correlation close to negative at all scales. Overall, the correlations between the nearest two age classes of white birch tended to increase with age, and the correlations tended to be closer to negative. Larger differences between the age classes tended to change the correlations from negative to no correlation to positive as scale increased.

The relationships between two different *DBH* classes of Qinghai spruce are illustrated in Fig.6. S2 and S1 showed no correlation, and positive correlations at 6 m, 10–11 m, and 22 m, and negative correlations at 2–3 m, 8–9 m, 18–19 m, 29–30 m, 34–35 m, 40–41 m, 45 m, and 49–50 m. However, there was an overall tendency of correlations to change from no correlation to a negative correlation as scale increased. All other classes illustrated opposite, but similar, tendencies as the correlations gradually changed from negative to no correlation to positive as spatial scale increased. From Fig.6, it is evident that the negative correlation mainly occurred at 0–42 m and no correlation and the positive correlations mainly occurred at 43–50 m. Overall, the competition between the larger *DBH* classes of Qinghai spruce tended to be stronger than that between the smaller *DBH* classes. In addition, the negative correlations were the dominant trend and the correlations tended to become positive as the spatial pattern increased.

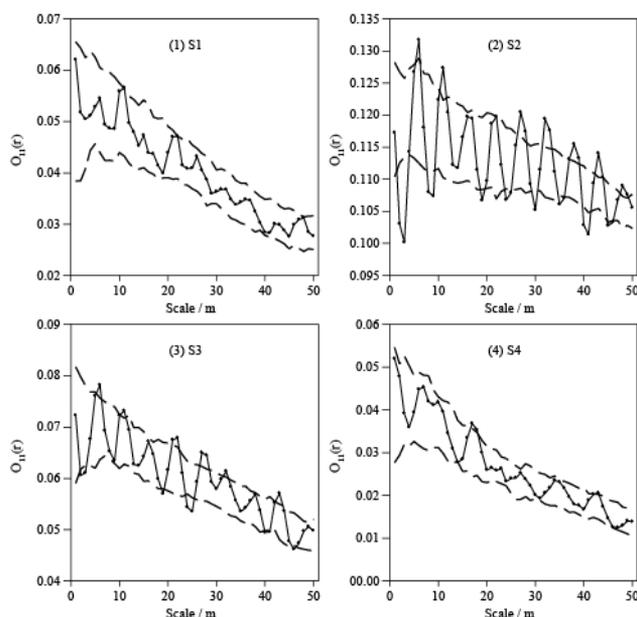


Fig.4. Spatial point patterns of Qinghai spruce. Solid lines indicate the sample statistic; dashed lines represent confidence intervals.

Qinghai spruce generally showed stronger negative correlations and showed negative correlations at more scales than white birch, which indicated that intraspecific competition in the Qinghai spruce population is stronger than in the white birch population (Fig.5 and Fig.6).

**Interspecific correlations between two different DBH (age) classes:**

Fig.7 illustrates the spatial correlations between white birch trees affected by Qinghai spruce trees. B2 and S1 clearly exhibited a negative correlation at 1–10 m, but no correlation at 11–50 m. The interspecific correlations between other *DBH* classes showed a similar tendency, as the correlations changed from negative to no correlation to positive with increasing scale. B3 and S1 showed no correlation at 31–36 m; B3 and S2 showed no correlation at 27–30 m; B4 and S1 showed no correlation at 36–46 m; B4 and S2 showed no correlation at 33–37 m; B4 and S3 showed no correlation at 38–40 m; and B4 and S4 showed no correlation at 38–42 m.

The correlations between Qinghai spruce trees affected by white birch trees showed similar trends, except for S2 and B1, as shown in Fig.8. S2 and B1 showed a trend that reached or was close to a positive correlation at 1–28 m and no correlation at 29–50 m, which indicated that the correlations tended to change from positive to negative. Correlations between other *DBH* classes all tended to change from a significant, negative correlation to no correlation to a positive correlation. S3 and B1 showed no correlation at 27–42 m; S3 and B2 showed no correlation at 37–43 m; S4 and B1 showed no correlation at 37–43 m; S4 and B2 showed no correlation at 38–44 m; S4 and B3 showed no correlation at 38–47 m.

It is clear from the negative correlations that strong interspecific competition dominated the two species and the smaller trees suffered serious stress from the bigger individuals of the other species (Fig.7 and 8).

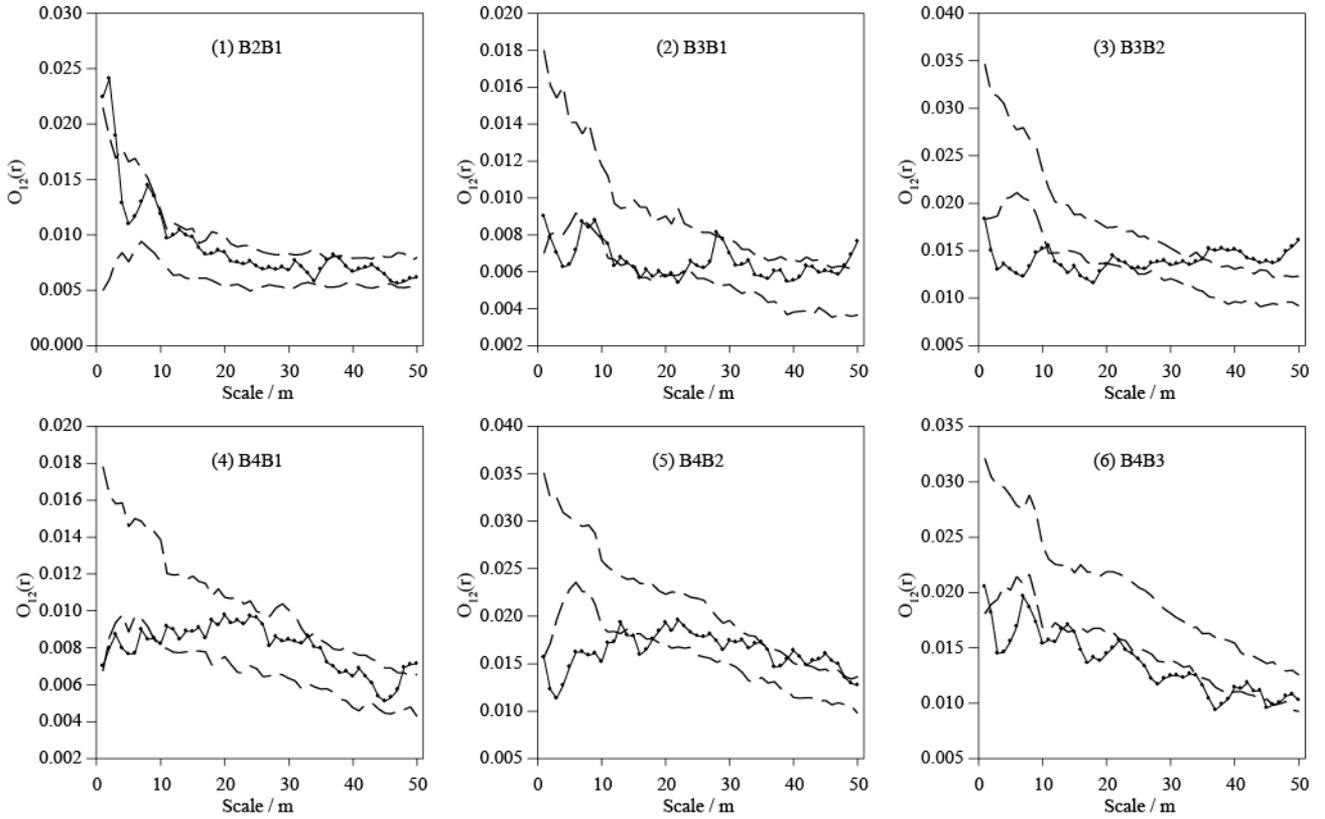


Fig.5. Spatial correlations between the different *DBH* classes of white birch. Solid lines indicate the sample statistic; dashed lines represent confidence intervals. All subfigures are named by “pattern 1 + pattern 2” in bivariate analyses, in which pattern 1 was fixed and pattern 2 was random. For example, B2B1 indicates white birch of *DBH* class 2 was fixed and white birch of *DBH* class 1 was random in bivariate analysis.

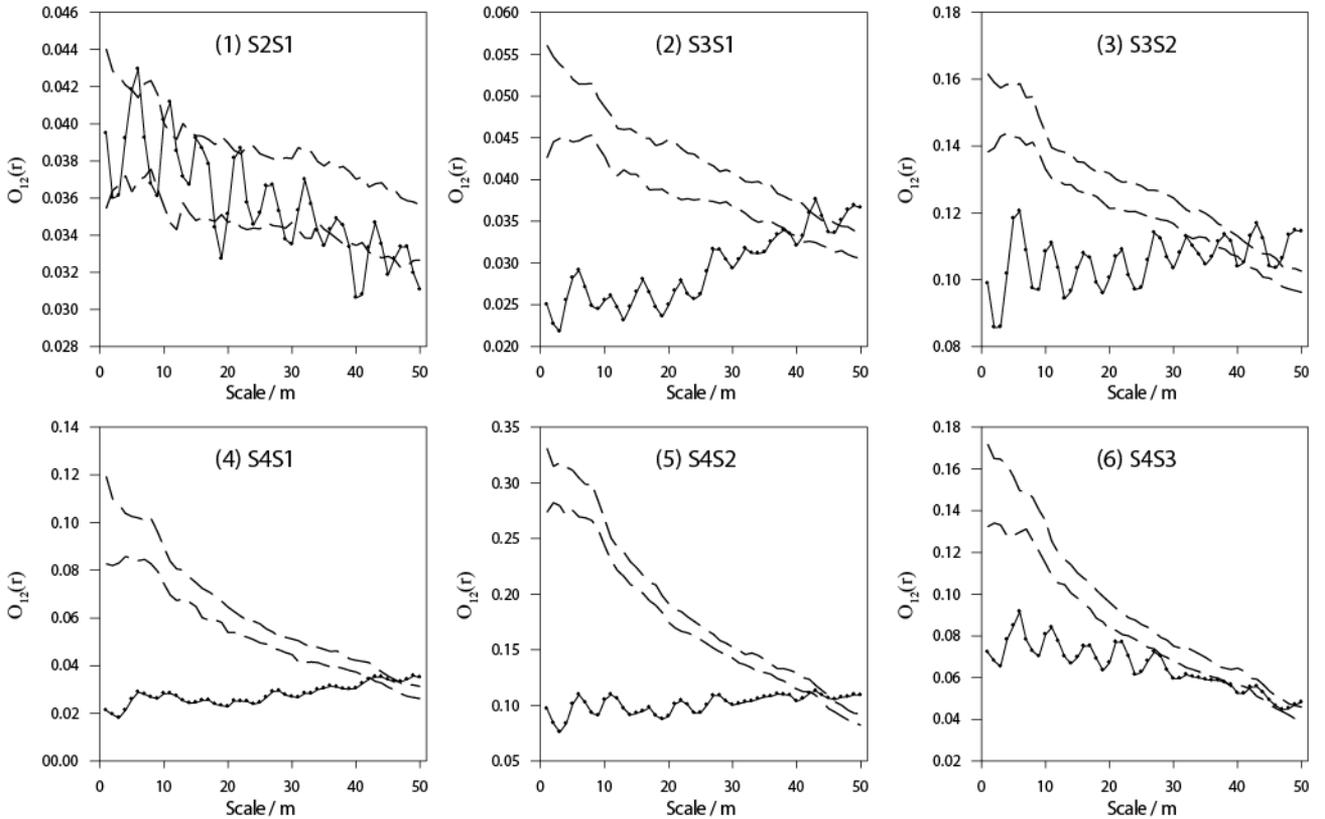


Fig.6. Spatial correlations between different *DBH* classes of Qinghai spruce. Solid lines indicate the sample statistic; dashed lines represent confidence intervals.

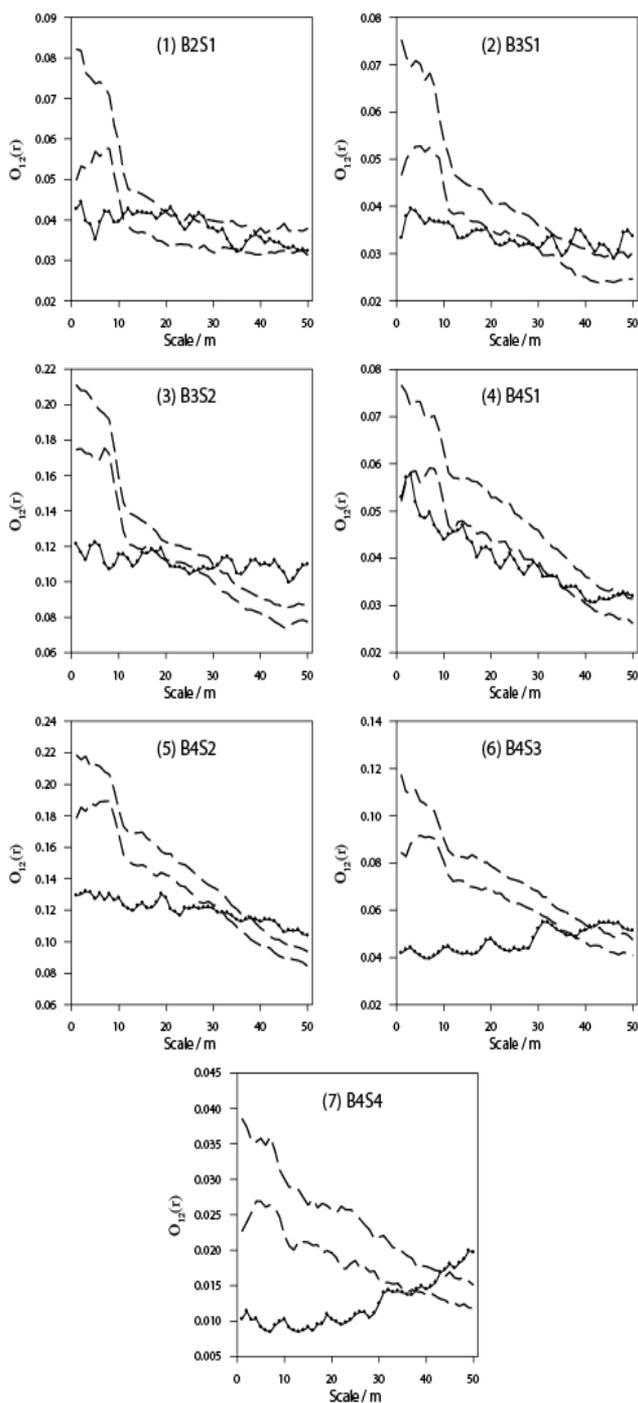


Fig.7. Spatial correlations between white birch affected by Qinghai spruce. Solid lines indicate the sample statistic; dashed lines represent confidence intervals.

## Discussion

**DBH (age) classes and spatial patterns:** Trees presented different spatial patterns at different developmental stages and ages, which was closely connected to the process of natural thinning, interference patterns, and environmental changes in the forest community. Individuals at the same developmental stage also showed different distribution patterns at different scales, which was mainly associated with spatial changes in environmental conditions. Usually, younger trees follow a clustered distribution as they often inhabit the lower canopy and are frequently distributed in

forest gaps or under older trees. In contrast, older trees generally fit a random or regular distribution as they have a relatively higher canopy that increases competition. In this study, all of the *DBH* (age) classes of the two species fit a random distribution.

Most of the *DBH* classes of white birch showed a similar spatial distribution pattern that was random at nearly all scales, with a tendency towards a clustered distribution at smaller scales. One explanation for this phenomenon may be related to environmental heterogeneity caused by microtopography, shrubs, a large canopy of adult birch. The thick humus horizon and litter layer indicated fertile soil under the white birch forest, which may have alleviated the effects of soil fertility on seed dispersal and the root suckers of white birch and led to the random distribution of white birch. However, white birch is a fast-growing and photophilic tree, and is generally a pioneer tree species in the natural plant regeneration process. Its seeds often fall onto deforested land, bare land, or glades in forest and grow rapidly. After the rapid growth of white birch trees into adults, more resources (light, water, nutrients) are required than during the juvenile stage and self-thinning may occur (Boyden *et al.*, 2005; Quesada *et al.*, 2009). The Qinghai spruce trees in the study area were planted artificially, and their growth also affected the white birch population. In addition, there were bushes in forest clearings that competed for resources with birch seedlings, which may have contributed towards the random distribution.

Although the Qinghai spruce showed a random distribution, the curve of the S2 and S3 classes was non-linear and showed a tendency for a clustered or regular distribution at different scales. The biological characteristics of this species are drought- and cold-resistant and shade-tolerant, which may have caused these distribution patterns. However, the Qinghai spruce in the study area did not regenerate naturally and were planted in an inappropriate way, and these factors might have been the primary reason for their distribution. This study also found that almost all Qinghai spruce trees were still alive, regardless of poor growth status. Qinghai spruce trees were planted three trees to a hole; normally only one tree grew into a large tree, the remaining two trees were still alive and existed as undersized trees. Additionally, because Qinghai spruce trees were mostly concentrated in S2 and S3 classes, their fitted curves showed irregular changes in the spatial point pattern analysis of the different *DBH* classes.

## Intraspecific correlations between two different *DBH* (age) classes:

There was no correlation between B2 and B1, which may be explained by the relatively smaller size of the trees that alleviated intraspecific competition between these two *DBH* classes. However, B2 and B1 were in adjacent growth and developmental stages, and had similar habitat requirements. Therefore, these two *DBH* classes were positively correlated at 1–3 m. B4 and B3 had relatively larger canopies and a large number of trees in these two classes occupied the same canopy layer, which caused strong competition; therefore, B4 and B3 showed negative correlations at almost all spatial scales. In addition, these two *DBH* classes showed negative correlations with the other two classes at relatively

smaller scales (normally  $\leq 20$  m). As B3 and B4 did not dominate the number of white birch trees or numerous gaps in the study area, there was a tendency for the correlations between these two *DBH* classes and the other two *DBH* classes to gradually change from no correlations to positive correlations.

The excessive plant density (three trees per hole, and one hole every 1.5–2 m) of the Qinghai spruce caused strong competition for sunlight and other resources. In this case, only one tree can grow normally in a hole and the remaining two will be seriously stressed, or all three will not grow to full size and remain as small trees. This may have been the main reason why the Qinghai spruce trees showed negative correlations at 1–42 m between two arbitrary *DBH* classes. Therefore, although positive correlations were observed at spatial scales close to 50 m, they were not significant.

**Interspecific correlations between two different *DBH* (age) classes:** In the natural regeneration process of Qinghai spruce and white birch, seeds of the Qinghai spruce germinate and grow up under the white birch forest. Subsequently, the adult Qinghai spruce compete for sunlight and water and cause the white birch to eventually die off. In this study, the spatial point pattern analysis of the white birch and Qinghai spruce indicated that the white birch restricted the growth of the Qinghai

spruce at most scales, and in general, the bigger *DBH* classes had wider spatial scales that restricted the growth of Qinghai spruce. However, this restraining effect is predicted to eventually weaken and change from restraint-no effect-promotion as the spatial scale increases.

The Qinghai spruce effect on the white birch showed similar properties, with the Qinghai spruce restricting the growth of white birch, but tend to promoting in relatively large spatial scale. The results showed that the white birch is a photophilic species and unsuitable for growing in shade. Otherwise, there was no spatial correlation between S2 and B1, but there were positive correlations at certain scales caused by the low height and small canopy of S2 and the wide planting rows of the Qinghai spruce trees. In addition, Qinghai spruce grows slower than white birch, which may explain why the white birch trees suppressed the growth of Qinghai spruce trees.

Removing the competitors surrounding target trees is an effective way to avoid the effects of neighboring competition that reduces the growth of valuable target trees in managed forest (Zhang *et al.*, 2013). Therefore, ecological thinning should be conducted in this forest to remove the Qinghai spruce trees that are in a poor growth state (mainly *DBH* S1 and S2), and those that are too close to the large white birch trees. Additionally, two trees should be removed if three Qinghai spruce trees in the same hole have similar growth statuses.

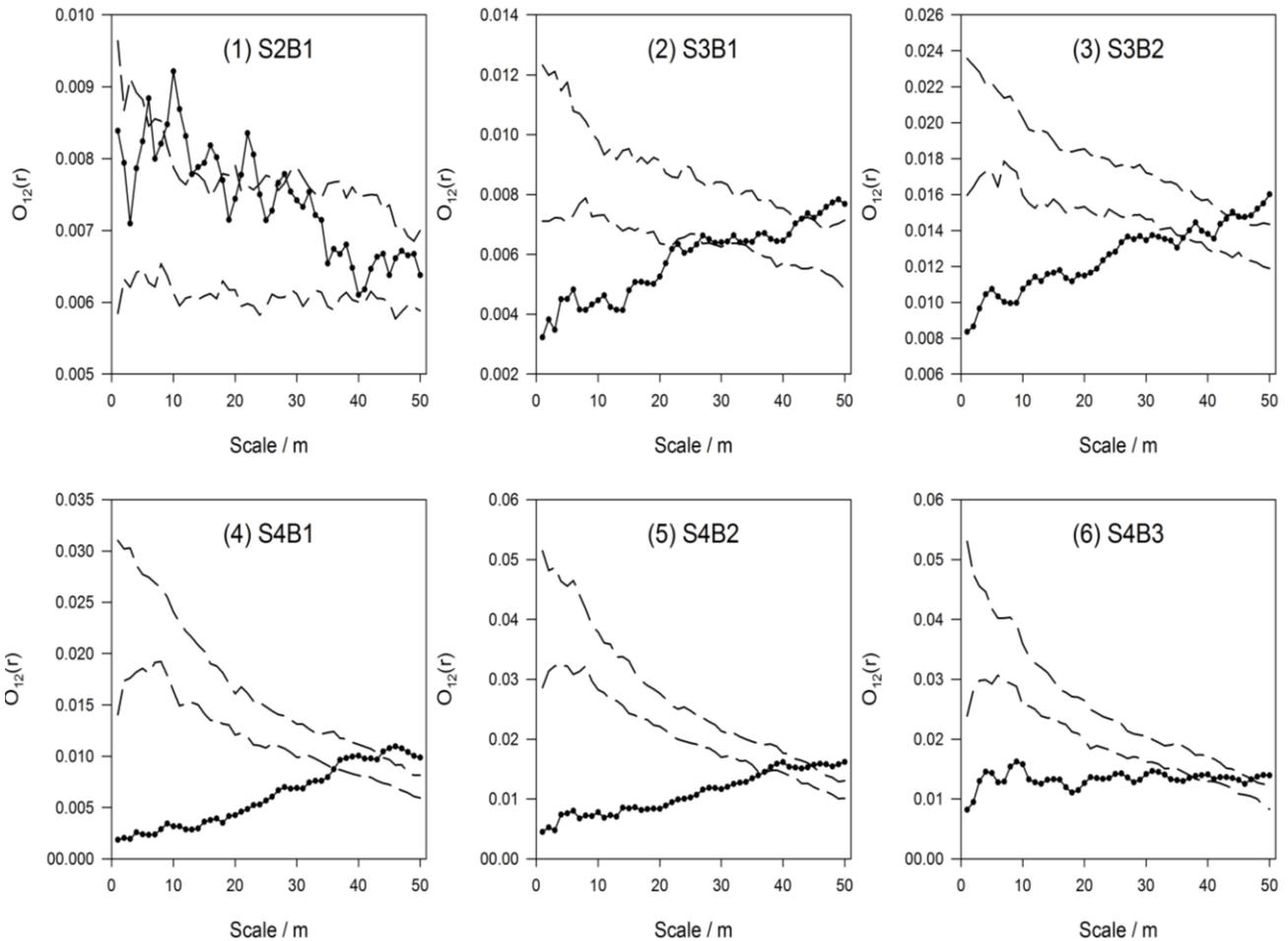


Fig. 3. Spatial correlations of Qinghai spruce affected by white birch. Solid lines indicate the sample statistic; dashed lines represent confidence intervals.

## Conclusions

The study areas were planted with Qinghai spruce trees under white birch natural secondary forest to promote artificial forest succession. After 30 years, intraspecific competition dominated the Qinghai spruce as its shade-tolerant ecological characteristics ensured that almost all Qinghai spruce seedlings survived in the shade of white birch, but also that most did not grow into adult trees. Relatively speaking, the intraspecific competition of white birch was weak, as all white birch trees were naturally regenerated, and the shade-intolerant ecological characteristics of this species meant that almost all survivors suffered stress from larger trees.

Strong, interspecific competition between white birch and Qinghai spruce dominated the spatial patterns and succession of the two species. The relatively higher growth of white birch enabled it to occupy the upper canopy of the forest quicker than Qinghai spruce, and restrict Qinghai spruce seedling growth. Meanwhile, the larger Qinghai spruce trees also restricted the natural regeneration of white birch. The shade-tolerant characteristic of Qinghai spruce seedlings but photophilic of adults enabled numerous Qinghai spruce trees to grow in a large forest clearing of white birch trees; therefore, the white birch forest will be replaced by a Qinghai spruce forest as the Qinghai spruce trees gradually mature. However, the Qinghai spruce may remain in the developing stage for an extended period because the white birch is still in growing.

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## References

- Akhavan, R., K. Sagheb-Talebi, E.K. Zenner and F. Safavimanesh. 2012. Spatial patterns in different forest development stages of an intact old-growth Oriental beech forest in the Caspian region of Iran. *Europ. J. Forest Res.*, 131(5): 1355-1366.
- Arévalo, J.R. 2013. Spatial analysis and structure of a cross-timber stand in the TallGrass Prairie Preserve (Pawhuska, Oklahoma). *J. Forestry Res.*, 24(1): 47-52.
- Baack, E.J. 2005. To succeed globally, disperse locally: effects of local pollen and seed dispersal on tetraploid establishment. *Heredity*, 94(5): 538-546.
- Barot, S., J. Gignoux and J. Menaut. 1999. Demography of a Savanna Palm Tree: Predictions from Comprehensive Spatial Pattern Analyses. *Ecology*, 80(6): 1987-2005.
- Batista, J.L.F. and D.A. Maguire. 1998. Modeling the spatial structure of tropical forests. *Forest Ecol. & Manag.*, 110(1-3): 293-314.
- Boyden, S., D. Binkley and W. Shepperd. 2005. Spatial and temporal patterns in structure, regeneration, and mortality of an old-growth ponderosa pine forest in the Colorado Front Range. *Forest Ecol. & Manag.*, 219(1): 43-55.
- Condit, R., P.S. Ashton, P. Baker, S. Bunyavechewin, S. Gunatilleke, N. Gunatilleke, S.P. Hubbell, R.B. Foster, A. Itoh and J.V. LaFrankie. 2000. Spatial patterns in the distribution of tropical tree species. *Science*, 288(5470): 1414-1418.
- Dale, M.R.T. 1999. *Spatial pattern analysis in plant ecology*. Cambridge University Press, London.
- Druckenbrod, D.L., H.H. Shugart and I. Davies. 2005. Spatial pattern and process in forest stands within the Virginia piedmont. *J. Veg. Sci.*, 16(1): 37-48.
- Ewela, J.J. and M.J. Mazzarino. 2008. Competition from below for light and nutrients shifts productivity among tropical species. *Proceedings of the National Academy of Sciences*, 105(48): 18836-41.
- Frost, I. and H. Rydin. 2000. Spatial pattern and size distribution of the animal-dispersed tree *Quercus robur* in two spruce-dominated forests. *Ecoscience*, 7(1): 38-44.
- Getzin, S., T. Wiegand, K. Wiegand and F. He. 2008. Heterogeneity influences spatial patterns and demographics in forest stands. *J. Ecology*, 96(4): 807-820.
- Hanus, M.L., D.W. Hann and D.D. Marshall. 1998. Reconstructing the Spatial Pattern of Trees from Routine Stand Examination Measurements. *Forest Sci.*, 44(1): 125-133.
- Hao, Z.Q., J. Zhang, B. Song, J. Ye and B.H. Li. 2007. Vertical structure and spatial associations of dominant tree species in an old-growth temperate forest. *Forest Ecol. & Manag.*, 252(1): 1-11.
- Lejeune, O. and M. Tlidi. 1999. A model for the explanation of vegetation stripes (tiger bush). *Journal of vegetation science : official organ of the International Association for Vegetation Science*, 10(2): 201-208.
- Levin, S.A. 1992. The problem of pattern and scale in ecology: the Robert H. MacArthur award lecture. *Ecology*, 73(6): 1943-1967.
- Li, L., S.G. Wei, Z.L. Huang, W.H. Ye and H.L. Cao. 2008. Spatial patterns and interspecific associations of three canopy species at different life stages in a subtropical forest, China. *J. Integ. Plant Biol.*, 50(9): 1140-1150.
- McDonald, R.I., R.K. Peet and D.L. Urban. 2003. Spatial pattern of *Quercus* regeneration limitation and *Acer rubrum* invasion in a Piedmont forest. *J. Veg. Sci.*, 14(3): 441-450.
- McIntire, E.J.B. and A. Fajardo. 2009. Beyond description: the active and effective way to infer processes from spatial patterns. *Ecology*, 90(1): 46-56.
- Niggemann, M. and R. Bialozyt. 2012. Marked point pattern analysis on genetic paternity data for uncertainty assessment of pollen dispersal kernels. *J. Ecology*, 100(1): 264-276.
- Perry, G.L.W., N.J. Enright, B.P. Miller and B.B. Lamont. 2013. Do plant functional traits determine spatial pattern? A test on species-rich shrublands, Western Australia. *Journal of Vegetation Science*, 24(3): 441-452.
- Pielou, E.C. 1969. An introduction to mathematical ecology. *Bioscience*, 78(1): 7-12.
- Pommerening, A., V. Lemay and D. Stoyan. 2011. Model-based analysis of the influence of ecological processes on forest point pattern formation-A case study. *Ecological Modelling*, 222(3): 666-678.
- Quesada, M., G. Sanchez-Azofeifa, M. Alvarez-Añorve, K. Stoner, L. Avila-Cabadilla, J. Calvo-Alvarado, A. Castillo, M. Espirito-Santo, M. Fagundes, G. Fernandes, J. Gamon, M. Lopezaraiza-Mikel, D. Lawrence, L. Morellato, J. Powers, F. Neves, V. Rosas-Guerrero, R. Sayago and G. Sanchez-Montoya. 2009. Succession and management of tropical dry forests in the Americas: Review and new perspectives. *Forest Ecol. & Manag.*, 258(6): 1014-1024.

- Richard, L., I. Janine, B. Davidfrp, G. Georg, G. Cvs and G. Iaun. 2009. Ecological information from spatial patterns of plants: insights from point process theory. *Journal of Ecology*, 97(4): 616-628.
- Ripley, B.D. 1977. Modelling spatial patterns. *Journal of the Royal Statistical Society. Series B (methodological)*: 172-212.
- Ripley, B.D. 1981. *Spatial Statistics*. John Wiley Sons, New York, USA.
- Schurr, F.M., O. Bossdorf, S.J. Milton and J. Schumacher. 2004. Spatial pattern formation in semi-arid shrubland: a priori predicted versus observed pattern characteristics. *Plant Ecol.*, 173(2): 271-282.
- Tilman, B.D. and P. Kareiva. 2005. The Role of Space in Population Dynamics and Interspecific Interactions. *Journal of Physics G Nuclear & Particle Physics*, 31(11): 1329-1343.
- Tuda, M. 2007. Understanding mechanism of spatial ecological phenomena: a preface to the special feature on "Spatial statistics". *Ecol. Res.*, 22(2): 183-184.
- Wang, X.G., J. Ye, B.H. Li, J. Zhang, F. Lin and Z.Q. Hao. 2010. Spatial distributions of species in an old-growth temperate forest, northeastern China. *Can. J. Forest Res.*, 40(6): 1011-1019.
- Wells, M.L. and A. Getis. 1999. The spatial characteristics of stand structure in *Pinus torreyana*. *Plant Ecol.*, 143(2): 153 - 170.
- Wiegand, T. 2004. Introduction to Point Pattern Analysis with Ripley's L and the O-ring statistic using the Programita software (Second draft version).
- Wiegand, T., F. Jeltsch, I. Hanski and V. Grimm. 2003. Using pattern-oriented modeling for revealing hidden information: A key for reconciling ecological theory and application. *Oikos*, 100(2): 209-222.
- Wiegand, T., F.L. He and S.P. Hubbell. 2013. A systematic comparison of summary characteristics for quantifying point patterns in ecology. *Ecography*, 36(1): 92-103.
- Wiegand, T., S. Gunatilleke, N. Gunatilleke and T. Okuda. 2007. Analyzing the spatial structure of a Sri Lankan tree species with multiple scales of clustering. *Ecology*, 88(12): 3088-3102.
- Wiegand, T. and K.A. Moloney. 2004. Rings, circles, and null-models for point pattern analysis in ecology. *Oikos*, 104(2): 209-229.
- Zhang, C.Y., Y.B. Wei, X.H. Zhao and K. von Gadow. 2013. Spatial characteristics of tree diameter distributions in a temperate old-growth forest. *PloS one*, 8(3): e58983.
- Zhang, M.T., X.G. Kang, J.H. Meng and L.X. Zhang. 2015. Distribution patterns and associations of dominant tree species in a mixed coniferous-broadleaf forest in the changbai mountains. *J. Mountain Sci.*, 12(3): 659-670.
- Zhang, J.T. 2011. *Quantitative Ecology (2<sup>nd</sup> Edition)*. Science Press, Beijing, China. (in Chinese)

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