

Effects of microtopography on spatial point pattern of forest stands on the semi-arid Loess Plateau, China

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Abstract: Microtopography may affect the distribution of forests through its effect on rain redistribution and soil water distribution on the semi-arid Loess Plateau, China. In this study, we investigated the characteristics of microtopography on two shady slopes (slope A, 5 hm², uniform slope; slope B, 5 hm², microtopography slope) and surveyed the height, the diameter at breast height and the location (x, y coordinates) of all selected individual trees (*Robinia pseudoacacia* Linn., *Pyrus betulifolia* Bunge, *Populus hopeiensis* Hu & Chow, *Armeniaca sibirica* Lam., *Populus simonii* Carr. and *Ulmus pumila* Linn.) on slope A and slope B in the watersheds of Wuqi county, Shaanxi province. Subsequently, the effects of microtopography on the spatial pattern of forest stands were analyzed using Ripley's *K(r)* function. The results showed that: (1) The maximal aggregation radiuses of the tree species on the uniform slope (slope A) were larger than 40 m, whereas those of the tree species on the microtopography slope (slope B) were smaller than 30 m. (2) On slope B, the spatial association of *R. pseudoacacia* with *P. betulifolia*, *A. sibirica*, *P. simonii* and *U. pumila* varied from being strongly negative to positive at microtopography scales. The spatial association of *Populus hopeiensis* Hu & Chow with *U. pumila* also varied from being strongly negative to positive at microtopography scales. However, there was no spatial association between *P. betulifolia* and *P. hopeiensis*, *P. betulifolia* and *A. sibirica*, *P. betulifolia* and *P. simonii*, *P. betulifolia* and *U. pumila*, *P. hopeiensis* and *A. sibirica*, *P. hopeiensis* and *P. simonii*, *A. sibirica* and *P. simonii*, *A. sibirica* and *U. pumila*, and *P. simonii* and *U. pumila*. On slope A, the spatial association between tree species were strongly negative. The results suggest that microtopography may shape tree distribution patterns on the semi-arid Loess Plateau.

Keywords: microtopography; univariate spatial patterns; aggregation; negative association; positive association

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Vegetation restoration is important for the control of soil and water loss, and has become a focus of forestry research (Zhu et al., 2012). In the process of vegetation restoration, it is crucial to select suitable tree species and vegetation configuration models based on local conditions (e.g. topography and soil moisture), especially for the Loess Plateau of China due to its fragmented topography (Yang et al., 2006; Wang et al.,

2009; Zhu et al., 2012). Rainfall is redistributed on fragmented topographies, causing differences in soil moisture (Zhao et al., 2010) and microhabitat in different topography types (Chimner and Hart, 1996; Nagamatsu and Miura, 1997; Lu et al., 2009; Zhao et al., 2010; Wang et al., 2011; Zhang et al., 2011a, b; Zhu et al., 2012).

In the 1980s, a forestation model that matched tree

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species with sites was developed in the Loess Plateau (Zhu, 1988). A conventional forestation model that used uniform planting points with the same row spacing along contours based on the site conditions of slopes was also proposed (Zou et al., 1980; Zhu et al., 2012). However, the trees planted based on the conventional forestation model developed into small old trees (Zhu et al., 2012). Recently, a forestation model based on microtopography was put forward for the Loess Plateau (Zhao et al., 2010; Zhu et al., 2012). The relationship between vegetation and microtopography has been analyzed in many countries. Sakai and Ohsawa (1993) classified 55 woody species into seven types using cluster analysis and principal coordinate analysis, and found that the seven vegetation types coincided with seven microtopographical facets at a scale of 10–100 m². Furthermore, different species were found in different microtopography types. For instance, different floristic compositions were found on ridge slopes, surrounding slopes and landslide slopes on Mt. Kiyosumi, central Japan (Sakai and Ohsawa, 1993); more cedar was found in drier areas, whereas shrubs and hardwoods were found in wetter areas in Michigan's Upper Peninsula (Chimner and Hart, 1996); and the various habitat niches of species were related to topography in a subtropical evergreen broad-leaved forest in the north of Okinawa Island, Japan (Tsutomu, 2003). In addition, the effects of microtopography on the infiltration of rainfall on slopes in Kenya (Thomas et al., 1991; Thompson et al., 2010), the canopy distribution in Okinawa Island, Japan (Tsutomu, 2003), and tree species diversity and forest structure in a tropical freshwater swamp forest in French Guiana (Piia et al., 2004) have been investigated. Similar research has also been conducted in China. For instance, the matching relationship between the community structure of a subtropical evergreen broadleaved forest and microtopography types was analyzed in Chebaling National Nature Reserve, Guangdong (Ma et al., 2010); the differences in the sprouting traits of the *Ginkgo biloba* populations in different micro-landforms of Guizhou province and Chongqing municipality were reported (Yang et al., 2011); and herbaceous community characteristics were studied in the microtopography of Wuqi county, Shaanxi province (Wang et al., 2012). Though these studies provide better information on forest restoration

and regeneration, they only offer qualitative descriptions and do not propose quantitative data regarding forestation, particularly about microtopography forestation. Nevertheless, spatial point pattern analysis can allow the quantification of the spatial distribution and co-occurrence patterns of the mapped positions of individual plants within a study region (Martínez et al., 2010). Different statistics have been proposed for the analysis of patterns within and between species in a scale dependent manner (Turkington and Harper, 1979). This feature of spatial point pattern analysis is important because most processes in plant communities are scale dependent (Levin, 1992; Wiegand and Moloney, 2004).

The purpose of this study was: (1) to investigate the effect of microtopography on the intra- and interspecies spatial pattern of six main tree species (*Armeniaca sibirica* Lam., *Populus simonii* Carr., *Ulmus pumila* Linn., *Pyrus betulifolia* Bunge, *Robinia pseudoacacia* Linn. and *Populus hopeiensis* Hu & Chow) inhabiting sites of different microtopography types in the semi-arid Loess Plateau of China; and (2) to show that microtopography should be considered as the basic unit of forestation on microtopography slopes.

1 Materials and methods

1.1 Study sites

The study was conducted on two shady slopes, Slope A located in Yangqingchuan (36°52'22"–36°52'32"N, 108°14'17"–108°14'32"E) and Slope B in Hegou (36°54'09"–36°54'23"N, 108°12'50"–108°13'01"E) watersheds in Wuqi county, northern Shaanxi (36°33'33"–37°24'27"N, 107°38'57"–108°32'49"E). Slope A (approximately 5 hm², calculated by ArcGIS 9.3) is a uniform slope without microtopography, and slope B (about 5 hm², calculated by ArcGIS 9.3) is composed of four microtopography types (sink hole, gully, platform and scarp; Fig. 1). The soil textures of the two slopes are nearly homogeneous at the study sites (Li and Shao, 2006). The soil moisture and nutrient distribution of slope A were uniform, but those of slope B were heterogeneous because of the microtopography (Zhang et al., 2011a, b; Zhu et al., 2012). Since the 1990s, the study sites have been undergoing conversion from cropland to forest, and some tree (*A.*

sibirica, *U. pumila*, etc.) and shrub (*Hippophae rhamnoides*, *Caragana korshinskii*, etc.) species of the same age are present. *A. sibirica*, *P. simonii*, and *U. pumila* only appear on slope A, whereas the forest stand on slope B consists of *A. sibirica*, *P. simonii*, *U. pumila*, *P. betulifolia*, *R. pseudoacacia*, *P. hopeiensis*, *Salix matsudana* and *Ailanthus altissima*. Slope A is a northern slope and slope B is a northeastern slope (the average inclination for each slope is 25°), and both

slopes were undisturbed during the conversion of cropland to forest. The region is characterized by a temperate continental monsoon climate that is warm and dry, with an annual mean temperature of 7.8°C and mean annual precipitation of 466 mm (based on data spanning 1957–2009). The annual variation in precipitation is large and there is an uneven distribution in different seasons, with most precipitation occurring from June to September.

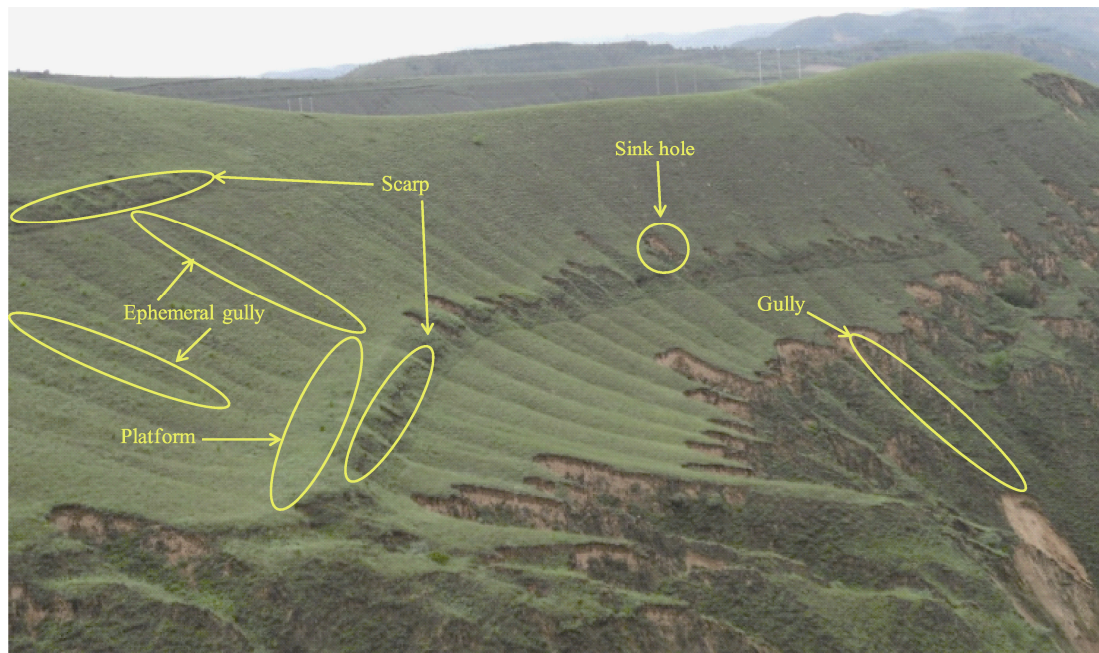


Fig. 1 Photo illustrating microtopography, including gully, sink hole, platform, scarp and ephemeral gully, on the slope of the Hegou watershed

1.2 Microtopography

Previously, microtopography was defined as the change in topography at a small scale, and it was divided into the seven units of crest slope, upper side slope, head hollow, lower side slope, foot slope, flood terrace and riverbed by Nagamatsu and Miura (1997). The microtopography types were also classified into three units (hummock, pool and intermediate area) by Chimner and Hart (1996). The definition and types of microtopography are not in complete accord with each other. In this study, the definition of microtopography is a local terrain of different sizes and shapes resulted from soil erosion, leading to the variation of habitat conditions such as soil moisture and nutrients within 1 m^2 or more (Wang et al., 2011; Zhu et al., 2012). Meanwhile, the types of microtopography consist of platform,

gully, sink hole, scarp and ephemeral gully (Fig. 1) (Zhao et al., 2010; Wang et al., 2011). In addition, previous studies showed that the soil moisture and nutrient contents in the sink hole, platform and gully were higher than those in scarp and ephemeral gully (Lu et al., 2009; Zhao et al., 2010; Wang et al., 2011; Zhang et al., 2011a, b).

1.3 Data collection

In July 2012, we surveyed every adult tree (individuals with a height greater than 1 m) within the study sites, and recorded their location (x , y coordinates), elevation, height, diameter at breast height (DBH; 1.3 m above ground) and microtopography type. We collected the coordinates and elevations of all trees using a GPS, measured the heights using a Blume–Leiss hypsometer, and obtained the DBH using a diameter

tape. This information was then added to a geographic information system (GIS), and a database was created. The locations of all the adult trees were mapped by the GIS (Fig. 2). The final data consist of the coordinates,

DBH, height, species identity and growth conditions (microtopography type or uniform slope) of each individual tree. Table 1 presents the sample sizes and basic information for the studied species.

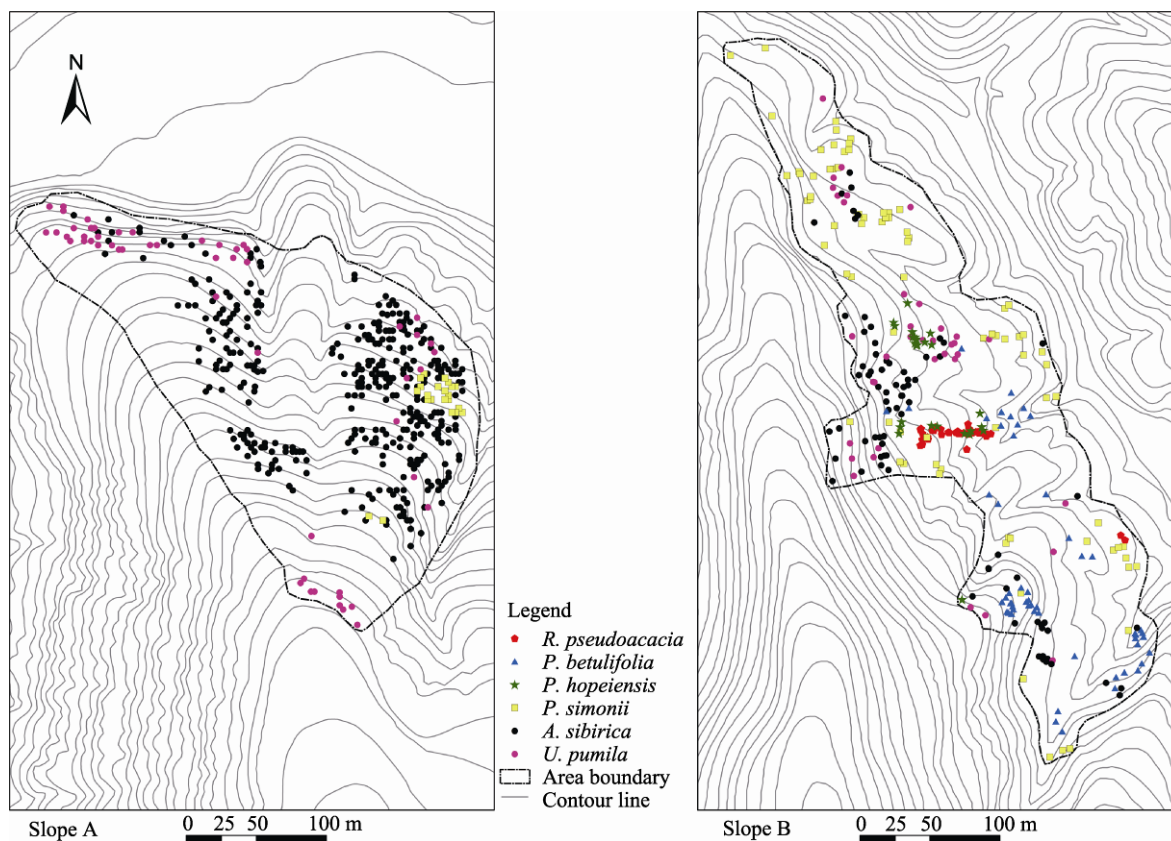


Fig. 2 Maps illustrating the locations of all adult trees in slope A and B

1.4 Data analysis

1.4.1 Univariate spatial pattern

Ripley's $K(r)$ function was used to analyze the observed mapped point patterns of trees in each stand (Ripley, 1976, 1981). The unbiased univariate estimator of the K -function for exploring univariate spatial pattern is:

$$K(r) = n^{-2} |A| \sum_{i \neq j} w_{ij}^{-1} I_r(d_{ij}). \quad (1)$$

Where n is the total number of trees in study site A; d_{ij} is the distance between the i^{th} (focal) tree and the j^{th} (neighboring) tree; $I_r(d_{ij})$ is an indicator function, equaling 1 if $d_{ij} < r$ and 0 otherwise; w_{ij} is included to correct for the edge effect, and it equals the proportion of the circumference of a circle centered at the i^{th} tree

with radius d_{ij} (w_{ij} is 1 if the entire circumference of the circle lies within A). To ensure sufficient neighboring pairs for constructing the K -function, the function was computed at a 1.0 m interval with distance $r \leq 100$ m (slope-scale).

The variance reduction form of the K -function,

$$L(r) = K(r)^{0.5} \pi^{-0.5} - r, \quad (2)$$

was used to compare the observed spatial patterns of each dominant tree species in each successional phase against a random pattern. $L(r)=0$ for complete spatial randomness (CSR), $L(r)>0$ for an aggregated pattern, whereas $L(r)<0$ for a regular pattern.

1.4.2 Bivariate spatial association

Bivariate spatial association is the spatial point pattern of two tree species (i.e. multiple point pattern analysis).

Table 1 Sample sizes, properties and spatial patterns for the six species

	Species					
	<i>A. sibirica</i>	<i>P. simonii</i>	<i>U. pumila</i>	<i>P. betulifolia</i>	<i>R. pseudoacacia</i>	<i>P. hopeiensis</i>
Location	Slope A/Slope B	Slope A/Slope B	Slope A/Slope B	Slope B	Slope B	Slope B
Microtopography	Uniform slope/Platform, sink hole, unrolling slope	Uniform slope/Platform, gully, unrolling slope	Uniform slope/Scarp, unrolling slope	Gully, platform, unrolling slope	Gully	Unrolling slope, platform, gully
<i>n</i> total	392/31, 27, 20	22/35, 23, 23	55/28, 10	21, 18, 15	45	9, 8, 8
DBH (cm)						
Maximum	38.5/30.0	48.2/47.0	39.4/32.0	35.0	18.0	38.0
Minimum	1.9/5.0	14.9/7.0	7.1/3.0	6.0	9.0	6.0
Mean	15.9/17.5	24.8/26.7	14.6/13.6	20.3	11.7	14.9
SD	6.7/5.9	8.4/6.8	7.2/6.4	5.4	3.0	8.5
Skewness	0.44/0.148	1.03/0.164	1.17/0.858	-0.149	0.913	1.453
Height (m)						
Maximum	9.2/10.2	15.2/27.5	10.1/6.8	11.4	8.5	17.1
Minimum	2.1/2.8	1.4/4.8	1.7/1.5	3.0	4.5	6.0
Mean	5.5/5.8	8.1/12.6	4.5/4.0	6.5	6.3	10.3
SD	1.5/1.4	4.0/4.5	1.7/1.3	1.9	1.6	2.6
Skewness	-0.22/0.36	-0.44/1.148	0.677/0.181	0.451	-0.107	1.092

Note: Slope A, uniform slope; Slope B, microtopography slope. The microtopography sequence is homologous with *n* total.

The second-order bivariate estimator of Ripley's *K*-function was defined for exploring interspecies competition as:

$$K_{12}(r) = (n_1 n_2)^{-1} \left| A \right| \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} w_{ij}^{-1} I_r(d_{ij}), \quad (3)$$

where n_1 and n_2 are the total number of trees of species 1 and 2 that occur in site A; other terms are the same as for Eq. 1.

The variance reduction bivariate transformation of $K_{12}(r)$ (Lotwick and Silverman, 1982) is:

$$L_{12}(r) = K_{12}(r)^{0.5} \pi^{-0.5} - r. \quad (4)$$

If species 1 and 2 are randomly associated, $L_{12}(r)=0$; if the two species are positively associated, $L_{12}(r)>0$; if they are negatively associated, $L_{12}(r)<0$.

1.4.3 Monte Carlo simulation inspection

To evaluate the significance level of non-CSR, the observed *L*-functions for the spatial pattern of each tree species and the interspecies spatial association at the two scales were compared to the intervals generated by the Monte Carlo simulation of random location selection, where the relative coordinates for the same number of trees were randomly generated.

In these intraspecies pattern analyses, if $L(r)$ at a distance r is above the upper limit of the confidence interval, the intraspecies pattern is defined as an aggre-

gated pattern; if $L(r)$ is below the lower limit of the confidence interval, it is defined as a regular pattern; and if $L(r)$ lies between the upper and lower limits of the confidence interval, it is CSR. In interspecies spatial association analyses, if $L_{12}(r)$ is above the upper (or below the lower) limit of the confidence envelope, pattern 2 is positively (or negatively) associated with pattern 1 at distance r (Hao et al., 2007); and if $L_{12}(r)$ is within the upper and lower limits of the confidence envelope, there is no association between patterns 1 and 2. The Monte Carlo simulation was repeated 99 times and an *L*-function was calculated each time. The second to minimum and second to maximum $L(r)$ at each distance r were used as the 99% Monte Carlo interval for each given r . The $L(r)$ function statistics were computed using ADE-4 software.

Subsequently, we obtained the intraspecies spatial patterns and interspecies spatial association for the uniform slope and the patterns for the microtopography slope.

2 Results

2.1 Univariate spatial patterns

2.1.1 Univariate spatial patterns on the uniform slope

An analysis of the tree species spatial distribution on

slope A revealed a predominant spatial aggregation pattern for *A. sibirica*, *P. simonii* and *U. pumila* at the scale of 0–100 m (Fig. 3). The observed spatial pattern curve of *A. sibirica* exhibited an inverted J-shape and reached the maximal aggregation radius at $r=70$ m;

however, the spatial pattern curves of *P. simonii* and *U. pumila* were unimodal and achieved peaks at $r=28$ and 40 m, respectively. In addition, the aggregation intensities of *A. sibirica* and *U. pumila* were less than 49, whereas that of *P. simonii* was 128.

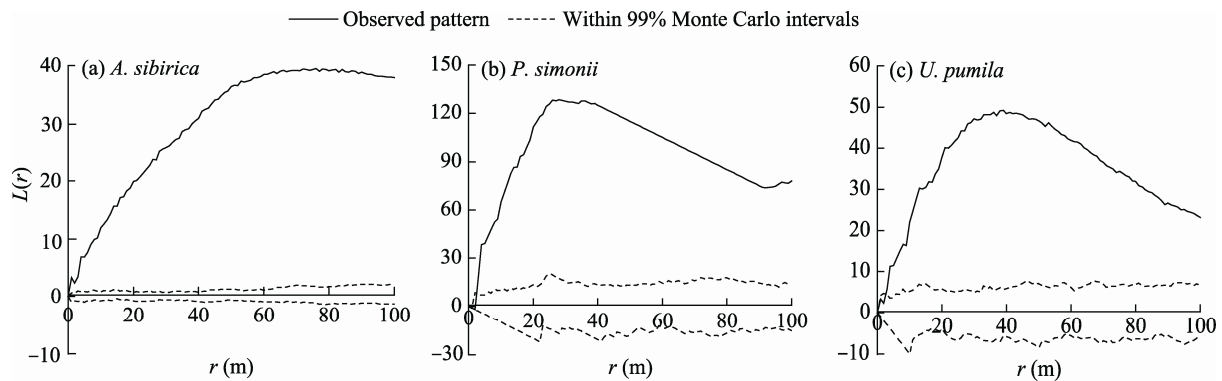


Fig. 3 Univariate spatial pattern analyses of the tree species on slope A. $L(r)$, intraspecies spatial pattern; r , spatial scale. The same below.

2.1.2 Univariate spatial patterns on the microtopography slope

All the spatial pattern curves were unimodal on slope B (Fig. 4). Only the spatial pattern of *R. pseudoacacia* showed an aggregation distribution at the scale of 0–100 m; however, the spatial patterns of the other tree species displayed aggregation distributions at small scales.

Although the spatial pattern of *R. pseudoacacia* showed aggregation distribution at 0–100 m, its maximal aggregation radius was reached at 29 m (Fig. 4a). The observed $L(r)$ of *P. betulifolia* fell within the Monte Carlo interval at a scale of up to 12 m and started at 28 m, indicating a random distribution; however, it showed aggregation at 12–28 m and reached the maximal aggregation radius at 15 m (Fig. 4b). *P. hopeiensis* was aggregated at 5–64 m, and randomly distributed at 0–5 and 64–100 m, with a maximal aggregation radius of 29 m (Fig. 4c). *A. sibirica* showed an aggregation distribution at 0–30 m and random distribution at 30–100 m with the maximal aggregated radius at 13 m (Fig. 4d). *P. simonii* shifted from aggregation at 0–54 m to random distribution at 54–100 m and reached the maximal aggregated radius at 22 m (Fig. 4e). However, *U. pumila* was randomly distributed on the scale of 0–15 m and

45–100 m and aggregated at 15–45 m with a maximal aggregated radius of 20 m. The maximum aggregation intensities of all the tree species were simultaneously larger than 50 (Fig. 4f), and ranged from 50 to 80 on the microtopography slope.

2.2 Bivariate spatial patterns of dominant tree species

2.2.1 Bivariate spatial patterns on the uniform slope

The observed $L_{12}(r)$ function for *A. sibirica* and *P. simonii* fell within the Monte Carlo interval at 0–20 and 47–78 m, indicating that there was no significant spatial association, only shifting to slightly significant, positive spatial association at the scales of 20–47 and 78–100 m, respectively. Nevertheless, the tree species pair of *U. pumila* and *A. sibirica* showed highly significant, negative spatial association, as well as the tree species pair of *U. pumila* and *P. simonii* at 0–100 m (Fig. 5).

2.2.2 Bivariate spatial patterns on the microtopography slope

In contrast to slope A, all the spatial associations of interspecies pairs on slope B exhibited from significantly negative spatial association to significantly positive association or no spatial association as the scale increased from 0 to 100 m (Fig. 6). The trend

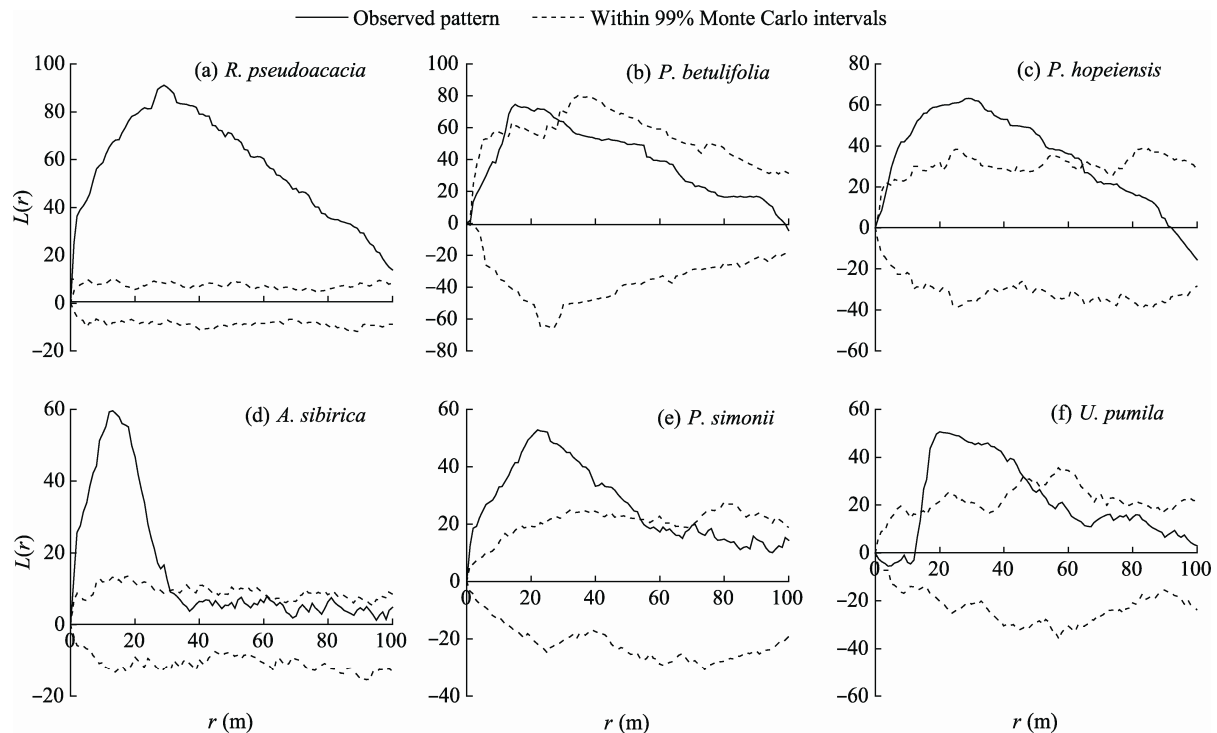


Fig. 4 Univariate spatial pattern analyses of the tree species on slope B

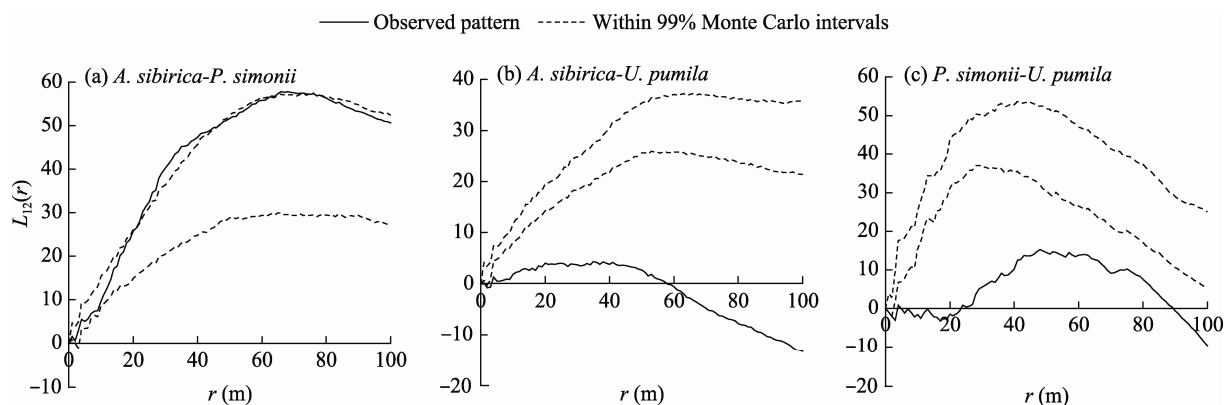


Fig. 5 Bivariate analyses exploring the spatial association of a given species with all other species on slope A at the scale of 0–100 m

revealed that the interspecies competition changed from intense to slight on slope B. Particularly, *A. sibirica* and *P. simonii* showed significantly negative spatial association at 0–13 m and shifted to no significant spatial association at 13–100 m (Fig. 6m). However, *A. sibirica* and *U. pumila* showed no significant spatial association at 0–100 m (Fig. 6n). *P. simonii* maintained the strongest negative spatial association with *U. pumila* at 13–31 m, with indistinct spatial association at 0–13 m and 31–100 m (Fig. 6o). This suggests that microtopography reduced interspe-

cies competition intensity to some extent and increased the number of tree species available for near-natural forestation.

3 Discussion

Exploring intraspecies and interspecies spatial associations can elucidate the effects of diverse microtopography types on microtopography forestation and management regimes (Lacambra et al., 2012; Zhang et al., 2012). The Loess Plateau was divided into six ecological regions based on different soil moisture

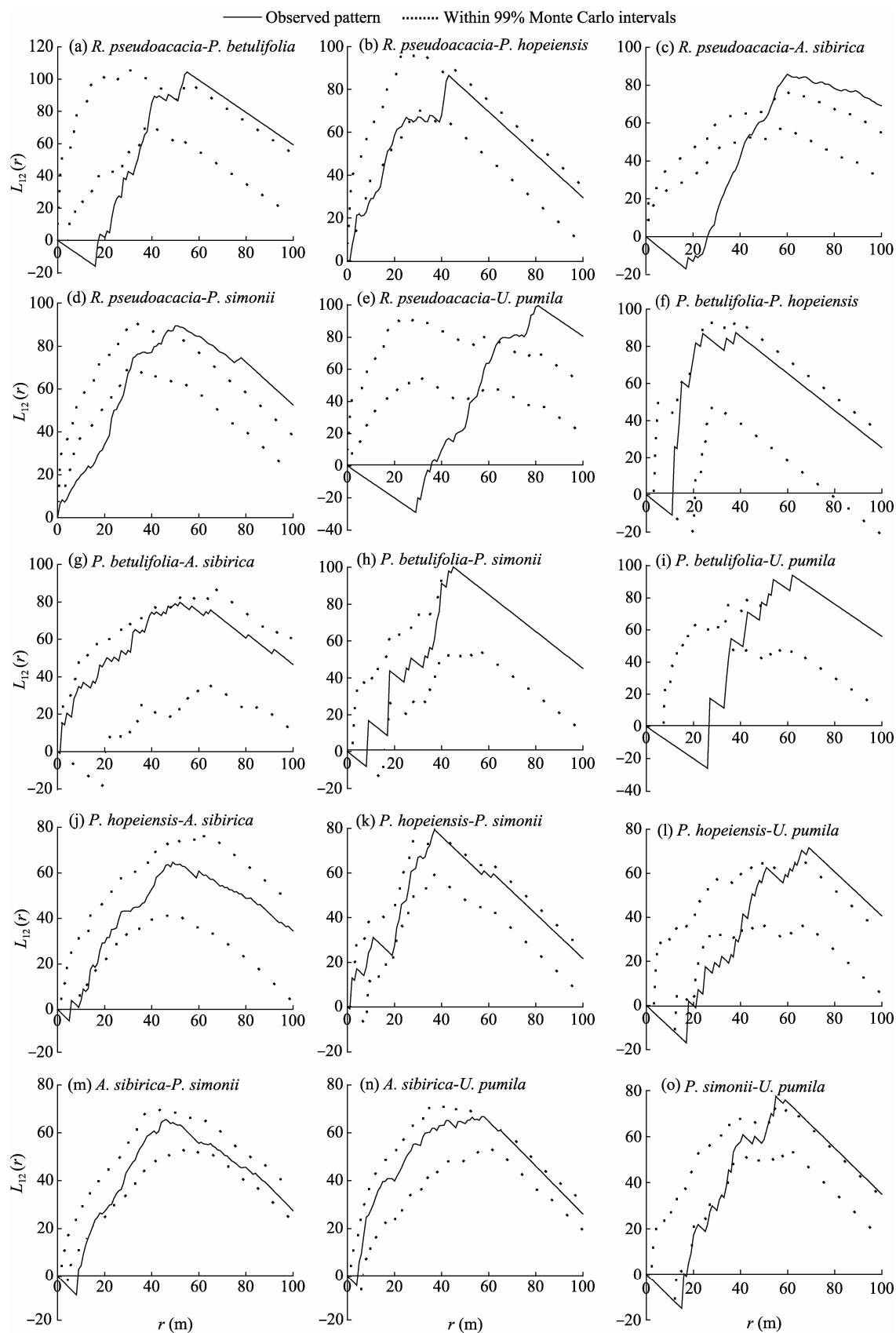


Fig. 6 Bivariate analyses exploring the spatial associations of the given species with all other species on slope B at the scale of 0–100 m

conditions for afforestation, and vegetation configuration models were proposed for the six regions (Yang et al., 1994). Subsequently, vegetation configuration models were adjusted by the loess slope, the gully slope, the top of the loess hill and the gully bottom according to the distribution of soil moisture, fertility as well as the sunlight and temperature on the slope (Ren et al., 2001). The traditional forestation model used uniform planting points with the same row spacing along the contours based on the site conditions of the slopes (Zou et al., 1980; Zhu et al., 2012), but did not take into account the catchment effect of microtopography (Li et al., 2011; Wang et al., 2011). Considering microtopography types as the basic forestation units produced different conclusions from the traditional model used for the Loess Plateau.

3.1 Intraspecies spatial patterns

The spatial distribution pattern of tree populations is closely related to the spatial scale (Lai et al., 2010). Manabe et al. (2000) proposed that the spatial pattern and spatial association pattern of tree species may be affected by intraspecies competition and the method of seed dispersal at smaller scales, whereas at larger scales, they may be determined by the heterogeneity or patchiness of the species distribution and different environmental conditions (such as terrain and soil moisture). In our study, the slope scales (5 hm²) were large, and the topographical characteristics of the microtopography affected the redistribution of soil moisture and nutrients (Zhao et al., 2010; Wang et al., 2011; Zhu et al., 2012). Therefore, the intraspecies spatial patterns of the species in our study were different for different microtopographies. The spatial pattern of *R. pseudoacacia* showed aggregated distribution at 0–100 m and all individuals lived in the gully on slope B, because this species does not like wind and the soil moisture of the gully was greater than that of the other microtopographies (Wang et al., 2012). So the intraspecies competition of *R. pseudoacacia* was weaker. The spatial distribution pattern of the other tree species varied from random to aggregated distribution, and then reverted to random distribution. This was mainly because there were few individuals when the scale was smaller, whereas several tree species formed patches (aggregated distribution) following the shape of the microtopography types on

the microtopography scale. Nevertheless, when the scale was larger than the microtopography scale, the soil moisture and nutrients of the slope were unevenly distributed, and the conditions of soil moisture and nutrients were better in the microtopography for the growth of tree species (Wang et al., 2011; Zhang et al., 2011a, b). Therefore, the intraspecies competition gradually became stronger, and the spatial distribution pattern changed from aggregated to random distribution. But the largest aggregated radiuses were less than 30 m. However, the intraspecies spatial distribution showed weaker competition and slight aggregation, and the maximum aggregated radiuses of the tree species were larger than 30 m, because of the uniform distribution of soil moisture and nutrients in slope A. In previous studies, the intraspecies spatial pattern also changed as the habitat conditions, such as terrain and soil moisture, varied (Richard Condit et al., 2000; Caillaud et al., 2010; Liu et al., 2012).

Therefore, the univariate spatial patterns of tree species in slope A and slope B may indicate that the effect of microtopographical factors on the intraspecies spatial distribution of all tree species on slope B was greater than intraspecies competition, because of the difference in the univariate spatial pattern between slopes A and B. The maximum aggregated radiuses for slope B were less than 30 m, yet those for slope A were larger than 28 m. This indicates that all the trees were arranged in small clumps in slope B. However, the aggregation intensities of all the tree species in slope B were larger than that of *A. sibirica* and *U. pumila* in slope A. These results also confirm that microtopography types should determine the choice of tree species for near-natural forestation.

3.2 Interspecies spatial associations

The interspecies spatial association patterns at a community-wide scale revealed that microtopography affected the bivariate spatial patterns and supported the mixed afforestation models on the microtopography slope at the scale of 0–100 m. For example, the species pairs, such as *P. betulifolia* and *P. hopeiensis*, *P. betulifolia* and *A. sibirica*, *P. betulifolia* and *P. simonii*, *P. betulifolia* and *U. pumila*, *P. hopeiensis* and *A. sibirica*, *P. hopeiensis* and *P. simonii*, *A. sibirica* and *P. simonii*, and *A. sibirica* and *U. pumila*, could be considered as mixed afforestation. However,

the interspecies competition between *R. pseudoacacia* and the other tree species changed from strong to weak as the scale increased, because the *R. pseudoacacia* individuals were distributed in the gully at the scale of approximately 30 m. Similarly, *U. pumila* and *P. hopeiensis*, and *U. pumila* and *P. simonii* also displayed a similar spatial association pattern, because the *U. pumila* individuals lived on the scarp and had a preference for full sunlight. However, they were shorter than the other tree species individuals (except *R. pseudoacacia*), and various species individuals inhibited each other. Franklin et al. (2002) and North et al. (2004) compared species composition, structure, spatial pattern and environmental factors (such as light and soil moisture) between two old-growth forests in the Pacific Northwest and southern Sierra Nevada, respectively. They found that the bivariate spatial patterns were influenced by higher moisture, shade tolerance, scale and topography. In addition, Li et al. (2011) found that the spatial associations of different strata were affected by the spatial scale and forest stand strata in a Schrenk Spruce forest of Northwest China. The results of all the above studies are similar to those of this study.

However, for the uniform slope A, *A. sibirica* was the main species, with fewer *P. simonii* and *U. pumila* individuals present. Because *P. simonii* individuals formed clumps and lived in the gaps of *A. sibirica*, the spatial association of *P. simonii* with *A. sibirica* was not strongly negative at the scale of 0–100 m. However, the spatial associations of *U. pumila* with *A. sibirica*, and *U. pumila* with *P. simonii* were strongly negative at the scale of 0–100 m, which may be due to the photophilic characteristics of *U. pumila* (Liu et al., 2012).

4 Conclusions

The use of spatial point pattern analysis is a complementary approach to the experimental study of plant communities at the level of species individuals. In this study area, microhabitats created by microtopography affected the intraspecies spatial pattern and the interspecies spatial association of tree species. The slope microtopography led to aggregated distribution of all tree species on the smaller scale and resulted in changes from significantly negative association to

significantly positive association for the tree species pairs. The results of this study show that microtopography plays an important role in near-natural forestation, particularly in the fragmented semi-arid area of China. More importantly, microtopography, including artificial microtopography, should be considered as the basic unit in afforestation to speed up the ecological restoration in semi-arid areas.

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