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RESEARCH ARTICLE

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Microenvironmental heterogeneity of physical soil properties in a broad-leaved *Pinus koraiensis* forest gap

Abstract Microenvironmental heterogeneity of soil physical properties in 0–20 cm and 20–40 cm soil layers in a broad-leaved *Pinus koraiensis* forest gap in Xiao Xing'anling Mountains were analyzed by geostatistical method. The results show that the amount of soil water, saturation water capacity, capillary water capacity and porosity in the top layer were greater than those in the lower layer, except for bulk density, where the opposite applied. Soil physical properties in the top soil layer had relatively higher ranges and coefficients of variation. The total and auto correlation spatial heterogeneity of soil physical properties in the top layer were larger than those in the lower layer. The soil water had a strong anisotropic structure in an easterly and northerly direction, but porosity shows isotropy in the same directions. With increasing spatial distance, the other three physical factors exhibited anisotropic structures. The mutual effect between semi-variograms of soil physical properties in the top layer within the spatial autocorrelation range was not significant. For spatial distribution of physical properties within different layers, the patches at the middle and lower ranks in the forest gap dominated. Patches at higher rank were only distributed in the 0–20 cm soil layer and were located north of the forest gap center.

Keywords broad-leaved *Pinus koraiensis* forest, forest gap, physical soil property, microenvironmental heterogeneity

1 Introduction

Forest gaps (canopy gaps) as small-scale disturbances, frequently occurring in forest ecosystems, are an important phase in the cycle of forest regeneration. Because of their special microenvironmental characteristics, they do not only provide regeneration sites for seedlings, but also take an important role in preserving forest structure, dynamics and species diversity (Brett et al., 1998). Many factors, such as improvement of light environment, water and heat conditions, changes in microtopography and decay of fallen trees after forest gap formation, lead to the spatial variation in soil physical properties within canopy gaps. Spatial soil heterogeneity is one of the most important soil attributes (Burgess and Webster, 1980). Research in spatial soil heterogeneity is theoretically very significant, not only to understand soil formation processes, its structure and function, but also to provide a definite reference for studying spatial plant distribution patterns and their effect on plant growth.

Broad-leaved *Pinus koraiensis* forests are generally regarded as a forest resource with great value and high yield, but it is confronted with a resource and ecological crisis as a result of excessive cutting. The objective of our study was to analyze spatial heterogeneity of soil physical properties in 0–20 and 20–40 cm soil layers in a broad-leaved *P. koraiensis* forest gap by a geostatistical theory and method in geography and to provide basic data and theoretical evidence for the research on forest gap regeneration, sustainable management of broad-leaved *P. koraiensis* forest ecosystem and a full explanation of biodiversity preservation mechanisms.

2 Study area

The study was carried out at the Liangshui National Nature Reserve of Northeast Forestry University (47°6′49″–47°16′10″N, 128°47′8″–128°57′19″E) in Dailing District, Yichun City, Heilongjiang Province, which lies in the easternmost part of Eurasia. The climate in this area is classified as a temperate continental climate with short summers and long winters, low temperatures and little sunshine. The zonal soil is a dark brown soil. The non-zonal soil consists of meadow soil, swamp soil and peaty soil. The zonal vegetation is dominated by *P. koraiensis*

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coniferous and broad-leaved mixed forests and belongs to the northern subzone vegetation of coniferous and broad-leaved mixed forests in the temperate zone. Forest coverage amounts to 98%. The entire distribution region is subordinate to a typical sub-region of broad-leaved Korean pine forests, typical of the zonal type of climax community. As the main composition of the broad-leaved *P. koraiensis* forest, *P. koraiensis* dominates accompanied by many temperate broad–leaved species, such as *Tilia amurensis*, *T. mandshurica*, *Betula costata*, *Quercus mongolica*, *Populus ussuriensis* Kom., *Ulmus laciniata* Mayr. and *Acer mono*.

3 Materials and methods

3.1 Soil sampling and analysis

The downward study site is located in a broad-leaved *P. koraiensis* forest at an elevation of 420 m, with a slope grade of 10–15° and a northern aspect. The plot area is 20 m × 20 m. Many overstory tree species, such as *P. koraiensis*, *Betula costata*, *Populus ussuriensis* Kom., *Betula platyphylla*, *Ulmus japonica*, *Acer ukurunduense* and understory tree species, such as *Syringa reticulata* var. *mandshurica*, *Acanthopanax senticosus*, *Corylus mandshurica*, and herbaceous plants (*Carex* spp. and others) were in our plot. The canopy gap size was about 200 m^2 created by multiple gap-makers. The reason for the forest gap formation is complicated, such as breakdown, snags and fallen trees (mound and pit). Tree species at the edge of the forest gap are mainly *P. koraiensis* and *B. costata* with an average height of 17.5 m. Sixty five sampling locations were selected in the forest gap and at the edge in the form of a regular grid. The minimum sampling interval was 2 m and the maximum 22.6 m (Fig. 1). In May, 2006, a soil profile was dug at every sampling location. Soil samples in the 0–20 cm and 20–40 cm soil layers were taken out by means of a central knife in order to measure soil physical properties. The soil samples were taken out by using aluminum boxes to determine the gravimetric soil water content and to further calculate the amount of soil water. The gravimetric of the soil water was measured by a drying method. Bulk density, saturation water capacity, capillary water capacity and porosity were measured by the central knife method (Chen, 2005).

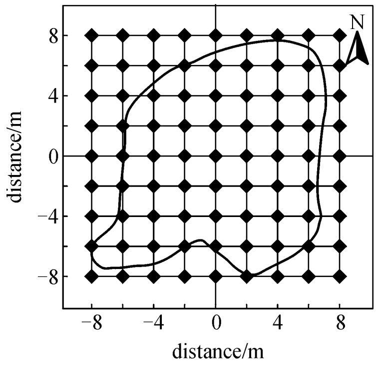

Fig. 1 Sampling location of soil in field. Note: abscissa and ordinate mean distance from centre of forest gap (m). The black line indicates the approximate contour of the gap.

3.2 Statistical analysis

In order to evaluate the average state and degree of total variation of the soil physical properties, their averages, standard deviations and coefficients of variation were calculated by classical statistics. The soil physical properties in and around the forest gap were analyzed, theoretical models of semi-variograms $\gamma(h)$ were established and their curves drawn by theory and method of geostatistics. The rules of spatial variation in soil physical properties were described by parameters, such as nugget, still, range, proportion, fractal dimension and anisotropic ratio (Wang, 1999; Wang et al., 2003). The soil physical properties in different positions were assessed by using a spatially local Kriging interpolation estimation. The spatial distribution patterns are illustrated. Basic statistics were obtained from SPSS Microsoft packages and spatial data statistics from GS + for Windows from a Microsoft geostatistics package.

4 Results and analysis

4.1 Classical statistics and analysis of soil physical properties in forest gap

Statistical parameters of the amount of soil water in different layers, bulk density, saturation water capacity, capillary water capacity and porosity in the forest gap in this broad-leaved *P. koraiensis* forest are presented in Table 1. The amount of soil water ($t = 4.60$), saturation water capacity ($t = 6.96$), capillary water capacity ($t = 7.44$) and porosity ($t = 7.04$) in the 0–20 cm soil layer were larger than those in 20–40 cm soil layer, for bulk density ($t = -6.63$), i.e., the opposite. There were highly significant differences between the 0–20 cm and the 20–40 cm soil layers ($p < 0.01$). The maximum values of soil physical properties in the same layer was 2–4 times as much as the minimum values. Their variation in the 0–20 cm soil layer was all greater than those in the 20–40 cm soil layer, but the variation moderated somewhat for other properties. That of capillary water capacity was the largest (0–20 cm: $CV = 27.69\%$; 20–40 cm: $CV = 26.94\%$), that of porosity was the smallest (0–20 cm: $CV = 12.77\%$; 20–40 cm: $CV = 11.80\%$) among all the five factors of soil physical properties stated above.

Table 1 Statistical parameters of physical properties at different soil layers

physical properties	depth/cm	mean	standard deviation	maximum	minimum	range	coefficient of variation/ %
volumetric soil water content/%	0–20	41.99	9.61	63.84	20.05	43.79	22.88
	20–40	35.35	6.56	47.47	20.97	26.50	18.54
Bulk density/ $(g\cdot cm^{-3})$	0–20	0.85	0.16	1.24	0.54	0.70	18.69
	20–40	1.04	0.17	1.45	0.75	0.70	16.00
saturation water capacity/%	0–20	78.69	20.99	122.56	37.18	85.41	26.67
	20–40	56.65	14.56	96.40	31.92	64.48	25.70
capillary water capacity/%	0–20	72.84	20.17	122.10	36.59	85.51	27.69
	20–40	50.40	13.58	81.17	20.96	60.21	26.94
porosity/%	0–20	64.70	8.26	88.53	45.67	42.85	12.77
	20–40	55.50	6.55	69.16	37.13	32.03	11.80

Note: 0–20 cm: $n = 73$; 20–40 cm: $n = 73$; $t_{0.05}$ (144) = 1.98; $t_{0.01}$ (144) = 2.61.

Table 2 Theoretical models of soil physical properties and corresponding parameters

physical properties	depth/cm	model	nugget (C_0)	still (C_0+ C)	range/m	proportion $C/(C_0+C)$	coefficient of determination (R^2)	fractal dimension
volumetric soil water content/%	0–20	Sph.	0.0025	0.0136	3.84	0.813	0.478	1.972
	20–40	Exp.	0.0017	0.0068	2.05	0.757	0.712	1.939
bulk density/ $(g\cdot cm^{-3})$	0–20	Sph.	0.216	1.0140	4.18	0.787	0.563	1.961
	20–40	Sph.	0.0199	0.0399	29.07	0.503	0.880	1.880
saturation water capacity/%	0–20	Sph.	0.0104	0.0649	4.11	0.840	0.374	1.973
	20–40	Exp.	0.0057	0.0225	2.15	0.749	0.620	1.931
capillary water capacity/%	0–20	Sph.	0.0087	0.0576	4.39	0.849	0.480	1.960
	20–40	Exp.	0.0039	0.0176	1.83	0.781	0.477	1.942
porosity/%	0–20	Exp.	0.0043	0.0176	2.05	0.756	0.528	1.968
	20–40	Exp.	0.0034	0.0134	1.26	0.746	0.267	1.934

Note: Sph. is spherical model; Exp. is exponential model.

4.2 Semi-variograms $\gamma(h)$ of soil physical properties in the forest gap

Because the spatial distribution of physical forest soil properties is continuous, their geostatistics in the forest gap may reflect rules of spatial variation. Semi-variograms $\gamma(h)$ are separated from the regionalization of variables in each sample variation based on their measurements (h) and can be used as tools for spatial analysis. The numerical value of a semi-variogram $\gamma(h)$ in the original coordinate system is called a nugget (C_0). A nugget means an experimental error and random variation caused by less than the minimum sampling scale and an arch high (C) represents spatial heterogeneity caused by autocorrelation. A still (C_0+ C) is equal to a nugget (C_0) plus an arch high (C). Spatial variation increases with increasing distance from the smaller nugget (C_0) to a relatively stable and larger still ($C_0 + C$). A still is the biggest variation of a determination factor. When the semi-variogram $\gamma(h)$ reaches a still, the spatial distance is known as the range, where its size expresses the scale of spatial heterogeneity (Wang et al., 2003).

The theoretical models of semi-variograms $\gamma(h)$ of soil physical properties and their related parameters are listed in Table 2. The still of all soil physical properties in the 0–20 cm layer were larger than those in the 20–40 cm layer. This result indicated that the degree of total spatial variation in soil physical properties in the topsoil layer was greater than that in the lower soil layer. The scale of spatial heterogeneity of the four physical factors, i.e., the amount of soil water, saturation water capacity, capillary water capacity and porosity in the 0–20 cm layer was greater than that in the 20–40 cm layer. Their spatial heterogeneity in the 0–20 cm layer was shown in the 2–4 m distance. In the 20–40 cm layer it was present in the 1–2 m distance for bulk density and it was the opposite case. The spatial heterogeneity in the 20–40 cm layer was expressed on a larger scale.

4.3 Components of spatial heterogeneity of soil physical properties in the forest gap

Spatial heterogeneity is mainly composed of two parts, i.e., a random part and an autocorrelation part. The ratio of nugget (C_0) to still ($C_0 + C$) and the ratio of arch high (C) to still ($C_0 + C$) are generally used to reflect the ratio of the random part or autocorrelation part to total spatial heterogeneity (Li and Reynolds, 1995). According to the ratio ($C/(C_0 + C)$) of arch high (C) to still ($C_0 + C$), spatial heterogeneity caused by spatial autocorrelation can be divided into three classes: $C/(C_0 + C) < 25\%$, weak variation; $25\% \leqslant C/(C_0 + C) \leqslant 75\%$, medium variation; $C/(C_0 + C) > 75\%$, strong variation (Cambardella et al., 1994).

The proportion ($C/(C_0 + C)$) of all soil physical properties in the 0–20 cm layer was larger than that in the 20–40 cm layer. This result shows that spatial heterogeneity of soil physical properties caused by spatial autocorrelation in the top soil layer was greater than that in the lower soil layer (Table 2). In spite of the top and lower soil layers, the spatial heterogeneity of the autocorrelation part was the main part of the total spatial heterogeneity. The spatial variation of bulk density (20–40 cm), water saturation capacity (20–40 cm) and porosity (20–40 cm) shows medium variation. The spatial heterogeneity of all soil physical properties induced by spatial autocorrelation in all soil layers exhibited strong variation. That of bulk density was the minimum at only 50.3%. Therefore, random variation on a small scale cannot be neglected. The spatial heterogeneity of the capillary water capacity (0–20 cm) was at maximum. 84.9% of the heterogeneity was brought about by spatial autocorrelation.

4.4 Anisotropy of soil physical properties in the forest gap

In our study, we judged the anisotropy of soil physical properties in the forest gap was from the ratio of semi-variograms $\gamma(h)$ in two directions: east and north. If this ratio fluctuated around 1, this illustrated that the change of the semi-variograms $\gamma(h)$ in both directions was similar and soil physical properties were isotropic. Otherwise, it was anisotropic. The anisotropic ratio of the amount of soil water (Fig. 2a) shows a comparatively large fluctuation. Its anisotropy was more obvious. The ratio of porosity (Fig. 2e) ranged around 1. Its anisotropy was not obvious. In fact, soil porosity shows isotropy. The anisotropic ratios of bulk density (Fig. 2b), saturation water capacity (Fig. 2c) and capillary water capacity (Fig. 2d) did not fluctuate widely within a range of 8 m and can be considered to be isotropic. These three physical soil factors in the 0–20 cm soil layer show apparent anisotropy at 10, 12 and 16 m, but their more apparent anisotropy in the 20–40 cm soil layer occurred at around 12 and 14 m.

4.5 Relativity of semi-variograms of soil physical properties in the forest gap

Correlation coefficients between all semi-variograms of soil physical properties within range of the 0–20 cm layer were less than those in the 20–40 cm layer. The degree of

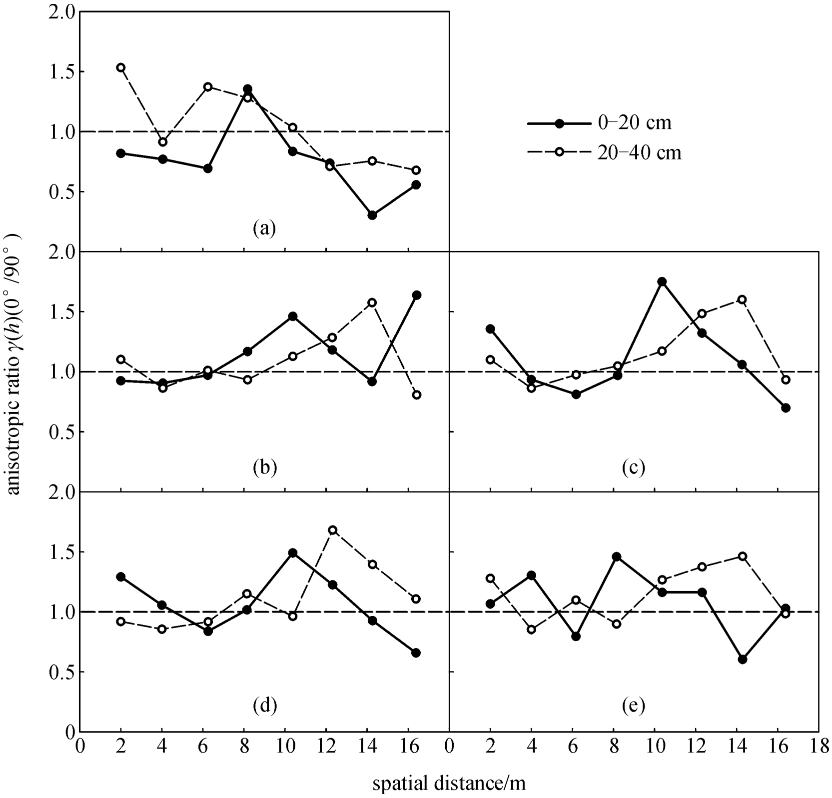

Fig. 2 Anisotropic ratios of semi-variograms in east and north directions. (a) soil water content, (b) bulk density, (c) saturation water capacity, (d) capillary water capacity, (e) porosity.

Table 3 Correlation coefficients between semi-variograms of soil physical properties within range

depth/cm	physical properties	volumetric soil water content/%	bulk density/(g·cm^{-3})	saturation water capacity /%	capillary water capacity /%
0–20	bulk density/(g·cm^{-3})	0.154			
	saturation water capacity /%	0.063	0.613		
	capillary water capacity /%	0.386	0.613	0.058	
	porosity /%	0.560	0.563	0.449	0.144
20–40	bulk density/(g·cm^{-3})	0.440			
	saturation water capacity/%	0.290	0.957**		
	capillary water capacity/%	0.503	0.884**	0.803*	
	porosity/%	0.571	0.788*	0.909**	0.523

Note: * means correlation significant at $\alpha = 0.05$ level; ** means correlation significant at $\alpha = 0.01$ level.

correlation between the semi-variograms of partial soil physical properties within these ranges reached significant and highly significant level between their semivariograms (Table 3). This result demonstrated that the relationship between soil physical properties in the lower layer were closer than those in the upper layer, but the semi-variograms of the soil physical properties within range of the top layer may be affected by other elements. In addition, lower correlation coefficients between the amount of soil water and the other four soil physical properties within range of the two soil layers indicated that their semi-variograms were little affected by the other four soil physical properties. They may be controlled by other major elements.

4.6 Spatial distribution patterns of soil physical properties in the forest gap

Data on limited sampling points were only obtained from the layout and sampling in the forest gap. If spatial distribution patterns of soil physical properties in the forest gap were fully taken into account, the variables at the non-sampling points would need to be interpolated and estimated. The method of Kriging spatial local interpolation and estimation can make the best linear unbiased estimates for the value of variables on the estimated points and can widely applied in ecological research.

In our study, soil physical properties in and around the forest gap were divided into five classes (a–e) (Fig. 3). For the 0–20 cm soil layer, the patches with large area in the middle rank (class c) in the forest gap dominated and their pattern intensity was large. Patches at the higher ranks (class a and b) were mainly located in the northern part of the forest gap, while the patches at the lower ranks (class d and e) were evenly distributed within the forest gap. For the 20–40 cm soil layer, the patches at the middle and lower ranks in the forest gap dominated (class c to e). The patches of class d occupied a larger area and their pattern intensity was relatively large. The patches of class c and e were evenly distributed within the forest gap. Patches at the relatively higher rank (class a and b) seldom occurred. As an example of porosity, for the 0–20 cm soil layer, the patches at middle rank (class c, 40%–60%) occupied large areas (about 50%). Patches at higher ranks (class a and b > 60%) were primarily located in the central and northern part of the forest gap. The patches of class d (20%–40%) dominated the patches at the lower ranks (class c and d < 40%). For the 20–40 cm soil layer, patches at relatively higher ranks (class a and b > 60%) were not present. Big patches of class d (20%–40%), occupying about 60% of the area, were in the majority. Patches of another two classes (class c, 40%–60%; class e, < 20%) were evenly distributed in the forest gap.

5 Discussion

Forest gaps (canopy gaps) are microstructures with special qualities and widely exist in many forests. Their formation strengthens the heterogeneity of the disturbed sites, which directly leads to changes in microtopography, increases in light levels and causes variation in temperature and humidity as well as in physical and chemical properties within forest gaps.

The results of the study by Wang and Wang (2000) show that apparent spatial heterogeneity exists in broad–leaved *P. koraiensis* forests. This result is basically consistent with those in our study. With reference to several parameters, such as range, proportion and fractal dimension, the degree of spatial heterogeneity of the soil physical properties within our broad–leaved *P. koraiensis* forest gap was higher than those inside a broad–leaved *P. koraiensis* forest. The main factors affecting our results were analyzed as follows:

After gap formation, mounds and pits of fallen trees and the emergence of root trays alter the microtopography within forest gaps, leading to a certain degree of direct interference with different soil layers (Harmon and Franklin, 1989). Furthermore, tree-falls in forest gaps, especially gap-makers, play an important role in the creation of a microtopography and supply of soil organic matter. These factors enlarge the degree of spatial

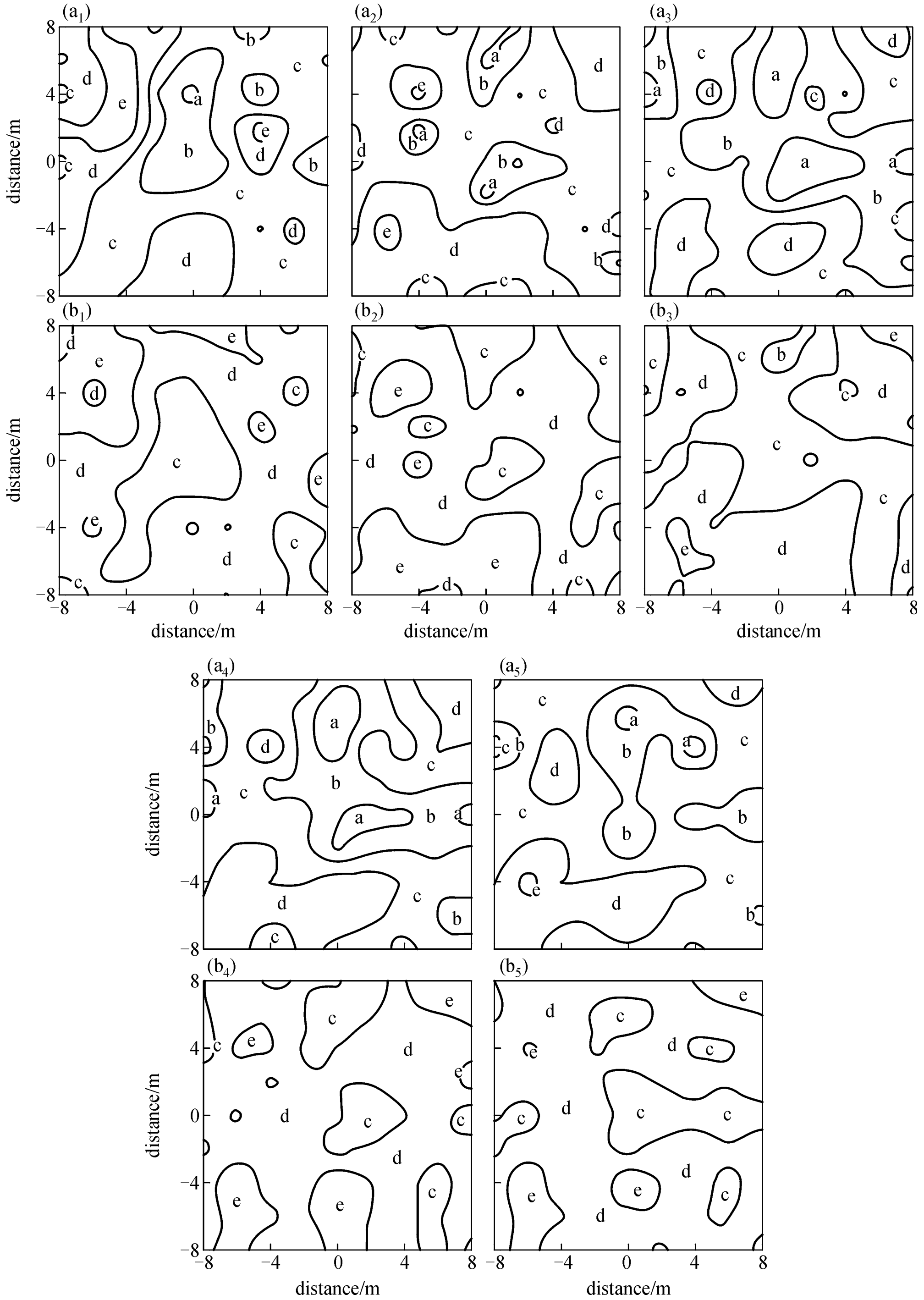

Fig. 3 Spatial distribution patterns of soil physical properties in forest gap.
Note: abscissa and ordinate are expressed as distance from gap center (m). Soil physical properties in and around forest gap are divided into five classes as follows: a_1 (0–20 cm soil layer) and b_1 (20–40 cm soil layer) represent soil water content (%), a > 60, 60 > b > 50, 50 > c > 40, 40 > d > 30, e < 30; a_2 (0–20 cm soil layer) and b_2 (20–40 cm soil layer) represent bulk density ($g \cdot cm^{-3}$), 0.6 < a, 0.7 > b > 0.6, 0.9 > c > 0.7, 1.1 > d > 0.9, e > 1.1; a_3 (0–20 cm soil layer) and b_3 (20–40 cm soil layer) represent saturation water capacity (%), a > 100, 100 > b > 80, 80 > c > 60, 60 > d > 40, e < 40; a_4 (0–20 cm soil layer) and b_4 (20–40 cm soil layer) represent capillary water capacity (%), a > 100, 100 > b > 80, 80 > c > 60, 60 > d > 40, e < 40; a_5 (0–20 cm soil layer) and b_5 (20–40 cm soil layer) represent porosity (%),a > 80, 80 > b > 60, 60 > c > 40, 40 > d > 20, e < 20.

heterogeneity of soil physical properties in forest gaps.

An uneven distribution of light levels on the soil surface in forest gaps might affect the decomposition of soil organic matter (Canham and Marks, 1985) and also causes an asymmetric distribution of soil organic matter, particularly on the soil surface. All these factors affect the spatial pattern of soil physical properties. Moreover, the light intensity was clearly higher in half of the northern part of the forest gap than that in other locations (Ritter et al., 2005) and photosynthesis active radiation (PAR) was also similar (Gagnon et al., 2003). We conclude that tree growth in the northern edge of the forest gap was better than in other locations. Their well-developed root systems and the rapid turnover of fine roots improved the physical properties of the soil. Rules of distribution of soil physical properties in this study basically agreed with those of light levels in past studies. It was, therefore, not difficult to conclude that the variation in light in the forest gap was a main element affecting soil physical properties.

Forest gap disturbances alter temperature and humidity conditions in a local environment. The maximum soil temperature in forest gaps is higher than that in the understory of the forest, but the minimum soil temperature was lower than that in the understory, its range in variation from maximum to minimum was larger and this would definitely affect soil humidity and decomposition of organic matter. Soil humidity in the top soil layer in the forest gap was lower than that in the understory, but the situation was reversed beyond a certain soil depth, i.e., soil humidity in forest gaps are higher than in the understories. Forest gaps change local soil humidity and result in the heterogeneity of soil humidity. This heterogeneous intensity is related to the size of the forest gap, as well as to dry and humid seasons (Canham, 1989; Zang, et al. 1999).

Forest gaps are a very important opportunity for regeneration and development of broad-leaved *P. koraiensis* forests. The microenvironment and growth of regeneration trees growth are differently controlled during the various phases of gap regeneration. Furthermore, microenvironment and the response of tree regeneration vary in differently sized forest gaps and with the different ways of gap formation. Mutual effect between environmental changes and tree growth exist (Canham, 1989; Zang, et al. 1999).Our study only referred to the forest gap of a definite size and in a certain phase of regeneration. We explained the spatial heterogeneity of soil physical properties in this special forest gap. For forest gaps of different sizes, different gap-makers and in a certain regeneration phase, the characteristics of spatial variation of soil physical properties is still not clear. Many long-term researches on location are still needed in the future.

6 Conclusions

The amount of soil water, saturation water capacity, capillary water capacity and porosity in the 0–20 cm layer in this broad–leaved *P. koraiensis* forest gap were greater than those in the 20–40 cm layer, except for bulk density, for which the opposite applied. As compared with the soil physical properties in the lower layer, those in the topsoil layer had relatively higher ranges and coefficients of variation.

The degree of total spatial heterogeneity of soil physical properties in the 0–20 cm layer in the broad–leaved *P. koraiensis* forest gap was higher than that in the 20–40 cm layer. The heterogeneity of soil physical properties caused by spatial autocorrelation also presented the same results. In spite of the top and lower soil layers, the spatial heterogeneity of the autocorrelation part was the major part of total spatial heterogeneity. The range of soil physical properties in the 0–20 cm layer was about 2–4 m. The spatial variation of bulk density in the 20–40 cm layer was shown on a larger scale. The range of the other four soil physical properties was about 1–2 m. The amount of soil water had a strong anisotropic structure in easterly and northerly directions, but porosity presented isotropy in the same direction. The other three physical properties exhibited isotropic structures in small spatial distances, but anisotropic structures with increasing spatial distances.

The mutual effect between semi-variograms of soil physical properties in the 0–20 cm layer within spatial autocorrelation range was not significant. The semi-variogram of the amount of soil water within spatial autocorrelation range of the two soil layers was little affected by the other four soil physical properties.

Given the spatial distribution patterns of soil physical properties in this broad-leaved *P. koraiensis* forest gap, the patches at the middle and lower ranks dominate. Patches at relatively higher ranks only occurred in the 0–20 cm soil layer and were located in the northern part of the central gap.

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