



Plant species effect on the spatial patterns of soil properties in the Mu-us desert ecosystem, Inner Mongolia, China

Muneto Hirobe^{1,5}, Nobuhito Ohte², Nanae Karasawa³, Guo-sheng Zhang⁴, Lin-he Wang⁴ & Ken Yoshikawa³

¹Laboratory of Forest Ecology, Division of Environmental Science and Technology, Graduate School of Agriculture, Kyoto University, Kyoto 606-8502, Japan

²Laboratory of Forest Hydrology, Division of Environmental Science and Technology, Graduate School of Agriculture, Kyoto University, Kyoto 606-8502, Japan

³Faculty of Agriculture, Okayama University, Okayama 700-8530, Japan

⁴Inner Mongolia Agricultural University, Huhhot, Inner Mongolia, China

⁵Corresponding author*

Received 21 November 2000. Accepted in revised form 23 April 2001.

Key words: *Artemisia ordosica*, geostatistics, Mu-us desert, *Sabina vulgaris*, soil heterogeneity, soil physico-chemical properties

Abstract

Although *Artemisia ordosica* Krasch. and *Sabina vulgaris* Ant. are the dominant shrub species in the Mu-us desert ecosystem, they differ in their botanical traits. We investigated the spatial patterns of soil properties using geostatistical analysis to examine the effect of plant species on these spatial patterns. Comparison among three microsite types (under *A. ordosica*, under *S. vulgaris*, and the opening between vegetation) showed that *A. ordosica* generally had less effect than *S. vulgaris* on local soil properties. The long life-span, prostrate life-form, and evergreen leaf-habit of *S. vulgaris* may lead to a higher accumulation of organic and fine materials under *S. vulgaris*. The range of spatial autocorrelation found in the mass of organic matter on the soil surface was smaller than that of the coverage of *S. vulgaris* (11.5 m) which corresponded to the canopy patch size of this species, and was longer than the canopy patch size of *A. ordosica*. The ranges of total C and N, and pH (11.7–15.6 m) were similar to that of *S. vulgaris*. The range of available P (106.3 m) was comparable to that of the coverage of *A. ordosica* (86.2 m) considered to be the scale of the distribution of this species. The ranges of silt+clay and exchangeable K, Ca, and Mg (31.0–46.7 m) were not related to plant presence, and were similar to that of topography (43.1 m).

Introduction

Plant-induced heterogeneity in soil properties has been recognized in many types of ecosystems (Boettcher and Kalisz, 1990; Charley and West, 1975; Hirose and Tateno, 1984; Matson, 1990; Schlesinger and Pilmanis, 1998). Such heterogeneity may be particularly important in dry ecosystems because the aboveground plant cover is often discontinuous in these regions. Individual plants concentrate biomass in soils beneath

their canopies and modify biogeochemical processes (Burke, 1989; Burke et al., 1989; Schlesinger et al., 1990). Thus, the presence and absence of plant cover often present striking contrasts between microsites under shrub canopies and bare soil, called 'islands of fertility', in arid and semiarid ecosystems (Hook et al., 1991; Kelly and Burke, 1997; Schlesinger et al., 1996; Vinton and Burke, 1995). Plant species forming the aboveground vegetation cover are considered to have differential effects on local soil properties, and Chen and Stark (2000) examined them in an experimental plot where sagebrush and crested wheatgrass

* Fax.: +81-75-753-6080.

E-mail: mhirobe@kais.kyoto-u.ac.jp

had been planted. In naturally established stands of vegetation, however, the importance of plant presence may overshadow that of plant species (Vinton and Burke, 1995), as found in the results of pinyon-juniper woodlands (Padien and Lajtha, 1992) and shortgrass steppe (Vinton and Burke, 1995).

In the Mu-us desert ecosystem, two shrub species dominate the vegetation, but they have many differences in traits (Kobayashi, 1990; Yamanaka et al., 1998). *Artemisia ordosica* Krasch. is a deciduous half-shrub and has a life-span of about 10 years, while *Sabina vulgaris* Ant. is an evergreen coniferous shrub having a prostrate life-form and life-span of more than 50 years. These two species also develop canopy patches in quite different sizes. The spatial scale and magnitude of heterogeneity of soil properties associated with shrub islands depend on the spatial pattern of plant biomass (Hook et al., 1991). The life-span influences the spatial pattern of plant cover through time directly, and the life-form of dominant species is an important factor determining plant biomass (Vinton and Burke, 1995). Thus, it is expected that these striking differences in plant traits between *A. ordosica* and *S. vulgaris* will affect the biogeochemistry under their canopy including soil organic matter accumulation, and hence the spatial patterns of soil properties. The primary objectives of this study were to clarify the spatial patterns of soil properties and to examine the effect of shrub covers on these spatial patterns in the Mu-us desert ecosystem.

In this study, we performed a geostatistical analysis to evaluate the extent of the effect of the plant's presence and of abiotic processes on the spatial patterns of soil properties. Geostatistical analysis can also help us to determine the effect of *A. ordosica* and *S. vulgaris* on the spatial patterns of soil properties, because these two dominant shrubs in Mu-us desert show contrasting canopy patch sizes. Our hypotheses were that: (1) the spatial patterns of soil properties would depend on the scale of spatial autocorrelation determined by the patch size of *A. ordosica* and that of *S. vulgaris* depending on the relative influence of these two species, especially for the properties closely related biological processes (e.g., C and N contents), and (2) the different scale of autocorrelation may be seen for the properties affected more by physical processes (e.g., soil movement) than biological processes.

Materials and methods

Study site

The study was conducted at the experimental site of the Mu-us Shamo Desert Research Center (38°57'–39°01' N, 109°02'–109°17'E) in the Mu-us desert in the southern part of the Ordos plateau, Inner Mongolia, China. The elevation is about 1320 m. The mean annual temperature and precipitation in this area are 6.5°C and 345 mm, respectively (Kobayashi et al., 1995). Most of the precipitation falls as rain from July to September. The soil is derived from Mesozoic sandstone. The vegetation is dominated by two shrub species, *Artemisia ordosica* and *Sabina vulgaris* (Kobayashi, 1990; Yamanaka et al., 1998). *Artemisia ordosica* is a deciduous half-shrub and has a life-span of about 10 years. The size of an individual is 0.5–1 m in height and less than 2 m in canopy diameter. The patch size of *A. ordosica* generally corresponds with its individual size. In contrast, *Sabina vulgaris* is an evergreen coniferous shrub having a prostrate life-form, and a life-span of more than 50 years. The height is usually less than 1.5 m, but *S. vulgaris* community sometimes achieves a patch more than 15 m in canopy diameter. The average above- and belowground biomass of *A. ordosica* were about 260 and 200 g/m², and those of *S. vulgaris* were about 1600 and 2700 g/m², respectively (Yoshikawa and Li, 1989). Other common species include herbaceous species such as *Poa mongolica* (Rendile) Keng, *Asparagus dauricus* Fisch. ex Link, and *Cynanchum komarovii* Al. Iljinski. Plant nomenclature follows the Commissione Redactorum Florae Intramongolicae (1985, 1993, 1994).

A total of 201 sampling locations were established at 1-m intervals along a 200-m line in the slope length. The maximum difference in the height of the sampling locations was 3.1 m and the topography was rather gentle. The relative height of a sampling location was calculated by assuming the height of the lowest sampling location as zero. The census of vegetation and the soil sampling were carried out in late August 1999.

The census of vegetation

Along the 200-m line, we established a total of 201 quadrats. Each quadrat was a 1 × 1-m square having the center at each sampling location. The plant species and their coverage (%) in each quadrat were investigated.

Sampling of organic matter on the soil surface and soil

For each sampling location, we noted whether it was under the canopy of vegetation or opening between plants, and the plant species was also noted when it was beneath the vegetation. At each sampling location of 10×10 cm, organic matter on the soil surface was sampled and soil was taken from a 0–5-cm depth by a 100-ml soil core.

Laboratory analysis

Each sample of organic matter on the soil surface was oven-dried at 105°C and weighed. Each air-dried soil sample was sieved (<2 mm) and used for analyses of silt+clay content, total C and N, pH (H₂O), available P, exchangeable cations (K⁺, Na⁺, Ca²⁺, and Mg²⁺).

The silt+clay content was measured by sieving (0.02 mm mesh) after digestion of organic matter with H₂O₂ (Gee and Bauder, 1986). The total C and N concentrations were determined using a NC analyzer (Sumika Chemical Analysis Service, NC-900, Osaka, Japan). Soil pH was measured by a glass electrode in a 1:2.5 soil–water suspension. For available P, a 2.5-g subsample of soil was extracted with 50 ml of 0.5 M NaHCO₃, adjusted to pH 8.5, and the concentration of P in the extracts was determined colorimetrically using a molybdate–ascorbic acid method (Olsen and Sommers, 1982).

The exchangeable cations were extracted by shaking a 4-g subsample of soil with 40 ml of 1 M NH₄C₂H₃O₂ solution, adjusted to pH 7.0. The concentrations of K⁺ and Na⁺ in the extracts were determined by flame emission, and the concentrations of Ca²⁺ and Mg²⁺ in the extracts were determined by atomic absorption on a atomic absorption spectrophotometer (Hitachi, 170-30S, Tokyo, Japan).

Statistical analysis

The difference of average vegetation coverage among three height classes in the sampling location was determined by the chi-square test (SPSS, 1999). The multiple comparison of mean values among three microsite types (under the canopy of *A. ordosica* or *S. vulgaris*, or the opening between vegetation) was performed by the sequential Bonferroni test (Rice, 1989) after the determination of pairwise *P* values by Mann–Whitney test (SPSS, 1999).

The patterns of spatial variations in the relative height of the sampling location, the coverages of *A.*

ordosica and *S. vulgaris*, and soil properties were analyzed geostatistically (Goovaerts, 1998; Rossi et al., 1992). To minimize the effect of extreme outliers and to approximate a normal distribution, the data of the relative height of the sampling location and soil properties except pH were adjusted using a log_e(*x* + 1) transformation, and those of vegetation coverages were adjusted using an arcsine transformation. The calculation of semivariances from the field data and the fitting of models to semivariograms were performed using GS⁺ (Robertson, 1998). The semivariance, $\gamma(\mathbf{h})$, is calculated for each specific lag distance \mathbf{h} :

$$\gamma(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{i=1}^{N(\mathbf{h})} [z(x_i) - z(x_i + \mathbf{h})]^2 \quad (1)$$

where $N(\mathbf{h})$ is the number of pairs of points separated by distances \mathbf{h} , $z(x_i)$ is the measured sample value at point x_i , and $z(x_i + \mathbf{h})$ is the sample value at point $x_i + \mathbf{h}$.

The semivariance data was fit to either spherical, exponential, or linear functions depending on the better reduced sum of squares. Since semivariograms tended to become erratic at larger lag intervals, all semivariograms but one were constructed using 1-m lag intervals to a lag of 100 m (50% of the maximum lag interval) to ensure the substantial sample pairs for each lag interval. This resulted in a minimum of 101 pairs in the 99–100 m-interval and a maximum of 200 pairs in the smallest lag interval (0–1 m). One exception to this was the coverage of *S. vulgaris*; the semivariogram of this variate was fit to linear function at this scale, but suggested a nested structure. Therefore, separate variograms were fit over a lag of 75 and 100 m for the coverage of *S. vulgaris*. Model parameters were used to evaluate the magnitude of spatial dependence and the scale of spatial autocorrelation for each variate (Jackson and Caldwell, 1993; Robertson, 1987; Robertson et al., 1988). Nugget (C_0) is the variance that does not appear to be spatially dependent, and is either a random error or represents spatial dependence at scales smaller than the minimum distance examined (Isaaks and Srivastava, 1989). The scale of spatial autocorrelation is indicated by estimated spatial autocorrelation ‘range’. The proportion of structural variance (C) to the estimated total sample variation (sill; $C + C_0$) was calculated for the evaluation of the magnitude of spatial dependence.

Pearson’s correlation coefficient was calculated between the relative height of a sampling location

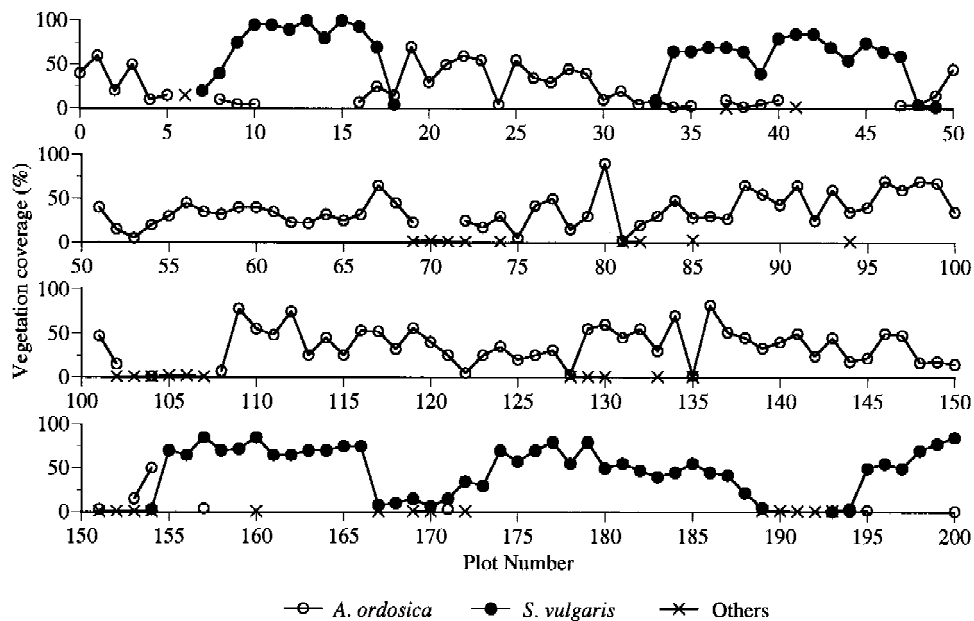


Figure 1. The coverages (%) of *Artemisia ordosica* (○), *Sabina vulgaris* (●), and other vegetation (×) at each sampling location.

Table 1. Average vegetation coverages of *Artemisia ordosica* and *Sabina vulgaris* in three height classes of the sampling location

Relative height of the sampling location (m)	Vegetation coverage (%)	
	<i>A. ordosica</i> ($P=0.373^\dagger$)	<i>S. vulgaris</i> ($P=0.012^\dagger$)
0-01	27.4	14.4
1-2	21.1	14.7
2<	19.0	29.3

† The significance of the χ^2 statistics conducted to compare the coverage of *A. ordosica* ($\chi^2=2.0$) or *S. vulgaris* ($\chi^2=8.8$), according to each height class. The χ^2 statistics was calculated based on the expected 1:1:1 ratio among three height classes.

and each soil property (SPSS, 1999). For correlation analysis, each data except pH was adjusted using a $\log_e(x + 1)$ transformation to approximate a normal distribution, since they were not normally distributed ($\chi^2 > 14.7$ with 7 df $P < 0.05$).

Results

Vegetation

The vegetation coverage in the study plot was 42.4%, and the coverages of *Artemisia ordosica* and *Sabina vulgaris* were 22.1 and 20.0%, respectively (Fig. 1).

The coverage of other plant species was only 0.3% and all of them were herbaceous species. The vegetation cover was discontinuous and the canopy of an individual of *A. ordosica* or a community patch of *S. vulgaris* was isolated from the canopies of surrounding *A. ordosica* or *S. vulgaris*. In our study plot, four entire patches and a part of a patch of *S. vulgaris* community was included. The coverage of *A. ordosica* was not different at any height classes in the sampling location, while that of *S. vulgaris* was high in the height class of (>2 m) (Table 1).

Variations of soil properties

The measured soil properties varied markedly, and the ranges were sometimes spanning an order of magnitude or more (Table 2). Coefficient of variation (cv) was the highest for the mass of organic matter on the soil surface, and most properties showed cvs between 30 and 60%.

In the comparison of mean values among microsite types, organic matter on the soil surface was greater in samples taken under vegetations than in samples from openings, and was greater under *S. vulgaris* than under *A. ordosica* (Table 3). Total C and N, and C/N ratio were greater under *S. vulgaris* than under *A. ordosica* or openings. Silt+clay and exchangeable Na were also greater under *S. vulgaris* than under *A. ordosica*, and exchangeable Ca and Mg were lower under *A. or-*

Table 2. The overall means and coefficient of variation [(SD÷mean)×100%] of selected soil properties in the Mu-us desert ecosystem (n=203). Soil properties other than the mass of organic matter on the soil surface were measured for soils taken from 0–5 cm depth

Soil property	Mean (min.–max.)	CV
Organic matter on the soil surface (g/100 cm ²)	1.72 (0.00–17.1)	161
Silt±clay (kg/m ²)	5.86 (1.28–13.4)	46
Total C (g/m ²)	546.2 (131.0–1627.5)	52
Total N (g/m ²)	41.1 (9.83–114.6)	51
C/N ratio	13.4 (8.20–18.5)	11
pH (H ₂ O)	8.61 (8.14–9.06)	2
Available P (g/m ²)	0.41 (0.06–1.05)	56
Exchangeable K (g/m ²)	9.77 (4.29–34.1)	38
Exchangeable Na (g/m ²)	0.76 (0.24–4.12)	48
Exchangeable Ca (g/m ²)	165.4 (59.9–236.6)	24
Exchangeable Mg (g/m ²)	5.54 (1.98–9.91)	30

Table 3. Selected soil properties under shrubs (*A. ordosica* or *S. vulgaris*) and in openings in the Mu-us desert ecosystem. Soil properties other than the mass of organic matter on the soil surface were measured for soils taken from 0–5 cm depth

Soil property	Microsite type		
	<i>A. ordosica</i> (n=65)	<i>S. vulgaris</i> (n=51)	Opening (n=85)
Organic matter on the soil surface (g/100 cm ²)	1.04 (0.14) ^a	4.21 (0.51) ^b	0.74 (0.22) ^c
Silt+clay (kg/m ²)	5.09 (0.27) ^a	6.05 (0.28) ^b	6.33 (0.35) ^{ab}
Total C (g/m ²)	486.0 (29.0) ^a	663.4 (42.0) ^b	522.0 (32.2) ^a
Total N (g/m ²)	37.5 (2.38) ^a	46.2 (2.52) ^b	40.7 (2.55) ^a
C/N ratio	13.2 (0.15) ^a	14.2 (0.21) ^b	13.0 (0.16) ^a
pH (H ₂ O)	8.61 (0.02) ^a	8.59 (0.02) ^a	8.62 (0.02) ^a
Available P (g/m ²)	0.50 (0.03) ^a	0.22 (0.01) ^b	0.45 (0.02) ^a
Exchangeable K (g/m ²)	10.2 (0.46) ^a	9.02 (0.26) ^a	9.88 (0.49) ^a
Exchangeable Na (g/m ²)	0.70 (0.03) ^a	0.80 (0.03) ^b	0.78 (0.05) ^{ab}
Exchangeable Ca (g/m ²)	151.4 (4.40) ^a	182.0 (3.38) ^b	166.0 (5.06) ^b
Exchangeable Mg (g/m ²)	4.98 (0.16) ^a	5.98 (0.18) ^b	5.70 (0.22) ^b

Means (standard errors). The values denoted by the same letter are not significantly different from each other among microsite types at $P < 0.05$ (the sequential Bonferroni test after pairwise Mann–Whitney test).

Table 4. Summary of variogram model parameters for the relative height of a sampling location and the coverage of vegetation in the Mu-us desert ecosystem. All semivariograms but one were constructed using 1-m lag intervals to a maximum lag of 100 m

Variate	Model	r^2	Nugget (C_0)	Sill ($C_0 + C$)	Range (m)	$C/(C_0 + C)$
Relative height	Spherical [#]	0.95	0	0.179	43.1	1.00
Coverage of <i>A. ordosica</i>	Spherical [#]	0.92	0.035	0.085	86.2	0.59
Coverage of <i>S. vulgaris</i>	Linear	0.73	0.081	–	–	–
	Spherical ^{#†}	0.37	0	0.139	11.5	1.00

[#]For $h \leq \text{range}$, $\gamma(h) = C_0 + (C - C_0) \cdot \{1.5 \cdot (h/\text{range}) - 0.5 \cdot (h/\text{range})^3\}$; $h > \text{range}$, $\gamma(h) = C$.

[†]Semivariogram was constructed using 1 m lag intervals to a maximum lag of 75 m.

Table 5. Summary of variogram model parameters for soil properties in the Mu-us desert ecosystem. All semivariograms were constructed using 1 m lag intervals to a maximum lag of 100 m

Soil property	Model	r^2	Nugget (C_0)	Sill ($C_0 + C$)	Range (m)	$C/(C_0 + C)$
Organic matter on the soil surface	Exponential [†]	0.20	0.064	0.432	5.1	0.85
Silt+clay	Spherical [#]	0.71	0.038	0.176	34.2	0.78
Total C	Exponential [†]	0.34	0.040	0.256	13.8	0.84
Total N	Exponential [†]	0.37	0.032	0.246	15.6	0.87
C/N ratio	Linear	0.24	0.0101	–	–	–
pH (H ₂ O)	Exponential [†]	0.56	0.005	0.021	11.7	0.76
Available P	Spherical [#]	0.97	0.0056	0.043	106.3	0.87
Exchangeable K	Spherical [#]	0.61	0.0541	0.1072	46.7	0.51
Exchangeable Na	Linear	0.66	0.0221	–	–	–
Exchangeable Ca	Spherical [#]	0.64	0.0308	0.0866	34.6	0.65
Exchangeable Mg	Spherical [#]	0.71	0.0227	0.0774	31.0	0.71

[†] $\gamma(h) = C_0 + (C - C_0) \cdot (1 - e^{-h/a})$; range=3·(a).

[#]For $h \leq$ range, $\gamma(h) = C_0 + (C - C_0) \cdot \{1.5 \cdot (h/\text{range}) - 0.5 \cdot (h/\text{range})^3\}$; $h >$ range, $\gamma(h) = C$.

dosica than under *S. vulgaris* or openings. In contrast, available P was lower under *S. vulgaris* than under *A. ordosica* or openings. Soil pH and exchangeable K showed no significant differences among microsite types.

Geostatistics

All semivariogram models were significant at $P < 0.01$ ($r^2 > 0.61$ and $F_{2,97} > 70.4$ for spherical models; $r^2 > 0.20$ and $F_{1,98} > 23.7$ for exponential and linear models; $r^2 = 0.37$, $F_{2,72} = 43.2$ for spherical model for the coverage of *S. vulgaris* over a range of 75 m). Semivariogram models showed a strong spatial dependence among sampling locations for almost all variates (Figs. 2 and 3). The proportion of structural variance (C) to total estimated variance (sill; $C + C_0$) was between 0.65 and 1.00 for variates other than C/N ratio and exchangeable Na (Tables 4 and 5).

The range of spatial autocorrelation was within 43.1 m for the relative height of the sampling location, within 86.2 m for the coverage of *A. ordosica* (Fig. 2 and Table 4). For the coverage of *S. vulgaris*, there might be two scales of variation which were 0–75 and 75–100 m. The semivariogram over 75 m for this variate suggested that 100% of the variation was spatially dependent on this scale and the range of spatial autocorrelation was within 11.5 m.

The range of spatial autocorrelation was within 5.1 m for the mass of organic matter on the soil surface, and within 11.7–15.6 m for total C, total N, and pH (Fig. 3 and Table 5). For silt+clay and exchangeable

cations except Na⁺, the range was within 31.0–46.7 m. Available P showed a much longer range than other properties. Semivariograms for C/N ratio and exchangeable Na were modeled as linear, but the nugget variance (C_0) of these properties accounted for 75 and 66% of estimated semivariance at a maximum lag distance, respectively.

Discussion

This study demonstrated that soil properties were spatially variable and some soil physical and chemical properties were different in soils beneath and between shrubs in the Mu-us desert ecosystem (Tables 2 and 3). Such 'islands of fertility' in arid and semiarid regions has been reported in many studies (Burke, 1989; Burke et al., 1989; Hook et al., 1991; Schlesinger et al., 1996). The possibility was suggested that the importance of plant presence on local soil properties may overshadow that of plant species in the naturally established vegetation in these regions (Vinton and Burke, 1995). However, the striking differences of plant traits between *Artemisia ordosica* and *Sabina vulgaris* allowed us to detect the effect of plant species on the local soil properties in the Mu-us desert ecosystem (Table 3). Values of soil properties under *A. ordosica* were always equal to or less than those in bare soils between shrubs except the mass of organic matter on the soil surface. Under *S. vulgaris*, soil properties, except available P, were higher than or equal to those in openings. These patterns were found not only for

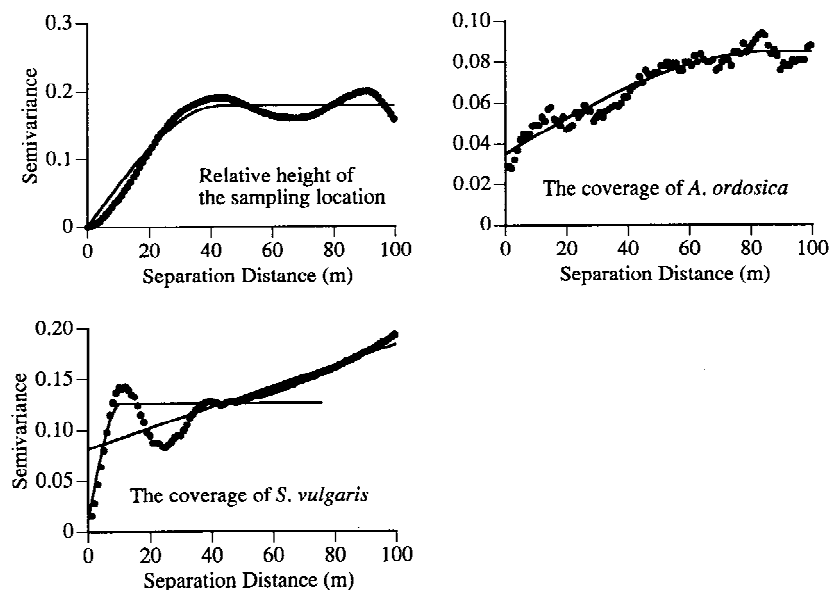


Figure 2. Semivariograms for the relative height of the sampling location and the coverages of *Artemisia ordosica* and *Sabina vulgaris*

the properties closely related to biological processes (organic matter on the soil surface, total C and N, and C/N ratio), but also in those relating to physical processes (silt+clay) and nonlimiting or nonessential elements (exchangeable Na, Ca, and Mg).

Spatially variable primary production and redistribution of surface soil are considered to be two major processes generating the heterogeneity of soil properties associated with plant cover in dry regions (Hook et al., 1991). The spatial patterns of primary production directly affect the spatial pattern of organic matter through the input of litter. The patterns of plant production also indirectly affect the patterns of limiting nutrients through the transfer of nutrients from soil around plants to soil under plants (Garner and Steinberger, 1989). Although there are no data available that deal directly with plant primary production in the Mu-us desert ecosystem, the average above- and belowground biomass of *A. ordosica* were about 260 and 200 g/m², and those of *S. vulgaris* were about 1600 and 2700 g/m², respectively (Yoshikawa and Li, 1989). These large differences of above- and belowground biomass may indicate the greater primary and litter productions of *S. vulgaris* than *A. ordosica*, and may lead to a higher accumulation of organic matter on the soil surface, total C and N, and the increase of C/N ratio under *S. vulgaris* (Table 3). The redistribution process of surface soil on a local scale may also contribute to the differences of soil properties between *A. ordosica* and *S. vulgaris*, because the silt+clay was

higher under *S. vulgaris* than under *A. ordosica* (Table 3). The accumulation of fine materials under shrubs may result from the capture of windblown materials by the shrub canopy (Coppinger et al., 1991; Elkins et al., 1986). In the Mu-us desert ecosystem, most precipitation falls as rain in summer, and the snow cover in the winter is occasional (Kobayashi et al., 1995). Therefore, the prostrate life-form and evergreen leaf-habit of *S. vulgaris* may prevent the soil movement under its canopy through the year, and allow the accumulation of fine materials and the stabilization of fallen litter as compared with the non-prostrate life-form and deciduous leaf-habit of *A. ordosica*. In contrast to other properties, available P was low under *S. vulgaris* (Table 3). This may also relate to the trait of *S. vulgaris*, because evergreen species can keep the growth-limiting nutrient in their biomass more effectively than deciduous species (Aerts, 1990). The leaf longevity of *S. vulgaris* was 3–4 years and the leaf biomass of *S. vulgaris* was about four times greater than the whole aboveground biomass of *A. ordosica* (Yoshikawa and Li, 1989). *Sabina vulgaris* may maintain soil labile P in its evergreen leaves. In addition, the long life-span of *S. vulgaris* means this species can occupy a place for a longer time than the relatively short-lived *A. ordosica*, and this may emphasize the effect of *S. vulgaris* on the local soil properties.

Geostatistics allowed us to determine the magnitude of spatial dependence and the scale of spatial autocorrelation of the relative height of the sampling

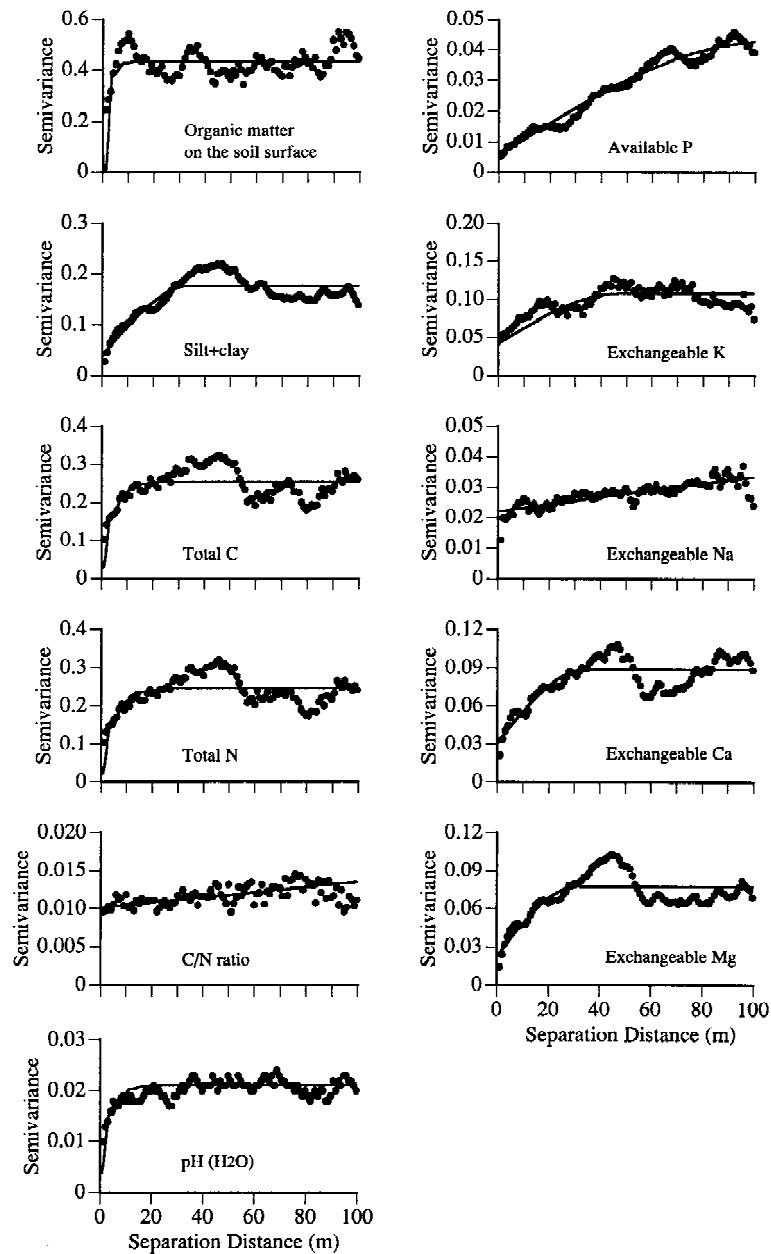


Figure 3. Semivariograms for the soil properties in the Mu-us desert ecosystem.

location, the coverage of each vegetation, and each soil property (Figs. 2 and 3 and Tables 4 and 5). Almost all variates showed a strong spatial dependence on the scale examined, but semivariograms of C/N ratio and exchangeable Na may indicate that the dissimilarity of these properties did not depend upon the distance among sampling locations. The range of spatial autocorrelation found in the coverage of *A. or-*

dosica was much longer than its canopy patch size (Table 4), although an individual of *A. ordosica* was isolated from surrounding individuals. This might be due to the coverage of *A. ordosica* for each sampling location was the sum of the coverages of two individuals in many cases. The coverages of vegetations in a 1×1 -m square may not be suitable especially for the detection of the canopy patch size of *A. ordosica*

Table 6. Correlations between the relative height of a sampling location and each soil property ($n=201$)

Soil property	Relative height
Organic matter on the soil surface	0.025
Silt+clay	-0.421***
Total C	-0.293***
Total N	-0.323***
C/N ratio	0.130
pH (H ₂ O)	0.404***
Available P	-0.462***
Exchangeable K	-0.425***
Exchangeable Na	-0.260***
Exchangeable Ca	-0.154*
Exchangeable Mg	-0.362***

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

by the geostatistical analysis. The range for the coverage of *A. ordosica* may show the scale of the spatial distribution of this species. In contrast, the range of spatial autocorrelation for the coverage of *S. vulgaris* almost corresponded to the patch size of a *S. vulgaris* community.

Some of the soil properties showed different spatial patterns as expected from the comparison of local soil properties among three microsite types (Tables 3 and 5). This may be because the spatial patterns of soil properties are affected not only by the presence and absence of vegetation canopy, but also by the density and the spatial distribution of vegetation (Imhoff et al., 2000). Moreover, the relative importance of biological and physical processes on the spatial patterns of soil properties change depending on the properties (Garner and Steinberger, 1989; Schlesinger et al., 1996), and also on the scale examined (Burke, 1989; Imhoff et al., 2000; Kelly and Burke, 1997; Schimel et al., 1985; Vinton and Burke, 1995). Thus, the presence and absence of the canopy of a vegetation patch (an individual of *A. ordosica* or a community of *S. vulgaris*) may not always be the most important factor in determining the spatial pattern of a particular soil property.

The range of spatial autocorrelation found in the mass of organic matter on the soil surface was smaller than that of the coverage of *S. vulgaris*, and was intermediate distance of the canopy patch sizes of *A. ordosica* and *S. vulgaris* (Tables 4 and 5). The ranges of total C and N, and pH were comparable to that of *S. vulgaris*. Therefore, the spatial patterns of these properties may be associated with plant cover, espe-

cially the cover by *S. vulgaris*. Although available P was low under *S. vulgaris* (Table 3), the range of this property did not correspond to that of *S. vulgaris* (Tables 4 and 5). For the spatial pattern of available P, the distribution of *A. ordosica* community may be more effective than the heterogeneity induced by the presence of the canopy patch of *S. vulgaris*, since the ranges of both available P and the coverage of *A. ordosica* were very long. Other soil properties (silt+clay and exchangeable cations except Na⁺) showed a range distance of 31.0–46.7 m and these ranges were similar to neither those of vegetation coverages nor the canopy patch sizes of vegetations. However, the range of these properties more or less corresponded to that of the relative height of the sampling location. Correlations between the relative height of a sampling location and each soil property were significant for almost all properties (Table 6). The correlation between the relative height and silt+clay indicated that slope processes caused accumulation of fine material in leeward and downslope positions as found in many other ecosystems (Burke et al., 1989; Jenny, 1980), even though the topography was rather gentle. Although topography was the only physical parameter considered in this study, topographic gradient is known as a prominent physical factor which creates spatial patterns of soil properties at landscape scale (Burke et al., 1989; Schimel et al., 1985). On the spatial scale examined in this study, these 'base-line' fluctuations of soil properties by the topographic gradient may be more effective for the spatial patterns of silt+clay and exchangeable cations (K⁺, Ca²⁺ and Mg²⁺) than plant-induced heterogeneity in these properties.

Chen and Stark (2000) pointed out that it is not clear if the nutrient cycle beneath the plant is different because the plant is there, or if the plant is there because the nutrient cycle is different in naturally established stands of vegetation. If the latter were true, *S. vulgaris* would be growing in the downslope positions where the fine material was accumulated by the slope processes (Table 6). However, both *A. ordosica* and *S. vulgaris* grew in all height classes of the sampling location and *S. vulgaris* flourished in the relatively higher part of the study plot (Table 1). Therefore, we can conclude with the plant species effects on the spatial patterns of soil properties in the Mu-us desert ecosystem that (1) the presence of the canopy patches of both *A. ordosica* and *S. vulgaris* is important for the mass of organic matter on the soil surface, (2) the presence of the canopy patch of *S. vulgaris* is more effective than that of *A. ordosica* for total C and N,

and pH, (3) the distribution of *A. ordosica* community may be influential for available P, and (4) the physical process according to topography may be more important for silt+clay and exchangeable K, Ca and Mg than plant-induced heterogeneity in these properties.

Acknowledgements

We wish to thank Dr. K. Koba for helpful comments on this paper. We are grateful to Drs. I. Ninomiya, N. Yamanaka, K. Sakamoto, H. Takeda, N. Osawa and N. Tokuchi for their valuable suggestions. Dr. R. Aerts and two anonymous reviewers improved this paper substantially. N. Osada and S. Hasegawa provided assistance on the statistical analyses. We appreciate the help of N. Yoshida and the staff of Inner Mongolia Agricultural University in the fieldwork. This study was partly supported by JSPS Research Fellowships for Young Scientists (No. 02489).

References

- Aerts R 1990 Nutrient use efficiency in evergreen and deciduous species from heathlands. *Oecologia* 84, 391–397.
- Boettcher S E and Kalisz P J 1990 Single-tree influence on soil properties in the mountains of eastern Kentucky. *Ecology* 71, 1365–1372.
- Burke I C 1989 Control of nitrogen mineralization in a sagebrush steppe landscape. *Ecology* 70, 1115–1126.
- Burke I C, Reiners W A and Schimel D S 1989 Organic matter turnover in a sagebrush steppe landscape. *Biogeochemistry* 7, 11–31.
- Charley J L and West N E 1975 Plant-induced soil chemical patterns in some shrub-dominated semi-desert ecosystems of Utah. *J. Ecol.* 63, 945–963.
- Chen J and Stark J M 2000 Plant species effects and carbon and nitrogen cycling in a sagebrush-crested wheatgrass soil. *Soil Biol. Biochem.* 32, 47–57.
- Commissione Redactorum Florae Intramongolicae 1985 Flora Intramongolica 1. Typis Intramongolicae Popularis, Huhhot, China. 294 p.
- Commissione Redactorum Florae Intramongolicae 1993 Flora Intramongolica 4. Typis Intramongolicae Popularis, Huhhot, China. 907 p.
- Commissione Redactorum Florae Intramongolicae 1994 Flora Intramongolica 5. Typis Intramongolicae Popularis, Huhhot, China. 634 p.
- Coppinger K D, Reiners W A, Burke I C and Olson R K 1991 Net erosion on a sagebrush steppe landscape as determined by cesium-137 distribution. *Soil Sci. Soc. Am. J.* 55, 254–258.
- Elkins N Z, Sabol G V, Ward T J and Whitford W G 1986 The influence of subterranean termites on the hydrological characteristics of a Chihuahuan desert ecosystem. *Oecologia* 68, 521–528.
- Garner W and Steinberger Y 1989 A proposed mechanism for the formation of 'fertile islands' in the desert ecosystem. *J. Arid Environ.* 16, 257–262.
- Gee G W and Bauder J W 1986 Particle-size analysis. In *Methods of Soil Analysis*. Part 1. Ed. A Mute. pp 383–411. ASA and SSSA, Madison, WI.
- Goovaerts P 1998 Geostatistical tools for characterizing the spatial variability of microbiological and physico-chemical soil properties. *Biol. Fertil. Soils* 27, 315–334.
- Hirose T and Tateno M 1984 Soil nitrogen patterns induced by colonization of *Polygonum cuspidatum* on Mt. Fuji. *Oecologia* 61, 218–223.
- Hook P B, Burke I C and Lauenroth W K 1991 Heterogeneity of soil and plant N and C associated with individual plants and openings in North American shortgrass steppe. *Plant Soil* 138, 247–256.
- Imhoff S, da Silva A P and Tormena C A 2000 Spatial heterogeneity of soil properties in areas under elephant-grass short-duration grazing system. *Plant Soil* 219, 161–168.
- Isaaks E H and Srivastava R M 1989 *Applied Geostatistics*. Oxford University Press, New York, USA. 561 p.
- Jackson R B and Caldwell M M 1993 The scale of nutrient heterogeneity around individual plants and its quantification with geostatistics. *Ecology* 74, 612–614.
- Jenny H 1980 *The Soil Resource: Origin and Behavior*. Springer, New York, USA. 377 p.
- Kelly R H and Burke I C 1997 Heterogeneity of soil organic matter following death of individual plants in shortgrass steppe. *Ecology* 78, 1256–1261.
- Kobayashi T 1990 Origin and land classification of the Mu us shadi desert in China. *J. Jap. Soc. Reveget. Tech.* 15, 43–57 (in Japanese).
- Kobayashi T, Liao R and Li S 1995 Ecophysiological behavior of *Artemisia ordosica* on the process of sand dune fixation. *Ecol. Res.* 10, 339–349.
- Matson P 1990 Plant–soil interactions in primary succession at Hawaii Volcanoes National Park. *Oecologia* 85, 241–246.
- Olsen S R and Sommers L E 1982 Phosphorus. In *Methods of Soil Analysis*. Part 2. Eds. A L Page, R H Miller and D R Keeney. pp 403–430. ASA and SSSA, Madison, WI.
- Padien D J and Lajtha K 1992 Plant spatial pattern and nutrient distribution in pinyon-juniper woodlands along an elevational gradient in northern New Mexico. *Int. J. Plant Sci.* 153, 425–433.
- Rice W R 1989 Analyzing tables of statistical tests. *Evolution* 43, 223–225.
- Robertson G P 1987 Geostatistics in ecology: interpolating with known variance. *Ecology* 68, 744–748.
- Robertson G P 1998 *GS⁺: Geostatistics for the Environmental Sciences*. Gamma Design Software, Plainwell, MI, USA. 152 p.
- Robertson G P, Huston M A, Evans F C and Tiedje J M 1988 Spatial variability in a successional plant community: patterns of nitrogen availability. *Ecology* 69, 1517–1524.
- Rossi R E, Mulla D J, Journel A G and Franz E H 1992 Geostatistical tools for modeling and interpreting ecological spatial dependence. *Ecol. Monogr.* 62, 277–314.
- Schimel D, Stillwell M A and Woodmansee R G 1985 Biogeochemistry of C, N, and P in a soil catena of the shortgrass steppe. *Ecology* 66, 276–282.
- Schlesinger W H and Pilmanis A M 1998 Plant-soil interactions in deserts. *Biogeochemistry* 42, 169–187.
- Schlesinger W H, Reynolds J F, Cunningham G L, Huenneke L F, Jarrell W M, Virginia R A and Whitford W G 1990 Biological feedbacks in global desertification. *Science* 247, 1043–1048.
- Schlesinger W H, Raikes J A, Hartley A E and Cross A F 1996 On the spatial pattern of soil nutrients in desert ecosystems. *Ecology* 77, 364–374.

- SPSS 1999 SPSS Base 10.0J for Windows. SPSS Inc., Chicago, IL. 484 p.
- Vinton M A and Burke I C 1995 Interactions between individual plant species and soil nutrient status in shortgrass steppe. *Ecology* 76, 1116–1133.
- Yamanaka N, Wang L and Yoshikawa K 1998 Seed production and seed bank of *Sabina vulgaris* Ant. in the Mu-us desert, Inner Mongolia, China. *J. Jpn. Soc. Reveget. Tech.* 23, 211–219 (in Japanese with English summary).

Yoshikawa K and Li S 1989 Stand structure of *S. vulgaris* in the Mu-us desert, China. *In* Proceedings of 1989 International Symposium for Japan and China Joint Research. pp 83–87. Inner Mongolian Research Group.

Section editor: R. Aerts