ORIGINAL ARTICLE

Spatial heterogeneity of soil moisture, microbial biomass carbon and soil respiration at stand scale of an arid scrubland

Yu-gang Wang · Hong Zhu · Yan Li

Abstract Studying the influence of plants on soil biological variables in an arid zone is important to the understanding of soil processes and relationships between above and below ground. The objective of this study was to quantify the pattern and degree of soil heterogeneity for soil moisture and its relationship with microbial biomass carbon and soil respiration using geostatistical techniques at stand scale of an arid scrubland. The experiment was conducted in a scrubland landscape using a 2×2 m grid within a 16×14 m plot in the lower reach of Sangong River watershed in Xinjiang, northwest China. The results revealed the following: (1) Soil moisture and soil microbial biomass carbon had moderate spatial variation, but soil respiration had strong variation. Spatial variability of soil moisture in the study plot decreased when soil moisture changed from wet in April to dry in June. In addition, correlations of soil moisture with microbial biomass carbon and soil respiration were positive and significant ($p < 0.005$). (2) Variation of soil microbial biomass carbon and soil moisture had a strong spatial autocorrelation in the study plot, mainly induced by structural factors, and the spatial autocorrelation of microbial biomass carbon and soil respiration was mainly determined by soil moisture. (3) The location of the high-value positions of soil moisture, soil microbial biomass carbon and soil respiration were clearly around the positions of scrubs in the study plot. Such information provided some insights to explain the spatial heterogeneity of soil properties at stand scale in an arid region.

Introduction

Soil microorganisms are important components of terrestrial ecosystems because they play a central role in organic matter decomposition and nutrient cycling, thereby affecting soil nutrient content and, consequently, primary productivity (Rutigliano et al. 2004). Microbial biomass is a small but important reservoir of nutrients—carbon (C), nitrogen, phosphorus and sulphur—and many transformations of these nutrients occur in the biomass (Dick 1992). Microbial biomass is the living component of soil organic matter and typically comprises 1–5 % of total organic matter content. Microbial biomass forms a base of the detritus food web and serves as a sink and source for most plant-available nutrients. Therefore, study on linkages between soil microbial biomass and environmental parameters would provide a better understanding of the factors that control nutrient cycling in the ecosystem (Ogram et al. 2006). In recent years, there has been considerable attention paid to their biophysical interactions with soil and the environment, especially variability of soil properties (Katra et al. 2007; Franklin and Mills 2009; Piotrowska and Dlugosz 2012).

Scrubs in arid and semi-arid environments have a strong influence on the vast spatial heterogeneity of soil properties (Van Miegroet et al. 2000; Qian et al. 2009). Heterogeneity of soil properties may lead to the invasion of these ecosystems by woody scrubs due to changes in the relatively uniform distribution of soil moisture (SM), microbial biomass carbon (MBC) and other soil chemical parameters (Li et al. 2008). Most soil properties do not have a consistent

Y. Wang · H. Zhu · Y. Li (✉)
State Key Lab of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Ecology, Chinese Academy of Sciences, 818 South Beijing Road, Xinjiang 830011, People's Republic of China
e-mail: liyan@ms.xjb.ac.cn

spatial distribution across ecosystems. Spatial variability of soil characteristics in desert ecosystems is largely controlled by the spatial organization of perennial plants, which create relatively stable 'islands of fertility' (Jonathan et al. 2002). There is virtually no information about the influence of these scrub-generated 'islands of fertility' on the microbial community (Gallardo and Schlesinger 1992). Soil microbes may respond differently to 'fertile' and space between scrubs of soils (Liu et al. 2010). Additionally, MBC is one of the general indices reflecting soil microbial activities (Wick et al. 1998), and is a very important factor in most ecosystems (Diedhiou et al. 2009). Furthermore, MBC can respond rapidly to soil nutrients beneath scrubs in a desert soil. In general, MBC tends to be higher in soils under plant canopies compared to inter-plant spaces. However, few studies have evaluated spatial heterogeneity of soil property between scrubs, when the importance of scrub-islands in structuring communities was evident (Ewing et al. 2007; Aanderud et al. 2008).

SM conditions are an important environmental factor that controls survival and activity of microorganisms in soils. The rapid change in SM may cause osmotic shock, inducing cell lysis and release of labile intracellular substrates (Li et al. 2011a). Therefore, SM plays a key role in controlling soil respiration (SR) and can replace temperature as the dominant factor affecting soil carbon dioxide (CO_2) effluxes. However, seasonal changes in soil and air temperature may lead to change in SM, thus influencing microbial activity and SR. SM can change by thaw snow in April with lower soil and air temperatures in Junggar Basin, northwest China; however, in June, SM can be lower with high soil and air temperatures (Zhou et al. 2012). It is well known that SR changes temporally and spatially due to environmental conditions and soil properties. In addition, SR is the sum of respiration of root and microbes and the oxidation of organic matter. The quantity of available C substrates affects plant and soil microbial respiration, and impacts on the sum respiration. However, the spatial variability in SR is still poorly documented—with most data based on forest ecosystems and only some from scrubland in dry environments (Qi et al. 2010). Previous work on the spatial heterogeneity of soil properties associated with plants has varied from mostly descriptive accounts to detailed analyses using spatial statistics (Cain et al. 1999). Little attention has been paid to temporal changes in the spatial distribution of SM and its relationship with MBC and SR over seasons. Therefore, quantitative knowledge is urgently required on how these factors influence each other in order to understand, and ultimately to predict and model, the resultant soil processes.

Soil in scrub ecosystems is known to be heterogeneous for different activities at several spatial scales (Ettema and Wardle 2002; Housman et al. 2007; Li et al. 2011b). Study of the influence of plants on soil biological variables in an arid zone is important to understand soil processes and the relationships between above and below ground come from studies of fertile soils. Studies conducted in scrub landscapes suggest that SM, MBC and SR may be spatially dependent at scales of >1 m, nested within variations at landscape scale (Franklin and Mills 2003). A simultaneous analysis of the spatial variability of SM relationships with MBC and SR could help identify these factors and determine their relative influence. Hence, the quantification and identification of these factors may be potentially valuable when examining relationships between soil variables (Pe'rie et al. 2006). The aim of this study was (1) to understand SM, MBC and SR spatial heterogeneity at the stand scale (i.e. range of meters) (2) to determine whether variability of SM coincides with spatial pattern variability of MBC and SR and (3) to provide a preliminary characterization of the spatial correlations using observed variation over two sampling dates.

Materials and methods

Study area

The study was carried out in a typical desert scrub landscape area of the lower Sangong River watershed (44°17′N, 88°00′E), which comprises the northern Tianshan Mountains and the southern edge of the Gurbantunggut Desert in Xinjiang, northwest China (Fig. 1). This region is located in a medium temperate arid climate with an annual mean air temperature of 6.6 °C, and annual mean precipitation of 163 mm, and an average annual free water evaporation of 1,780–2,453 mm. The main soil types are Haplic calcisols in the field site (FAO/UNESCO 1990). The soil is composed of 57.35, 7.65 and 35 % of silt, clay and sand, respectively, in the open land and correspondingly 66.73, 4.38 and 28.89 % under the canopies. The dominant vegetation is *Tamarix ramosissima* Ledeb. in the site. Other plants include *Reaumuria soongorica* Maxim. (typical height 10–25 cm), *Ceratocarpus arenarius* L. (typical height 5–30 cm) and *Suaeda physophora* Pall. (typical height 20–50 cm)—these account for >35 % of the total vegetation coverage (which is <30 %) of which the remainder is ephemeral herbaceous plants. Dispersed grasses such as *Petrosimonia sibirica* Bge. and *Salsola nitraria* Pall. are also present.

In the study plot (Fig. 1), 42 soil sampling sites were collected at nodes of a 2 × 2 m grid within a 16 × 14 m plot. Each soil sampling site was sampled with five replicates by a 4 cm diameter auger to a depth of 15 cm. After sampling, the five replicates of soil samples were mixed
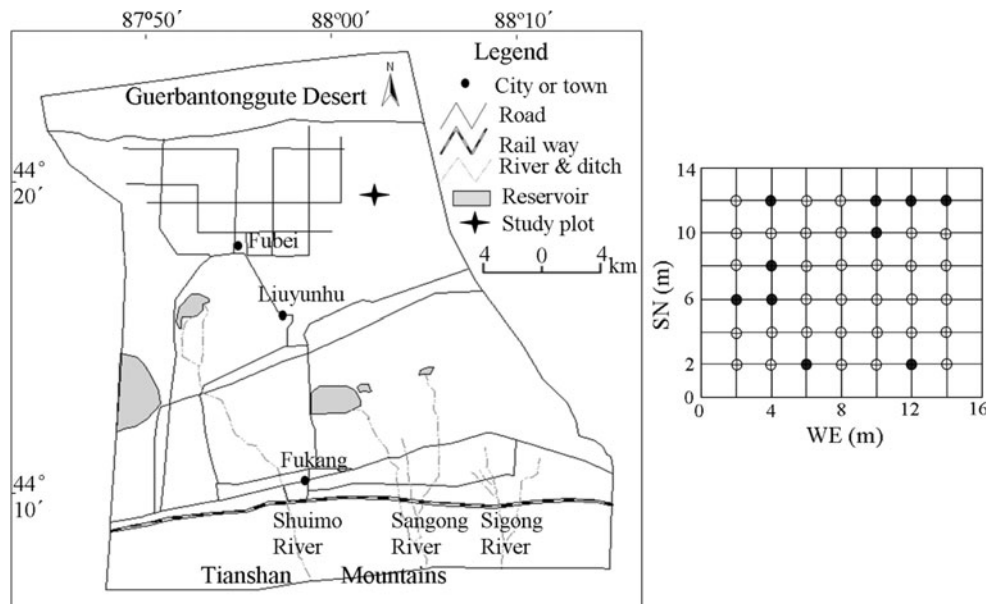
together for each site. Soils were sampled twice in April and June. Soil sampling times were chosen considering the fact that SM can influence MBC and SR. Soils were sampled in April when SM was high while soil and air temperatures were low; and in June when SM was low while soil and air temperatures were high. All soil samples were stored in a refrigerator at −4 °C. SR was measured in the plot using an infrared gas analyzer system (model CIRAS-1, PP Systems, Hitchin, UK) equipped with a flow-through closed chamber. At the time of measurements, the chamber (which had an area of 78 cm^2 and a volume of 1,170 cm^3) was inserted 3 cm into the surface soil. SR was measured three times for 120 s at each sampling point. A sampling interval was sufficiently long to get reliable estimates of SR according to the equipment handbook of PP Systems. SM was calculated from mass loss on drying at 105 °C for 12 h. MBC was measured using the fumigation extraction method. In the laboratory, the material from each core was passed through a 4 mm sieve, and roots were removed from soil samples. Then MBC was measured on a 10 g subsample of soil (oven-dry equivalent) using the method of Dilustro et al. (2005), and calculated using the method of Nunan et al. (1998) on an oven-dry weight (105 °C) basis.

Statistical procedures

Descriptive statistics (mean, maximum value, minimum value and standard deviation, SD) were calculated. Normality of the datasets was assessed using the one-sample Kolmogorov–Smirnov (K–S) test, and the correlations between SM and MBC, and SM and SR were analyzed with SPSS 11.5a software.

Spatial heterogeneity of SM, MBC and SR data was examined using geostatistical tools useful for describing spatially structured phenomena. The theoretical basis of geostatistics used in the current study was described in several studies (e.g. Morris 1999; Grundmann and Debouzie 2000; Vieublé-Gonod et al. 2006). Classical parametric statistics cannot be used to evaluate autocorrelated data without violating the central assumption of sample independence. Geostatistics provides a means for defining the autocorrelation and for using knowledge about its strength and scale to interpolate values of variates at unsampled locations (Goovaerts 1999). Its general form is as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{x=1}^{n} (z_x - z_{x+h})^2 \tag{1}$$

where $N(h)$ is the number of lag pairs at distance interval h, and z is the value of parameter at location x and $x + h$. The GS$^+$ 5.3.2 program (Robertson 2000) was used to calculate $\gamma(h)$ and theoretical model parameters of $\gamma(h)$ for all variables. The maps were interpolated using ordinary block kriging at a block size of 2 m. Semivariogram modeling and kriging estimation were performed on the basis of residuals.

Results

Descriptive statistics of SM, MBC and SR

Table 1 displays the summary statistics of the SM, MBC and SR attributes for the sample sites. The values of MBC changed in the range 0.22–383.62 µgC g^{-1} soil, and the coefficient of variation (CV) was <27 %. The CV for SM

Table 1 Descriptive statistics for microbial biomass carbon (MBC), soil moisture (SM) and soil respiration (SR)

Variable	Mean	SD	CV	Min	Max	Skewness	Kurtosis	K–S	CC
MBC (μgC g^{-1})	95.45	95.86	1.004	0.217	383.6	1.677	2.47	1.39	0.57*** (MBC $\times$ SM)
SM_A (%)	11.08	3.72	0.336	4.71	21.84	1.03	1.17	0.89	
SR (g m^{-2} h^{-1})	0.072	0.087	1.214	0.017	0.316	1.49	0.99	1.74	0.46*** (SR $\times$ SM)
SM_J (%)	9.85	1.60	0.163	7.17	14.49	0.83	0.89	0.72	

K–S one-sample Kolmogorov–Smirnov test, *SD* standard deviation, *CV* coefficient of variation, *CC* correlation coefficient

*** Significant at $p < 0.005$. SM_A and SM_J indicate measurements performed in the scrubland plot during April and June, respectively

was higher in June than in April. Values of CV for both MBC and SM were >10 %, indicating that they were moderately variable in the surface soil of the study plot (Peigné et al. 2009; Chen et al. 2010). SR values were in the range 0.01–0.31 g m^{-2} h^{-1}, with CV >90 %, indicating that SR was strongly variable (Jordan et al. 2009). In addition, the correlations between SM and MBC in the study plots were lower than those between SM and SR; and SM was positively correlated with MBC and SR (Table 1, $p < 0.005$), which indicated that increased SM would increase MBC and SR at the scrub scale. The K–S test indicated that data of all variables were distributed normally (Table 1). Results of the K–S test suggested that under natural conditions SM, MBC and SR were enabled for the analysis of spatial heterogeneity in the study plot.

Spatial structure of SM, MBC and SR

The semivariograms for SM, MBC and SR are shown in Fig. 2. Key parameters of the semivariogram are given in Table 2. The optimal theoretical models of SM in April and June were spherical models, with Gaussian models for MBC and SR (Table 2; Fig. 2). The coefficients of determination (R^2) were >0.58 and the *F* test for R^2 was highly significant ($\alpha = 0.01$). These indicated that the theoretical model well reflected the spatial structural characteristics of SM, MBC and SR in the surface soil of the study plot. The values of SM for nugget to sill ratios changed from 0.03 in April to 0.16 in June, indicating a change from a strong to moderate spatial autocorrelation. The corresponding nugget to sill ratios for MBC was <0.25, suggesting a strong spatial autocorrelation, and indicating that spatial dependence of MBC and SM was mainly structural factors. However, the values of SR for nugget to sill is between 0.25 and 0.75, indicating a moderate spatial autocorrelation. The possible cause for the spatial variability of MBC and SR was SM, as statistics showed that SM was significantly correlated with MBC and SR in the studied plot (Table 1). The range of spatial dependence is defined as the distance to the point corresponding to the sill; the nugget estimates the proportion of the total variation that is inherent in the smallest sampling lag. The percentage soil
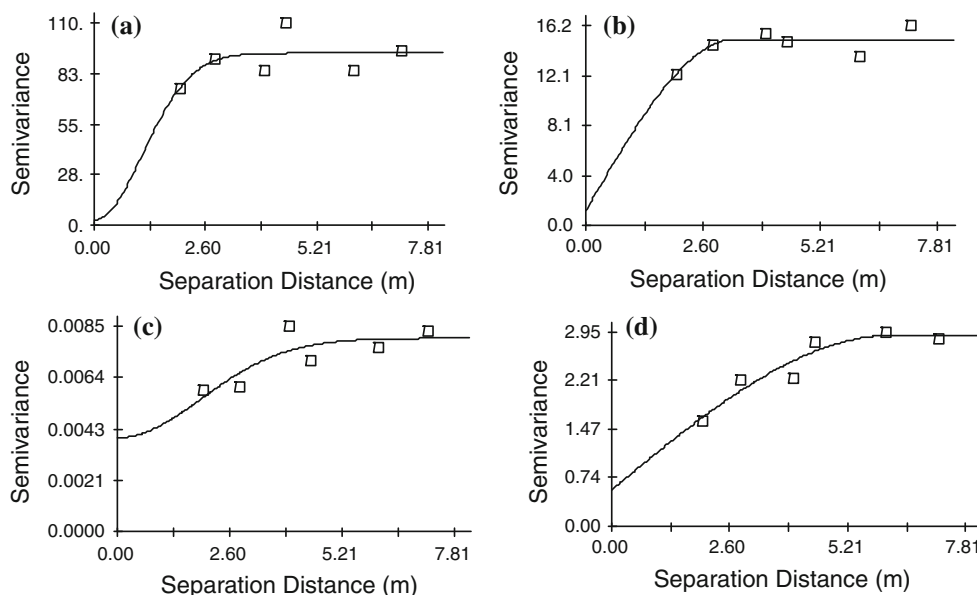

Fig. 2 Empirical and fitted models (*lines*) of microbial biomass carbon (**a** MBC), soil moisture (**b** SM in April), soil respiration (**c** SR) and soil moisture (**d** SM in June), *blank squares* (*square box*) represent the empirical semivariograms

Table 2 Correlation parameters and *F* test of theoretical variogram models for microbial biomass carbon (MBC), soil moisture (SM) and soil respiration (SR)

Sample	Model	Nugget	Sill	Range (m)	Nugget/Sill	R^2	*F*-value
MBC	Gaussian	2.80	93.60	3.17	0.03	0.585	8.83**
SM_A	Spherical	1.17	15.03	3.30	0.08	0.643	12.53**
SR	Gaussian	0.0039	0.0080	4.78	0.49	0.690	391.51**
SM_J	Spherical	0.556	2.901	6.19	0.19	0.909	27.63**

** Means of *F* test significance at $\alpha = 0.01$; SM_A and SM_J indicate measurements performed in the scrubland plot during April and June, respectively

moistures in April and June are strongly spatially dependent or lowly variable across space. The smaller sill value and the smaller nugget value in June support low variability in soil moisture at the scale sampled. The SM values in April are much more variable in the spatial scale, but they display stronger spatial correlation as indicated by the smaller range parameter (3.3 m). The larger range parameter for SR (4.87 m) indicates a larger scale of spatial dependence. The low values for nugget to sill ratios in the present analysis indicated that soil disturbance during sampling was not notable because the large interval (2 m) and the cross-semivariograms involving SM, MBC and SR tended to have a small nugget effect at the scrub scale. Such semivariograms indicated that biological heterogeneity was important at scales well below the sampling lag of this study.

Spatial patterns of SM, MBC and SR

Maps indicate the location of area of high values for SM, MBC and SR. The prediction map of SM, MBC and SR (Fig. 3) was created with the GS$^+$ program using a 2×2 m grid. Kriged contour maps for these variables showed a patchy distributed pattern around the scrubs (Fig. 3). The positions of high MBC values are close to the cross signs on maps, as are the high SR values. The high SM values occur near to the cross signs on maps, but low SM values in open land without scrubs. There were changed SM patterns between April and June in the plot, and slight changes in position for the respective high values. The kriging interpolation for SM showed a smoothly varying deterministic trend component and a more rapidly varying stochastic component.

On the MBC map (Fig. 3), the positions of high MBC values are close to the places where scrubs appear on maps, as are the high SR values. The high SM values occur near to the scrubs on maps, but low SM values in the open land without scrubs. Nevertheless, some differences are evident. There were changed SM patterns between April and June in the plot, and slight changes in position for the respective high values. The kriging interpolation for SM showed a

smoothly varying deterministic trend component and a more rapidly varying stochastic component. In addition, whatever MBC, SM, or SR, values of mean are significantly higher in sub-scrub canopy sites than neighboring open sites (Table 3, $p < 0.05$). The results of statistics for MBC, SM and SR between sub-scrub canopy sites and neighboring open sites in Table 3 were consistent with those of kriged contour maps shown in Fig. 3, suggesting higher values around scrub, indicating scrub as an island for MBC, SM and SR. In general, maps can be well designed to directly exhibit spatial distribution of MBC, SM and SR.

Discussion

The results revealed that the variations of SM were moderate in the study scale, but there was difference in values of means and CVs. In April, abundant snow-melted water penetrated into the soil due to low air temperature and weak transpiration, which created high means and higher CV (Table 1). However, there were lower means and lower CVs of SM in June due to the higher air temperature and the great loss of soil water by transpiration. Variance generally decreases with decreasing SM due to the diminishing impact from infiltration and runoff that created spatial variations (Famiglietti et al. 1998). Consequently, the spatial variability of SM decreased when SM changed from wet to dry as the drying processes reduced the spatial variability that was created in the wetting process (Table 1). This result differed from those of Choi et al. (2007) and Chen et al. (2010), but was consistent with those of Robinson and Dean (1993) and Yang et al. (2011). Thus, spatial variability of SM in the study plot was higher in April than in June.

In the scrub plot, structural factors such as stochastic elements had the most impact on the spatial heterogeneity of MBC and SM, which include such factors as experimental and sampling error, soil structure and biology (Morris 1999; Grundmann and Debouzie 2000; Stoyan et al. 2000). However, SR had a short spatial range in the
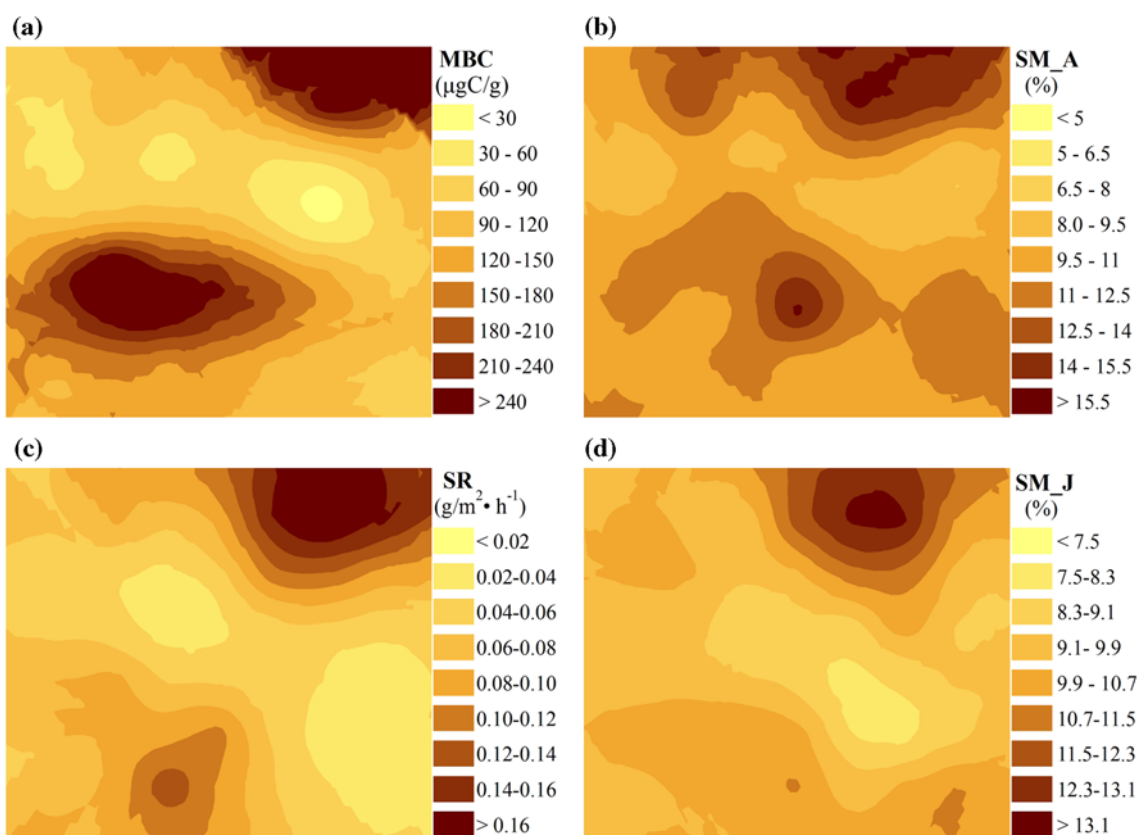
Fig. 3 Isopleths for soil microbial biomass carbon (**a** MBC), soil moisture (**b** SM in April), soil respiration (**c** SR) and soil moisture (**d** SM in June)

study plot. This may be caused by desert environment factors such as SM, temperature and evaporation. Microbial properties and processes were mainly controlled by properties such as SM, organic matter content, pH values or texture (Sebai et al. 2007). There were significant ($p < 0.005$) positive correlations between SM and MBC, and between SM and SR (Table 1). Obviously, the variation of SM can directly or indirectly influence the spatial variation of MBC and SR, which helps to explain the mechanisms behind the heterogeneity (Qi et al. 2010). It is possible that SM limits the MBC and influences SR in desert scrubland (Gallardo and Schlesinger 1992). This can partially explain the differences in the spatial variability of properties in this study. Xu and Qi (2001) suggested that SM and soil temperature explained most of the temporal variations (76–95 %) of soil CO_2 efflux, but <34 % of the spatial variation. Stoyan et al. (2000) also reported a highly significant correlation between SM and SR in poplar plots, and Han et al. (2007) indicated SM was a factor controlling spatial variation in SR. Therefore, SM was one of the main environmental factors to influence the changes of MBC and SR, all of which were consistent with previous studies.

Spatial variability of soil characteristics occurs on certain scale, where scrubs control the spatial heterogeneity of soil characteristics. Stoyan et al. (2000) estimated that the main causes of soil heterogeneity around poplar trees in 2 m^2 plots were likely to be controlled in part by root and plant residue patterns at micro scales. Vegetation plays an important role in soil spatial heterogeneity of soil characteristics. The favorable conditions for microbes are concentrated in soil under scrub canopies, thereby improving SR (Qi et al. 2010). Litter materials fall into soil under the canopy, which increases soil substrate contents and these were probably the sources of MBC and SR. Microbial biomass is the living and active part of the soil organic matter, and builds up with increased accumulation of organic matter during soil development (Jenkinson and Ladd 1981; Diaz-Ravina et al. 1993). So the values of MBC and SR are more concentrated mostly around scrubs (Fig. 3; Table 3). The areas with high SR and SM values coincided with those of high MBC values. These patterns showed that the spatial structure at plant scale might be due to the higher accumulation of scrub litter and shade under their canopies, suggesting vegetation cover had fundamental effects on soil properties (Aweto 1981; Busse et al. 2001).

Scrubs under arid climatic conditions influence the chemical, physical and biological characteristics and quality of soils. One explanation for this pattern could be

Table 3 Mean values of MBC, SM and SR for sub-scrub canopy and neighboring open sites in the study plot

Sites	MBC(μgCg^{-1} soil)	SM_A (%)	SR (g m^{-2} h^{-1})	SM_J (%)
Sub-scrub canopy sites ($n = 10$)	179.29 ± 40.22[a]	15.34 ± 1.12[a]	0.198 ± 0.023[a]	10.89 ± 0.53[a]
Open sites ($n = 32$)	67.22 ± 10.28[b]	9.53 ± 0.42[b]	0.027 ± 0.004[b]	9.48 ± 0.26[b]

The table data are the mean $\pm$ SE (m). In the same column, different superscripts indicate significantly different values at $p < 0.05$. SM_A and SM_J indicate measurements performed in the scrubland plot during April and June, respectively

higher SM close to scrubs and the resultant impact on SR. The scrub branches and leaves play a role in intercepting precipitation and forming shade, which decreases SM losses. MBC exhibited a marked concentration around scrubs, as did SR. This could also be due to the C release from litter materials and derived from roots (Dagmar 2004). The soils under scrub canopies provide a stable microenvironment, where more residues are generated and thus also soil microbial biomass. Microbial activities are enhanced because plant exudates concentration in the rhizosphere zone (Lambers and Poorter 1992), which could serve as substrates for microbial growth, thus increasing MBC (Salt et al. 1998). Vegetation can have fundamental effects on soil characteristics (Singh et al. 2004), mainly due to the contribution of organic matter to soil by supplying C and energy sources from root exudates and litter materials.

Concluding remarks

The current study provided some insightful information on the spatial heterogeneity of soil properties at stand shrub-scale in an arid region of northwest China. SM and MBC had moderate spatial variation, but SR had strong variation. The spatial variability of SM decreased when SM changed from wet in April to dry in June. In addition, variation of SM and MBC had a strong spatial autocorrelation, which was mainly induced by structural factors. The mean values of SM, MBC and SR were higher in sub-scrub canopy sites than neighboring open sites. Correlations of SM with MBC and SR were positive, indicating SM as one of the major factors influencing the change of MBC and SR. Such information provided some insights into spatial heterogeneity of soil properties at stand scale of an arid scrubland.

References

Aanderud ZT, Shuldman MI, Drenovsky RE, Richards JH (2008) Shrub-interspace dynamics alter relationships between microbial community composition and belowground ecosystem characteristics. Soil Biol Biochem 40:2206–2216

Aweto AO (1981) Secondary succession and soil fertility restoration in south western Nigeria II. Soil fertility restoration. J Ecol 69:609–614

Busse MD, Ratcliff AW, Shestak CJ, Powers RF (2001) Glyphosate toxicity and the effects of long-term vegetation control on soil microbial communities. Soil Biol Biochem 33:1777–1789

Cain ML, Subler S, Evans JP, Fortin MJ (1999) Sampling spatial and temporal variation in soil nitrogen availability. Oecologia 118:397–404

Chen HS, Zhang W, Wang K, Fu W (2010) Soil moisture dynamic under different land uses on karst hillslope in northwest Guangxi, China. Environ Earth Sci 61:1105–1111

Choi M, Jacobs JM, Cosh MH (2007) Scaled spatial variability of soil moisture fields. Geophys Res Lett 34:L01401. doi:10.1029/2006GL028247

Dagmar T (2004) Shifts in rhizosphere microbial communities and enzyme activity of *Poa alpina* across an alpine chronosequence. Soil Biol Biochem 36:1685–1698

Diaz-Ravina M, Acea MJ, Carballas T (1993) Microbial biomass and its contribution to nutrient concentration on forest soils. Soil Biol Biochem 25:25–31

Dick RP (1992) A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric Ecosyst Environ 40:25–36

Diedhiou S, Dossa EL, Badiane AN, Diedhiou I (2009) Decomposition and spatial microbial heterogeneity associated with native shrubs in soils of agroecosystems in semi-arid Senegal. Pedobiologia 52:273–286

Dilustro JJ, Collins B, Duncan L, Crawford C (2005) Moisture and soil texture effects on soil CO$_2$ efflux components in southeastern mixed pine forests. For Eco Manag 205:85–95

Ettema CH, Wardle DA (2002) Spatial soil ecology. Trends Ecol Evol 17:177–183

Ewing SA, Southard RJ, Macalady JL, Hartshorn AS, Johnson MJ (2007) Soil microbial fingerprints, carbon and nitrogen in a Mojave Desert creosote-bush ecosystem. Soil Sci Soc Am J 71:469–475

Famiglietti JS, Rudnicki JW, Rodell M (1998) Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. J Hydrol 210:259–281

FAO/UNESCO (1990) Soil map of the world. Revised legend Rome

Franklin RB, Mills AL (2003) Multi-scale variation in spatial heterogeneity for microbial community structure in an eastern Virginia agricultural field. FEMS Microbiol Ecol 44:335–346

Franklin RB, Mills AL (2009) Importance of spatially structured environmental heterogeneity in controlling microbial community composition at small spatial scales in an agricultural field. Soil Biol Biochem 41:1833–1840

Gallardo A, Schlesinger WH (1992) Carbon and nitrogen of soil microbial biomass in desert ecosystems. Biogeochemistry 18:1–17

Goovaerts P (1999) Geostatistics in soil science: state-of-the-art and perspectives. Geoderma 89:1–45

Grundmann GL, Debouzie D (2000) Geostatistical analysis of the distribution of NH_4^+ and NO_2^--oxidizing bacteria and serotypes at the millimeter scale along a soil transect. FEMS Microbiol Ecol 34:57–62

Han G, Zhou G, Xu Z, Yang Y, Liu J, Shi K (2007) Biotic and factors controlling the spatial and temporal variation of soil respiration in an agricultural ecosystem. Soil Biol Biochem 39:418–425

Housman DC, Yeager CM, Darby BJ, Sanford RL, Kuske CR, Neher DA, Belnap J (2007) Heterogeneity of soil nutrients and subsurface biota in a dryland ecosystem. Soil Biol Biochem 39:2138–2149

Jenkinson D, Ladd LN (1981) Microbial biomass in soil: measurement and turnover. In: Paul EA, Ladd JN (eds) Soil biochemistry, vol 5. Marcel Dekker, New York, pp 415–471

Jonathan H, Robert S, Stanley D (2002) Soil resource heterogeneity in the Mojave Desert. J Arid Environ 52:222–269

Jordan A, Jurasinski G, Glatzel S (2009) Small scale spatial heterogeneity of soil respiration in an old growth temperate. Biogeosci Discuss 6:9977–10005

Katra I, Blumberg DG, Lavee H, Sarah P (2007) Spatial distribution dynamics of topsoil moisture in shrub microenvironment after rain events in arid and semi-arid areas by means of high-resolution maps. Geomorphology 86:455–464

Lambers H, Poorter H (1992) Inherent variation in growth rate between higher plants: a search for physiological causes and ecological consequences. Adv Ecol Res 34:283–362

Li JR, Okin GS, Alvarez L, Epstein H (2008) Effects of wind erosion on the spatial heterogeneity of soil nutrients in two desert grassland communities. Biogeochemistry 88:73–88

Li CH, Li Y, Tang L (2011a) Comparison of soil properties and microbial activities between air-dried and rewetted desert and oasis soils in northwest China. Commun Soil Sci Plan 42:1833–1846

Li CJ, Li Y, Ma J (2011b) Spatial heterogeneity of soil chemical properties at fine scales induced by *Haloxylon ammodendron* (Chenopodiaceae) plants in a sandy desert. Ecol Res 26:385–394

Liu ZF, Fu BJ, Zheng X, Liu GH (2010) Plant biomass, soil water content and soil N:P ratio regulating soil microbial functional diversity in a temperate steppe: a regional scale study. Soil Biol Biochem 42:445–450

Morris SJ (1999) Spatial distribution of fungal and bacterial biomass in southern Ohio hardwood forest soils: fine scale variability and microscale patterns. Soil Biol Biochem 31:1375–1386

Nunan N, Morgan MA, Herlihy M (1998) Ultraviolet absorbance (280 nm) of compounds released from soil during chloroform fumigation as an estimate of the microbial biomass. Soil Biol Biochem 30:1599–1603

Ogram A, Bridgham S, Corstanje R, Drake H, Küsel K, Mills A, Newman S, Portier K, Wetzel R (2006) Linkages between microbial community composition and biogeochemical processes across scales. In: Verhoeven JTA, Beltman B, Bobbink R, Whigham DF (eds) Wetlands and natural resource management. Springer, Berlin, pp 239–268

Pe′rie C, Munson AD, Caron J (2006) Use of spectral analysis to detect changes in spatial variability of forest floor properties. Soil Sci Soc Am J 70:439–447

Peigné J, Vain J, Cannavacciuolo M, Bottollier B, Chaussod R (2009) Soil sampling based on field spatial variability of soil microbial indicators. Eur J Soil Biol 45:488–495

Piotrowska A, Dlugosz J (2012) Spatio–temporal variability of microbial biomass content and activities related to some physicochemical properties of Luvisols. Geoderma 173–174: 199–208

Qi Y, Dong Y, Jin Z, Peng Q, Xiao S, He Y (2010) Spatial heterogeneity of soil nutrients and respiration in the desertified grasslands of Inner Mongolia China. Pedosphere 20(5):655–665

Qian Y, Wu Z, Yang H, Jiang C (2009) Spatial heterogeneity for grain size distribution of eolian sand soil on longitudinal dunes in the southern Gurbantunggut Desert. J Arid Land 1(1):26–33

Robertson GP (2000) Geostatistics for Environmental Sciences: GS+ User's Guide, Version 5. Gamma Design Software, Plainwell, Michigan, pp 200

Robinson M, Dean TJ (1993) Measurement of near surface soil water content using a capacitance probe. Hydro Process 7:77–86

Rutigliano FA, Ascoli RD, De Santo AV (2004) Soil microbial metabolism and nutrient status in a Mediterranean area as affected by plant cover. Soil Biol Biochem 36:1719–1729

Salt DE, Smith RD, Raskin I (1998) Phytoremediation. Annu Rev Plant Physiol Plant Mol Biol 49:643–668

Sebai TE, Lagacherie B, Soulas G, Martin-Laurent F (2007) Spatial variability of isoproturon mineralizing activity within an agricultural field: geostatistical analysis of simple physicochemical and microbiological soil parameters. Environ Pollut 145: 680–690

Singh AN, Raghubanshi AS, Singh JS (2004) Comparative performance and restoration potential of two *Albizia* species planted on mine spoil in a dry tropical region, India. Ecol Eng 22:123–140

Stoyan H, De Polli H, Bohm S, Robertson GP, Paul EA (2000) Spatial heterogeneity of soil respiration and related properties at the plant scale. Plant Soil 222:203–214

Van Miegroet H, Hysell MT, Johnson AD (2000) Soil microclimate and chemistry of spruce-fir tree islands in northern Utah. Soil Sci Soc Am J 64:1515–1525

Vieublé-Gonod L, Chadoeuf J, Chenu C (2006) Spatial distribution of microbial 2,4-dichlorophenoxy acetic acid mineralization from field to microhabitat scales. Soil Sci Soc Am J 70:64–71

Wick B, Kuhne RF, Vlek PLG (1998) Soil microbiological parameters as indicators of soil quality under improved fallow managements systems in south-western Nigeria. Plant Soil 202:97–107

Xu M, Qi Y (2001) Soil-surface CO_2 efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. Glob Change Bio 7:667–677

Yang ZP, Ouyang H, Zhang XZ, Xu X, Zhou C, Yang W (2011) Spatial variability of soil moisture at typical alpine meadow and steppe sits in the Qinghai-Tibetan plateau permafrost region. Environ Earth Sci 63:477–488

Zhou HF, Zheng XJ, Zhou BJ, Dai Q, Li Y (2012) Sublimation over seasonal snowpack at the southeastern edge of a desert in central Eurasia. Hydrol Process 26:3911–3920