Environ Earth Sci (2011) 63:477–488
DOI 10.1007/s12665-010-0716-y

ORIGINAL ARTICLE

Spatial variability of soil moisture at typical alpine meadow and steppe sites in the Qinghai-Tibetan Plateau permafrost region

Zhaoping Yang · Hua Ouyang · Xianzhou Zhang · Xingliang Xu · Caiping Zhou · Wenbin Yang

Received: 4 August 2009 / Accepted: 13 August 2010 / Published online: 12 October 2010

Abstract Permafrost degradation has the potential to significantly change soil moisture. The objective of this study was to assess the variability of soil moisture in a permafrost region using geostatistical techniques. The experiment was conducted in August 2008 in alpine steppe and meadow located in the Qinghai-Tibetan Plateau permafrost region. Four soil depths (0–10, 10–20, 20–30 and 30–40 cm) were analyzed using frequency domain reflectometry, and sampling made of 80 points in a 10 m × 10 m grid were sampled. Soil moisture was analyzed using classical statistics to appropriately describe central tendency and dispersion, and then using geostatistics to describe spatial variability. Classical statistical method indicated that soil moisture in the permafrost region had a normal distribution pattern. Mean surface soil moisture in alpine meadow was higher than that in alpine steppe. The semivariograms showed that soil moisture variability in alpine cold steppe was larger than that in alpine meadow, which decreased with depths. Nugget values in alpine steppe were low (0.1–4.5), in contrast to alpine cold meadow. Soil moisture in alpine steppe had highly structured spatial variability with more than 93.4% spatial heterogeneity, and the range decreased with depth. Soil moisture content in alpine cold meadow had a moderate spatial dependence with a range of 51.3–169.2 m, increasing with depth.

Keywords Soil moisture · Spatial heterogeneity · Semivariogram · Permafrost · Qinghai-Tibet Plateau

Introduction

Soil moisture stored near the land surface affects a wide variety of earth system interactions over a range of spatial and temporal scales (Famiglietti et al. 1998). The moisture content of surface soils exerts a major control on the partitioning of net radiation into latent and sensible heat, and of rainfall into runoff and infiltration. It is an important component of the energy and water cycle because it controls interactions between the land surface and the atmosphere. Soil moisture provides thermal inertia to the climate system (though to lesser degree); storing and later releasing heat, dampening out diurnal and seasonal variations in surface temperatures (Wei 1995). Regional variations in soil moisture can enhance dryline formation, initiate convection, and increase precipitation recycling (Chang and Wetzel 1991; Chen and Avissar 1994; Basara et al. 1999).

Given the importance of surface soil moisture to Earth system processes, quantification of its spatial–temporal behavior is receiving increased attention from the hydrologic community. Soil moisture is highly variable in space

Z. Yang · H. Ouyang (✉) · X. Zhang · X. Xu · C. Zhou · W. Yang
Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences,
11A Datun Road, Chaoyang District,
Beijing 100101, People's Republic of China
e-mail: ohua@igsnrr.ac.cn

Z. Yang
Nanjing Institute of Environmental Sciences,
Ministry of Environmental Protection,
Nanjing 210042, China

H. Ouyang
International Centre for Integrated Mountain Development,
G.P.O. Box 3226, Khumaltar, Kathmandu, Nepal

Z. Yang
Graduate School of Chinese Academy of Sciences,
Beijing 100049, China

and time (Western and Blöschl 1999), and is controlled by many factors such as weather, soil texture, vegetation and topography. An understanding of the soil moisture balance and its variability (spatial and temporal) is important for understanding patterns of climate change, for developing and evaluating land surface models, for designing surface soil moisture observation networks (Liu et al. 2001) and for quantifying linkages between a region's hydrology, ecology and physiography (geology) (Petrone et al. 2004).

The permafrost area on the Qinghai-Tibet Plateau is estimated to be about 1.5×10^6 km^2 (Jin et al. 2000). Climate warming over past decades has caused degradation in permafrost widely and quickly (Nelson and Anisimov 1993; Anisimov et al. 2007; Cheng and Wu 2007; Wu and Zhang 2008). The main manifestations of degraded permafrost due to climate change or human disturbance are permafrost thinning and the degradation of vegetation. Permafrost degradation entails major effects on ecosystems, to a large extent determining the soil hydrological and nutritional status, which in turn is pivotal in determining vegetative coverage, plant community structure and productivity. Sufficient water supply is very important in maintaining stability of alpine grassland ecosystems (Wang et al. 2006a). With permafrost degradation, alpine swamps and alpine meadows with high vegetation coverage degrade rapidly into alpine steppes. Alpine meadows and steppes on the Qinghai-Tibetan Plateau would turn into desertified land and bare rocks with decrease of soil moisture due to further permafrost degradation (Wang et al. 2001).

During permafrost degradation, alpine meadows and alpine steppes are two important phases of the retrogressive succession with decrease of soil moisture content (Wang et al. 2001; Guo et al. 2007). Alpine ecosystems on the Qinghai-Tibetan Plateau have a unique eco-hydrological structure due to long-term freeze-thawing and existence of ground ice, where soil moisture is the key ecological factor controlling ecological processes. This gives rise to strong coupling between soil moisture regime and both ecological patterns and processes in the permafrost region. To better understand the relationship between permafrost degradation and retrogressive succession of alpine ecosystems, it is of great importance to understand the mechanisms of soil moisture spatial variability in permafrost regions.

Deriving conclusions from soil moisture measurements at only a few locations may result in large uncertainties, as soil moisture can be highly variable. A promising approach to reduce and quantify these uncertainties is the geostatistical sampling technique (Schneider et al. 2008). The geostatistical method characterizes and quantifies spatial variability, performs rational interpolation, and estimates the variance of the interpolated values. The approach was developed originally by mining engineers to asses spatial variability in soil samples for gold ore (Matheron 1963; Webster and Oliver 1990), and was then used extensively in the environmental field (Polhmann 1993) to resolve site-specific problems. Many researchers have studied the spatial variability of surface soil moisture, and Famiglietti et al. (1998) have provided comprehensive summaries of their results. In this study, we investigated surface soil moisture heterogeneity in alpine steppe and the alpine meadow in Qinghai-Tibetan Plateau permafrost region with geostatistical analysis. The objectives of the study were: (a) to characterize the mean and variance of soil moisture in alpine steppe and alpine meadow; and (b) to quantify spatial variability characteristics of surface soil moisture in alpine steppe and alpine meadow.

High-resolution ground-based monitoring is required to characterize soil moisture variability accurately. However, ground-based methods are excessively labor- or equipment-intensive to remain feasible with increasing spatial scale and sampling frequencies. In view of the intensive labor demands of ground-based monitoring, this study was initiated within an area of 100×80 m^2 (Fig. 1) and soil moisture content was measured based on four depths (0–10, 10–20, 20–30, 30–40 cm), using frequency domain reflectometry at 10-m intervals. Although the spatial scale of the study is small, this research has implications for a range of issues in ecology and hydrology. First, a thorough knowledge of small-scale soil moisture variability will provide a foundation for better understanding hydrological, ecological and biogeochemical processes in the Qinghai-Tibet Plateau permafrost region, many of which are related nonlinearly to soil moisture content. Second, because alpine meadows and steppes are two of the most important ecosystem types, this work will provide a basis for characterizing soil moisture variations at larger scales in the permafrost region. Consequently, this work will provide insight into the parameterization of soil moisture dynamics in larger-scale hydrological models, into design of larger-scale soil moisture observation networks, and into the effects of permafrost degradation on the terrestrial hydrological cycle. Finally, this study will contribute towards an improved understanding of the representativeness of point soil moisture measurements as indicators of larger-scale average moisture conditions, and of the relationship between permafrost degradation and ecosystem retrogressive succession.

Materials and methods

Study site description

The region is located in the plateau-continental climatic zone. Its climate is cold and dry, and the freezing period extents from September to April. Two ecosystems are included in this study: an alpine steppe located in

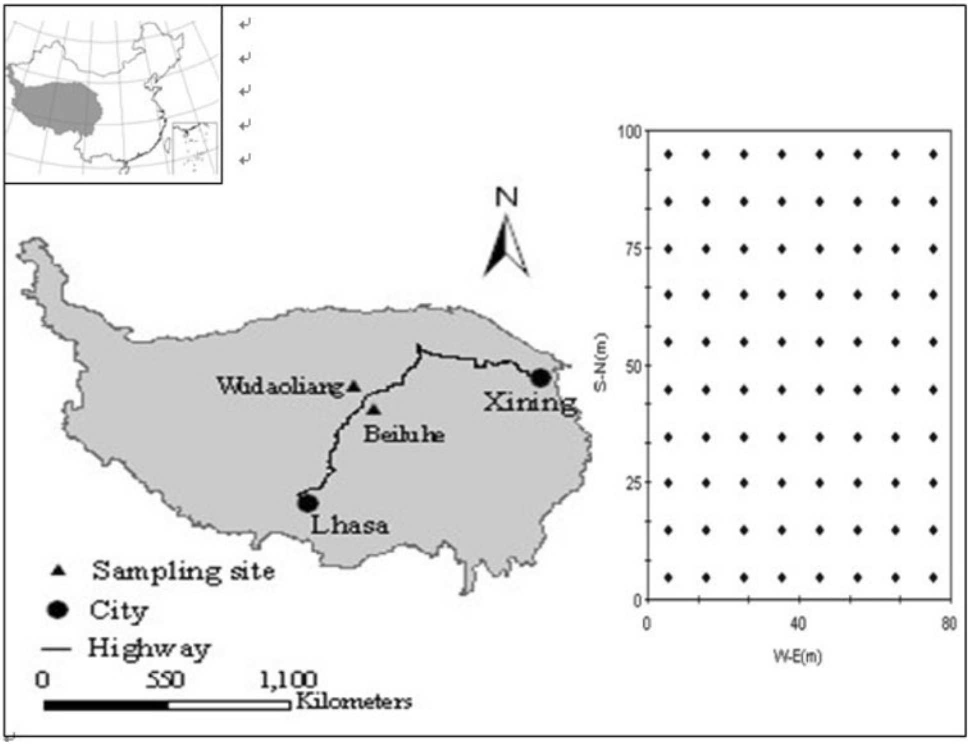


Fig. 1 Location of sampling sites, and map of soil sampling points

Wudaoliang, and an alpine meadow located in Beiluhe (Fig. 1). Sample plots were located in the permafrost region. Permafrost conditions are shown in Table 1, and soil properties of alpine steppe and alpine meadow are listed in Table 2.

The alpine steppe site is at 35°12′28″N and 93°04′9″E, 4,632 m a.s.l. Mean annual precipitation is 266.5 mm, of which ~84% falls between June and September. The region located on a high altitude alluvial plain, with a permafrost table at 2.0–2.5 m depth in June. Mean monthly air temperature is <0°C except from June to September, and average annual air temperature is −5.6°C. Soils are mainly thin alpine steppe soils, of low fertility and high gravel content. Vegetation was dominated by *Stipa purpurea* Griseb. and associated gramineous weeds, with simple structure and low coverage.

The alpine meadow site is at 34°49′28.1″N and 92°56′7.3″E, 4,738 m a.s.l. Annual mean temperature and precipitation are −3.8°C and 290.9 mm, respectively. The average depth of the active layer is 1.4–3 m and annual soil temperature ranges from −3.0 to −1.0°C. Vegetation was dominated by *Kobresia humilis*. Other main species include *Kobresia pygmaea*, *K. capillifolia*, and *Poa crymopnila*. Coverage is ~60–70%; however, in local areas of patch mosaic the coverage is <40%. Soils were predominantly Mattic Cryic Cambisols (NSSO 1998) under the Chinese taxonomy. These soils are characterized by a Mattic epipedon, and increasing clay and silt and decreased soil organic matter (SOM) with increasing depth.

Experimental design and data collection

One 8,000 m^2 study site was set up at each experimental field, which was 100 m long from south to north and 80 m wide from west to east. Survey stakes were located at 10-m intervals in two directions (see Fig. 1) resulting in a total of 80 locations for moisture content sampling.

Volumetric soil moisture content in the topsoil layer (0–10, 10–20, 20–30, 30–40 cm) was measured using frequency domain reflectometry (FDR) (ML2x Theta probe, Delta T Devices Ltd., Cambridge, UK) on 8th August in 2008. There was no rainfall events observed within 7 days before sampling, and all measurements were finished on the same day. The sensor rods of the Theta probe were

Table 1 Permafrost characteristics of alpine steppe and alpine meadow

Ecosystem type	Frozen soil thickness (m)	Ice-rich frozen soil percentage (%)	Mean air temperature (°C)	Mean ground temperature (°C)	Permafrost table (m)
Alpine steppe	20.0–60.0	12.6–44.6	−4.0–5.0	0–1.5	2.4
Alpine meadow	50.0–120.0	38.5–68.2	−3.8–4.0	0–1.0	1.8

Table 2 Soil properties of alpine steppe and meadow

Ecosystem type	Organic matter content (g kg^{-1})	Total nitrogen (g kg^{-1})	Bulk density (g cm^{-3})	>0.5 mm soil grain size content (%)
Alpine steppe	9.90	2.10	1.30	8.12
Alpine meadow	43.60	2.35	1.06	2.15

0.06 m in length and 0.025 m in diameter. The probe measures the integrated moisture content in the cylindrical volume spanned by the rods. The rods were inserted vertically into the soil profile. Soil moisture was obtained from the measured signal with the built-in calibration curve, which fits well to independent moisture measurements conducted in the field. The FDR was calibrated in the Qinghai-Tibetan Plateau permafrost region, and the determination accuracy was ±2%. In each layer soil moisture was measured three times, respectively, and the mean value was used.

Data analysis

Statistical analysis of these data was performed in two steps: (1) descriptive statistics such as mean, variance, coefficient of variation, minimum value, and maximum value were calculated using SPSS 13.0 software, and normality was assessed using the one-sample Kolmogorov–Smirnov (KS) test for goodness of fit; and (2) semivariograms were constructed and fitted to curve types.

The geostatistical analysis was carried out with the free software GS+. The geostatistical analysis investigates whether sampling points close to each other are more similar than sampling points with a larger separation. The relation of two samples separated by a distance h can be expressed by the experimental semivariogram $r\,(h)$:

$$r(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z(x_i) - Z(x_i + h)\right]^2 \tag{1}$$

where $N\,(h)$ denotes the number of data pairs in a particular distance class (or lag) h, $Z(x_i)$ is a sample z located at x_i, and $Z\,(x_i + h)$ is a sample separated from $Z(x_i)$ by the distance h. Due to the sampling scheme, there are different distance classes h.

According to optimum regression analysis and comparison of different line type, the spherical model and exponential were fitted to the experimental variogram to interpolate the data to unsampled locations in different layers. The spherical (Eq. 2) and exponential (Eq. 3) model were calculated as follows:

$$\begin{cases} r(h) = C_0 + C\left[\frac{3h}{2a} - \frac{h^3}{2a^3}\right] h \le a \\ r(h) = C_0 + C\, h > a \end{cases} \tag{2}$$

$$r(h) = C_0 + C\left(1 - e^{-\frac{h}{a}}\right) h > a \tag{3}$$

where C_0, a, and $C_0 + C$ are the nugget, range and sill in the idealized variogram. The nugget marks the initial semivariance and indicates variability at distances smaller than the shortest sampling distance. The difference between the nugget and the highest values of r (h) is called the sill. Without the presence of a nugget variance, the sill is the overall span of the semivariance within the population. The range indicates the separation where semivariance reaches its maximum, which equals the separation below which measurements are correlated.

The quality of the semivariogram fit to the data was indicated using a regression coefficient R^2 and an F test calculated as:

$$F = \left[R^2/(1 - R^2)\right]\left[(N - K)/(K - 1)\right] \tag{4}$$

where K is the number of variables in the regression model, and N is the number of samples.

The kriging method is an optimal interpolation method, with an unbiased interpolated value and minimal estimation variance (Webster and Oliver 2001; Outeiro et al. 2008). Once the best theoretical semivariogram was fit to the experimental semivariogram, we interpolated the data using ordinary kriging (OK) applied to a fundamental block of pixels (e.g., 2 × 2, 3 × 3) to estimate soil moisture for areas where no measurements were taken, from the spatial correlation structure of the sample data given by the semivariogram. Finally, model performance was assessed by cross validation. In cross-validation analysis each measured point in a spatial domain is removed individually from the domain and its value estimated via kriging. The regression coefficient represents a measure of the goodness of fit for the least-squares model describing the linear regression equation. A perfect 1:1 fit would have a regression coefficient (slope) of 1.00.

Results

Statistical distribution of soil moisture

Before the spatial structure investigated, the data were analyzed using classical statistical methods to understand general soil moisture characteristics (Table 3). Mean and median soil moisture values in study area were similar, indicating that these measures of central tendency were not

Table 3 Descriptive statistics for soil moisture

Soil layer (cm)	Mean (% v/v)	Minimum (% v/v)	Maximum (% v/v)	Media (% v/v)	SD (% v/v)	CV (%)	KS value
Alpine steppe							
0–10	20.20	37.50	10.00	18.30	7.16	35.47	1.12
10–20	24.42	14.10	36.70	24.60	6.37	26.08	0.88
20–30	24.97	13.30	37.90	24.20	6.35	25.43	0.34
30–40	24.99	13.30	35.80	26.35	5.92	23.77	0.24
Alpine meadow							
0–10	35.86	46.50	23.95	35.25	5.21	14.53	0.56
10–20	37.96	49.20	23.00	39.35	5.25	13.83	0.18
20–30	36.71	45.70	24.00	37.65	4.46	12.14	0.30
30–40	35.15	45.00	22.60	35.60	4.44	12.62	0.11

CV coefficient of variation, *KS* one-sample Kolomogorov–Smirnov test

dominated by outliers in the distributions. The KS test ($\alpha = 0.05$ probability level) also indicated that the soil moisture data were distributed normally (Table 3). Our results agreed with earlier studies (Nyberg 1996; Pan et al. 2008), and suggested that under natural conditions near-surface soil moisture was distributed normally in alpine ecosystems, enabling analysis of spatial heterogeneity.

Mean and coefficient of variation (CV) of soil moisture

Mean soil moisture and its CV are presented in Table 3 and Fig. 2. Mean surface soil moisture in the alpine meadow was higher than that in the alpine steppe. In alpine steppe the mean soil moisture in the upper 10 cm was 20.2% and increased gradually to 24.99% with increasing depth. In alpine meadow there was an increase and then slight decreasing in soil moisture, and maximum mean soil moisture content was 25.37% existed in the 10–20 cm layer.

The CV represents the discrete degree of a random variable, and can be used to classify the variability as strong if CV ≥30%, moderate for CV between 10 and 30%, and weak with CV ≤10% (Xue et al. 2002). The CV values of soil moisture for the alpine steppe ranged between 23.77 and 35.47%. The highest CV of soil moisture (35.47%) occurred at 0–10 cm, indicating soil moisture variability in this layer was strong. Soil moisture variability for the alpine meadow was moderate, with the CV varying from 12.14 to 14.53%. The data suggested that variation was larger in the alpine steppe than in the alpine meadow (Fig. 2). This result was consistent with several investigations which have noted that the coefficients of variation were low when the soil had higher water content (Robinson and Dean 1993; Grego et al. 2006). Considering also the fact that soil moisture content in topsoil decreased gradually with permafrost degradation on the Qinghai-Tibetan Plateau, the CV of soil moisture content increased with permafrost degradation.

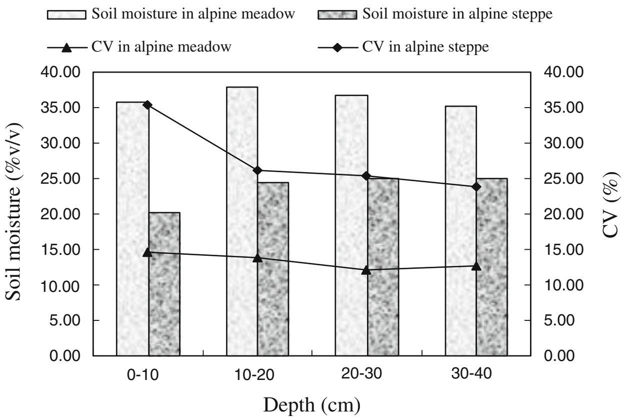


Fig. 2 Volumetric soil moisture content (%) and CV (%)

Spatial variability of soil moisture

The parameters of the fitted soil moisture semivariograms summarized in Table 4 were generated from spherical (Eq. 2) and exponential (Eq. 3) models, which were the best-fitting descriptors for this data set. All the semivariogram models were acceptable for fitting to the raw data according to the *F* test (Eq. 4) (Table 4).

Theoretically, a variogram of a random function should be close to zero when the separation distance *h* approaches zero. However, in reality a discontinuity is often present. This discontinuity was called the nugget effect, and large nugget values indicated that variability at scales smaller than the sample spacing could not be neglected (Cambardella et al. 1994). The nugget value at 10–20 cm in alpine steppe was 4.5 and showed nugget effect (Table 4, Fig. 3). However, the nugget values were less than 0.5 in other cold steppe layers. Low nugget values did not mean that there were no measurement errors in the data, nor was there no random variation in the variable. The low nugget effects probably occurred due to small random variations and measurement errors, and because the space

Table 4 Semivariogram models of soil moisture and corresponding parameters

Depth (cm)	Model	C_0	$C_0 + C$	a (m)	$C_0/(C_0 + C)$ (%)	R^2	F
Alpine steppe							
0–10	Spherical	0.1	101.2	123.4	0.1	0.969	187.55
10–20	Spherical	4.5	70.0	113.4	6.4	0.970	194.00
20–30	Spherical	0.1	70.2	106.9	0.1	0.974	224.77
30–40	Spherical	0.5	62.0	109.1	0.8	0.971	200.90
Alpine meadow							
0–10	Exponential	8.3	30.2	51.3	27.4	0.860	36.86
10–20	Spherical	11.9	31.6	60.7	37.7	0.974	224.77
20–30	Spherical	11.7	32.8	167.0	35.7	0.912	62.18
30–40	Spherical	12.6	30.3	169.2	41.6	0.841	31.74

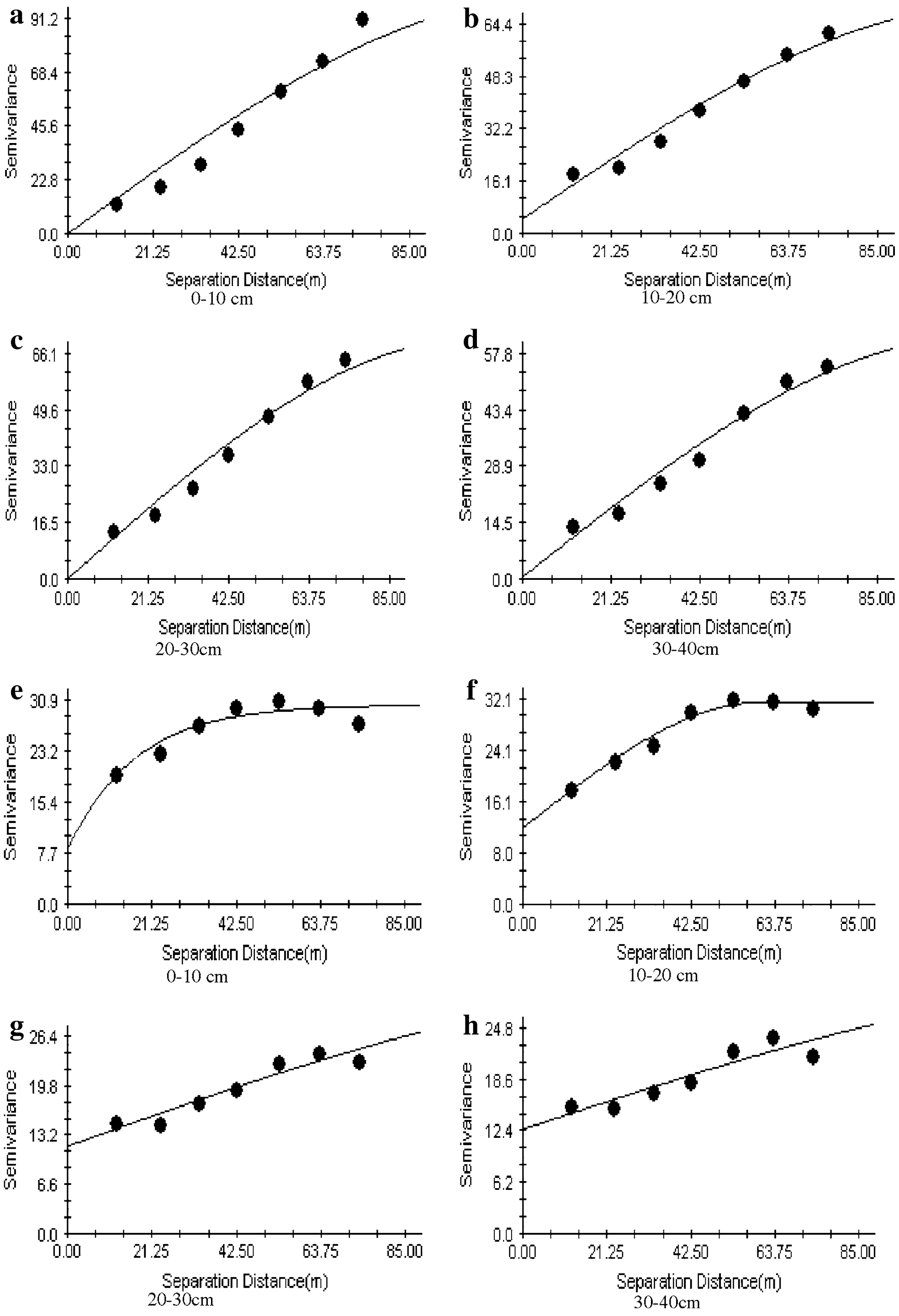
$F(1, 5)_{0.05} = 6.608$, $F(1, 5)_{0.01} = 16.26$

interval for data collection was too large to trap these random variations and measurement errors (Liu et al. 2001). All soil moisture values were obtained in the same way, so we inferred the high nugget value of 10–20 cm resulted mainly from difference of vegetation condition. In Qinghai-Tibetan Plateau alpine steppe, belowground biomass was distributed mainly at 0–10 cm and root distribution decreased rapidly at 10–20 cm, which increased variability within scales smaller than the sample spacing. The alpine meadow nugget values ranged from 8.3 to 12.6 and showed an apparent nugget effect like that in alpine steppe. High nugget values in this case could be due to data not being collected at sufficiently small spacing to reveal continuous behavior of soil moisture.

The value of the sample variogram where it levels off is called the sill (Ma et al. 2006). If a sill exists, the process is stationary and the sill should be equivalent to the variance of the random function, because when the variogram reaches its sill the covariance of variables approaches zero. The sill denotes the total spatial variation, so the higher the sill the larger the spatial variation. The alpine steppe sills were between 62.0 and 101.2 and exhibited a clear decrease with depth (Table 4; Fig. 3). However, the sill in alpine meadow had the opposite tendency. In alpine meadow the soil is wet, moisture is relatively uniform, and hence the sill is low. Soil moisture at 20–30 cm in alpine meadow has high spatial heterogeneity mainly due to root distribution at 0–30 cm, and which decreases rapidly below 30 cm. The high sill at 0–10 cm in alpine steppe may be due to changes in microtopography and vegetation coverage. Generally, alpine steppe exhibited greater spatial variation than alpine meadow. The difference of the sills between the two ecosystems resulted mainly from intense change in surface soil, microtopography and vegetation coverage over a small range, which lead to uneven distribution of soil moisture and increased variability of soil moisture in alpine steppe. Another reason is soil moisture content. Mean soil moisture content in alpine steppe was relatively low (Table 4), leading to high heterogeneity due to small areas of drought co-existing with wet areas (Hills and Reynolds 1969). In the meanwhile, when the soil has lower water content, other soil properties such as hydraulic conductivity may affect random processes.

Degree of structural spatial variation

The difference in degree of structured spatial variation is indicated by variation in the nugget effect, and of the sill. The ratio of the nugget effect to total semivariance provides indication of the degree of spatial variability. If this ratio is less than 25% there is strong spatial dependence; for 25–75% there is moderate spatial dependence; and greater than 75% there is weak spatial dependence (Cambardella et al. 1994). The ratio in alpine steppe was less than 25% (Table 4; Fig. 4), indicating soil moisture had highly structured spatial variability. For the alpine meadow, the ratios were between 27.4 and 41.6%, and the soil moisture had moderate autocorrelation heterogeneity. Therefore, there is stronger spatial dependence in the alpine steppe than that in the alpine meadow. Random variation in soil moisture at 10–20 cm was highest in alpine steppe, resulting mainly from root distribution decreasing rapidly in this layer, which increased spatial heterogeneity. In alpine meadow, soil moisture at 30–40 cm had a high sill value, indicating the degree of random variation occupying total spatial heterogeneity was high. This was due mainly to decreased root distribution and increasing gravel content with the depth, and permafrost thaw in the deep active layer also influenced deep soil moisture distribution. The most striking feature in Fig. 4 is the magnitude of the difference between alpine steppe and alpine meadow. This suggests that spatial variation of soil moisture in the alpine steppe was more strongly correlated than in the alpine meadow. Random variation was between 27.4 and 41.6% in alpine meadow occurring mainly at scales smaller than sampling spacing, and was much larger than in alpine steppe.



0-10 cm

10-20 cm

20-30cm

30-40cm

0-10 cm

10-20 cm

20-30cm

30-40cm

Fig. 3 Semivariograms for moisture content values. **a**–**d** are alpine cold steppe, **e**–**h** are alpine cold meadow

Scale of structural spatial variation

The range in a variogram is the distance at which the variogram reaches the sill. The variability beyond this range does not depend on the separation distance and the variables are no longer related spatially. The range can be viewed as a zone of influence of a variable, or a transition from a state of spatial correlation to a state of absence of correlation (Petrone et al. 2004). It is a direct measurement of the scale of spatially correlated variation. The larger the range, the larger the scale of the correlated spatial variation is. In this study, the range of soil moisture in the two ecosystems exhibited different change modes (Table 4; Fig. 5). The maximum range in alpine steppe was 123.4 m, occurring at 0–10 cm. The general trend in alpine steppe was decrease of range with increasing depths (Table 2).

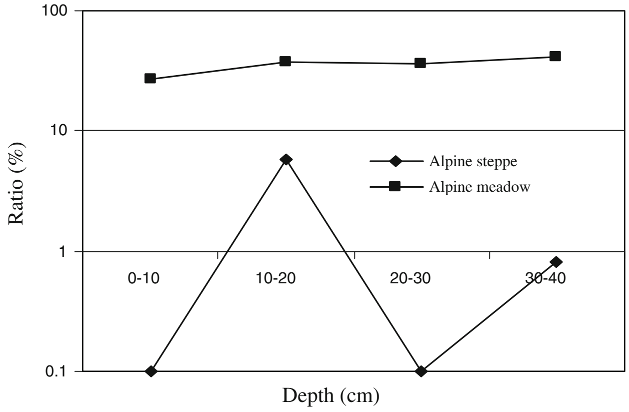


Fig. 4 Ratio of the nugget effect to spatial variance

The range in alpine meadow increased with depth and changed between 51.3 and 169.2 m (Table 4; Fig. 5). The alpine ecosystems geostatistical parameters do not agree with those reported in the literature. Ranges indicated by Zhang et al. (2007) are longer than those in this study, while those indicated by Liu et al. (2008) are shorter. Close inspection of these data reveals that there is a tendency for data collected at larger spacings to have larger ranges. Therefore, differences between previously reported values and those in our study may be due to differences in sample spacing. Differences in climate, soil and vegetation will also contribute.

Observed versus predicted values

Kriging is an interpolator; it produces a smoothed representation of the spatial data. By comparing the soil moisture data with the interpolated data (estimated data), cross-validation results were obtained of the variogram model (Table 5; Fig. 6). The standardized root-mean-square values and regression coefficients shown in Table 5 indicate that the estimated value of soil moisture was close to the measured value. Figure 6 also shows that the established variogram model was precise.

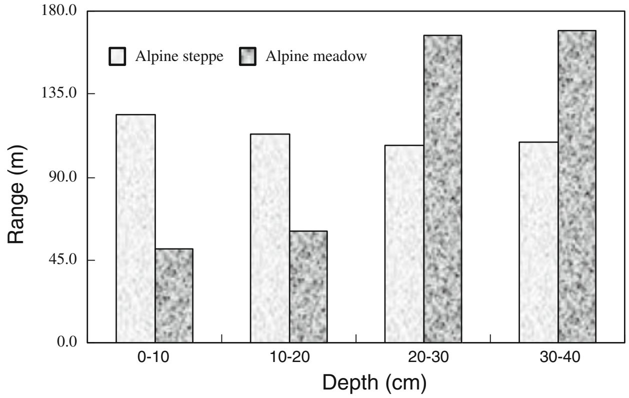


Fig. 5 Scale of structural spatial variation

Discussion

Difference in soil moisture variation between alpine steppes and meadows

In this study, vertical and spatial variability of soil moisture in the alpine steppe was higher than in the alpine meadow. This is due mainly to differences in soil physical properties, vegetation status and permafrost environment between the two ecosystems. Soil in the alpine steppe was thin layer and had high gravel content, which increased with the depth and in some areas reached 60% volume percentage at 40–50 cm. Soil in the alpine meadow was thick, had high organic matter content and low gravel content. This weakened soil heterogeneity, leading to decreased spatial variability of soil moisture. Average vegetation coverage in alpine meadow was ~60% in study area, and held relatively higher soil moisture than the alpine steppe. In alpine steppe, the proportion of bare land was high and vegetation coverage was ~30%. An apparent spatial pattern existed in the alpine steppe due to differences in vegetation coverage and mosaic distribution of bare land and vegetation, which increased spatial heterogeneity of soil moisture. Permafrost condition was important in influencing soil variability. Groundwater depth is related strongly to the permafrost table on the Qinghai-Tibetan Plateau. Permafrost plays an important role in maintaining soil moisture in the active layer, which is crucial for vegetation growth. Soil water migrates to the bottom of the active layer following permafrost thaw in the deep active layer, resulting in uneven distribution of soil moisture in permafrost regions. Low permafrost stability can maintain high soil moisture in the active layer. Therefore, alpine meadow soil moisture was higher than that in alpine steppe, and had lower soil moisture spatial heterogeneity.

Effects of permafrost degradation on variability of soil moisture

As material foundation of cold region, Permafrost is crucial for ecological balance in permafrost regions. In the context of global change permafrost is degrading, causing alpine swamps to change into alpine meadows, then into alpine steppe and lastly into alpine desert steppes. Permafrost degradation has the potential to significantly change soil moisture, alter soil physical and chemical properties and vegetation type and coverage, all of which influenced the variability of soil moisture in permafrost regions.

Table 5 Cross-validation of variogram model and regression coefficient

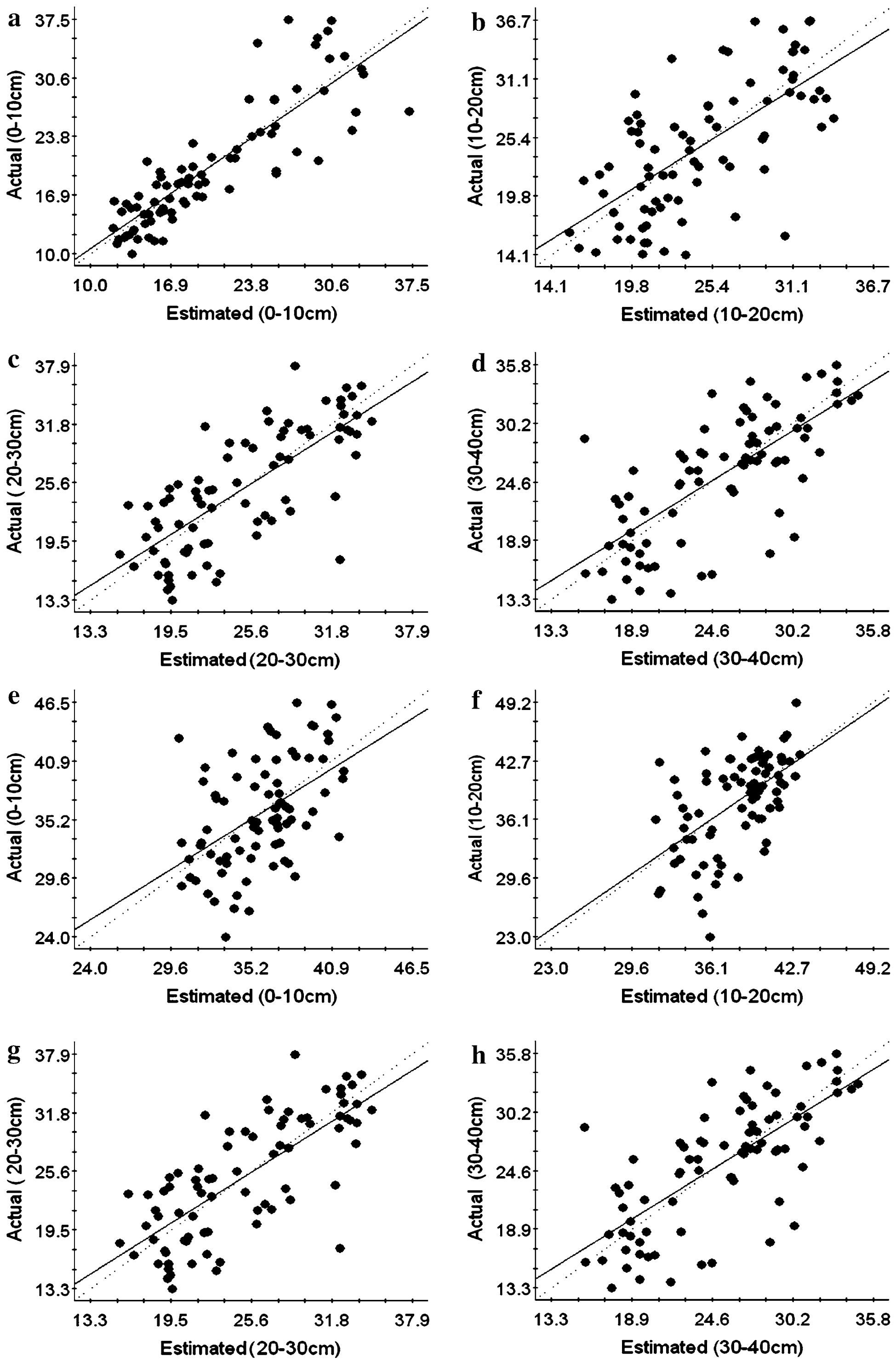
Depth (cm)	Mean relative error	Standardized root mean square	Regression coefficient
Alpine steppe			
0–10	0.133	0.514	0.940
10–20	0.158	0.744	0.855
20–30	0.129	0.601	0.905
30–40	0.123	0.680	0.857
Alpine meadow			
0–10	0.102	0.867	0.856
10–20	0.089	0.824	0.941
20–30	0.083	0.881	0.876
30–40	0.088	0.878	0.905

Some studies have reported the significant influence of soil moisture content on soil moisture variability. Pan et al. (2008) showed that following the dry period after rain events, soil moisture reduced, inducing a decrease in variability. Reynolds (1970) suggested that variability might be the largest after a rainfall event and lowest after an extended dry period. Hills and Reynolds (1969) proposed that the variance peaks in the mid-range of mean moisture, when small areas of rapid drying might co-exist with wet areas, resulting in more heterogeneous wetness conditions (Famiglietti et al. 1998). In alpine swamps, topsoil soil moisture was high and soil was almost saturated, leading to uniform conditions so the variability was low (Wang et al. 2006b). Under permafrost degradation soil moisture transferred gradually to and froze at the permafrost table under the pressure gradient of temperature and water vapor, and led to decrease of soil moisture in the top active layer (Wang et al. 2006b). The extent of soil moisture saturated in the topsoil decreased along the degradation gradient from alpine swamps to alpine desert steppes. Lower topsoil moisture caused increased variability of soil moisture, which could be tested by our results that alpine meadow soil moisture variability was larger than in alpine steppe. Severe permafrost degradation could lead to an extremely dry in soil environment and change the alpine steppe into alpine desert steppe. Variability might be lowest after an extended dry period when soil heterogeneity would be minimized (Reynolds 1970), from which we deduce that variability of soil moisture in the alpine desert steppe would be lower than the alpine meadow and alpine steppe.

Soil heterogeneity affects the distribution of soil moisture through variations in texture, organic matter content, structure and macroporosity, all of which affect fluid transmission and retention properties of the soil column (Crave and Gascuel-Odoux 1997; Niemann and Edgell 1993). Changes in soil properties in retrogressive alpine ecosystem succession generated by permafrost degradation are mainly soil coarsening, decreasing organic matter and increasing small openings, volume weight and saturated hydraulic conductivity (Wang et al. 2006b). The content of sand and gravel >0.5 mm in the surface layer of alpine meadow soil shows an increase in the form of the quadratic parabola with increasing thickness of the active layer, and the alpine steppe soils exhibit a similar trend (Wang et al. 2006a). Organic content influences soil moisture (Liu et al. 2005) and infiltration processes (Li and Fan 2006). Therefore, decrease in organic content in permafrost degradation might alter the distribution of topsoil moisture. Changes in soil physical and chemical properties resulting from permafrost degradation cause considerable changes in soil heterogeneity and further lead to changes in soil moisture variability in permafrost regions. However, the extent of changes in soil properties influenced the variability of soil moisture during permafrost degradation has been unclear.

Vegetation influences soil moisture variability by affecting soil hydraulic conductivity, the rate of evaporative drying and evapotranspiration, and adding organic matter to the soil surface layer (Famiglietti et al. 1998). The degree to which these factors affect soil moisture distribution varies with succession stage, vegetation type and coverage during permafrost degradation. Some studies (Lull and Reinhart 1955; Reynolds 1970) have noted that vegetative coverage was a major factor influencing soil moisture variability, and variability increased with decreasing canopy coverage. With permafrost degradation, decreasing vegetation coverage caused increasing evaporation rate and infiltration capacity, and decreasing interception capacity and topsoil soil moisture content, which lowered the effect of soil heterogeneity and led to high variability of soil moisture (Chai et al. 2008). The moisture-retention capacity of alpine steppe topsoil does not persist when the vegetation coverage rate is <50% (Wang et al. 2006b). There was a significant correlation between vegetation coverage and the soil moisture. Increase of soil moisture with vegetation coverage can be described as a quadratic parabolic equation within the 20 cm depth (Wang et al. 2003).When vegetation coverage was very low in the alpine desert steppe, any available soil moisture evaporated quickly, evapotranspiration was moisture-limited, and soil moisture was generally close to the wilting point, which led to the uniform distribution of soil moisture. However, the spatial patterns resulting from a mosaic of low vegetation coverage and bare land increased soil microenvironment heterogeneity and changed variability of soil moisture. In permafrost degradation, there was a tendency for plant individual miniaturization (Wang et al. 2005). It is therefore likely that interception losses

Fig. 6 Cross-validation of the variogram model for different soil layers. *Dots* represent scatter of measured and estimated soil moisture data, *dashed line* is the 1:1 line. **a–d** are alpine steppe, **e–h** are alpine meadow



increased because leaf area index decreased under permafrost degradation. Under ecosystem change roots conglomerated gradually in the surface soil (Wang et al. 2005). In the alpine meadow roots were distributed mainly at 0–20 cm and in the alpine steppe at 0–10 cm. This change in root structure under ecosystem succession could influence the vertical variability of soil moisture.

The variability of soil moisture in permafrost regions resulted from interaction between basic ecological processes, physical processes and the freezing-thawing cycle at different spatio-temporal scales. Based on our analysis above, the variability of soil moisture increased with permafrost degradation and then decreased when the ecosystem degraded into alpine desert steppe.

Conclusions

Soil moisture in alpine steppe and alpine meadow was normally distributed, as shown by the KS test ($\alpha = 0.05$ probability level). The mean surface soil moisture in alpine meadow was higher than in alpine steppe. In alpine steppe the variability of soil moisture at 0–10 cm was strong and moderate at other layers, and was larger than in alpine cold meadow where the CV ranged from 12.14 to 14.53%.

Spherical and exponential geostatistical models were the best-fit models to simulate soil moisture in the research area. The model parameters indicated that there were apparent nugget effects in alpine meadow, with nugget values between 8.3 and 12.6. Nugget values in alpine steppe ranged from 0.1 to 4.5. The variograms had a clear sill in all cases. In contrast to the low sill values in alpine cold meadow, there was higher spatial variability in the alpine steppe, with sills decreasing with depth. Soil moisture content in the alpine meadow presented a moderate spatial dependence with a range of 51.3–169.2 m, increasing with depth. In alpine meadow the proportion of random variability comprising the total spatial variability was between 27.4 and 41.6%. This was much larger than in alpine steppe, and occurred mainly at scales smaller than sample spacing. Soil moisture in alpine steppe had highly structured spatial variability, and the range decreased with increasing depths.

The variability of soil moisture in alpine swamp is low, and increases gradually from alpine meadow to alpine steppe due to the effects of soil heterogeneity increasing with permafrost degradation. When the ecosystem degrades into alpine desert steppe, variability decreases with the succession stage because of the uniform distribution of soil moisture caused by an extremely dry soil environment. Although the spatial scale of this study was small, this research has implications for a range of hydrology issues. Further spatial analysis studies at the plot scale need to be conducted to analyze effects of precipitation and snowmelt on soil moisture variability. To characterize the temporal dynamics of soil moisture variability in the permafrost region, sampling frequency should also be addressed in future.

Acknowledgments This study was funded by NKBRSF, PR China (No. 2005CB422005) and the National Basic Task Project (2006FY110200).

References

Anisimov OA, Vaughan DG, Callaghan TV (2007) Polar regions (Arctic and Antarctic). Climate change 2007: impacts, adaptation and vulnerability. In: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, pp 653–685

Basara JB, Brotzge JA, Crawford KC (1999) The influence of soil moisture on the atmosphere during the summer of 1997. In: Proceedings of the 14th conference on hydrology, pp 337–340

Cambardella CA, Mooman AT, Novak JM (1994) Field-scale variability of soil properties in central Iowa soil. Soil Sci Soc Am J 58:1501–1511

Chai W, Wang GX, Li YS (2008) Response of soil moisture under different vegetation coverage to precipitation in the headwaters of the Yangtze River. J Glaciol Geocryol 30(2):329–337

Chang JT, Wetzel PJ (1991) Effects of spatial variations of soil moisture and vegetation on the evolution of prestorm environment: a numerical case study. Mon Weather Rev 119:1324–1340

Chen F, Avissar R (1994) The impact of land surface wetness on mesoscale heat fluxes. J Appl Meteorol 33:1324–1340

Cheng GD, Wu TH (2007) Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. J Geophys Res. 112:F02S03. doi:10.1029/2006/JF000631

Crave A, Gascuel-Odoux C (1997) The influence of topography on time and space distribution of soil surface water content. Hydrol Process 11:203–210

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

Grego CR, Vieira SR, Antonio AM (2006) Geostatistical analysis for soil moisture content under the no tillage cropping system. Sci Agric (Piracicaba, Braz) 63(4):341–350

Guo ZG, Niu FJ, Zhan H (2007) Changes of grassland ecosystem due to degradation of permafrost frozen soil in the Qinghai-Tibet plateau. Acta Ecol Sin 27(8):3294–3301

Hills TC, Reynolds SG (1969) Illustrations of soil moisture variability in selected areas and plots of different sizes. J Hydrol 8:27–47

Jin HJ, Li SX, Wang SL (2000) Impacts of climatic change on permafrost and cold regions environment in china. Acta Geogr Sin 55(2):161–173

Li XZ, Fan GS (2006) Influence of organic matter content on infiltration capacity and parameter in field soils. Trans CSAE 22(3):188–190

Liu SX, Mo XG, Li HB (2001) Spatial variation of soil moisture in china: geostatistical characterization. J Meteorol Soc Jpn 79(1B): 555–574

Liu SC, Lu JL, Ma AS (2005) Effect on organic matter to the water retention capability and effect of water and fertility of Huangrang-soil. Agric Res Arid Areas 23(3):65–68

Liu LJ, Zhang H, Luo L (2008) Spatial heterogeneity of soil water of alpine area in eastern Qinghai-Tibet plateau. J Wuhan Univ (Nat Sci Ed) 54(4):414–420

Lull HW, Reinhart KG (1955) Soil moisture measurement. USDA Southern For Exp Sta, New Orleans, LA, Occas Paper No. 140

Ma FY, Li XR, Zhang JG (2006) Spatial heterogeneity of soil moisture in Shapotou sand-fixing artificial vegetation area. Chin J Appl Ecol 17(5):789–795

Matheron G (1963) Principles of geostatistics. Econ Geol 58:1246–1266

National Soil Survey Office (NSSO) (1998) Soil of China. Chin Agric Press, Beijing, China (in Chinese)

Nelson FE, Anisimov OA (1993) Permafrost zonation in Russia under anthropogenic climatic change. Permafr Periglac Process 4(2):137–148

Niemann KO, Edgell MCR (1993) Preliminary analysis of spatial and temporal distribution of soil moisture on a deforested slope. Phys Geogr 14(5):449–464

Nyberg L (1996) Spatial variability of water content in the covered catchment at Gardsjon, Sweden. Hydrol Process 10:89–103

Outeiro L, Aspero F, Úbeda X (2008) Geostatistical methods to study spatial variability of soil cations after a prescribed fire and rainfall. Catena 74:310–320

Pan YX, Wang XP, Jia RL (2008) Spatial variability of surface soil moisture content in a re-vegetated desert area in Shapotou, Northern China. J Arid Environ 72:1675–1683

Petrone RM, Price JS, Carey SK (2004) Statistical characterization of the spatial variability of soil moisture in a cutover peatland. Hydrol Process 18:41–52

Polhmann H (1993) Geostatistical modeling of environmental data. Catena 20:191–198

Reynolds SG (1970) The gravimetric method of soil moisture determination, III: an examination of factors influencing soil moisture variability. J Hydrol 11:288–300

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

Schneider K, Huisman JA, Breuer L (2008) Ambiguous effects of grazing intensity on surface soil moisture: a geostatistical case study from a steppe environment in Inner Mongolia, PR China. J Arid Environ 72:1305–1319

Wang GX, Cheng GD, Shen YP (2001) Research on ecological environmental change in the Changjiang–Yellow Rivers source regions and their integrated protection. Lanzhou Univ Press, Lanzhou, pp 29–35

Wang GX, Shen YP, Qian J (2003) Study on the influence of vegetation change on soil moisture cycle in alpine meadow. J Glaciol Geocryol 25(6):653–659

Wang YB, Wang GX, Shen YP (2005) Degradation of the eco-environmental system in alpine meadow on the Tibetan plateau. J Glaciol Geocryol 27(5):633–670

Wang GX, Li YS, Wu QB (2006a) Impacts of permafrost changes on alpine ecosystem in Qinghai-Tibet plateau. Sci China Ser D: Earth Sci 49(11):1156–1169

Wang YB, Wang GX, Shen YP (2006b) Response of typical high-cold frozen soil to change of the high-cold ecosystem on Tibetan plateau. J Glaciol Geocryol 28(5):633–671

Webster R, Oliver MA (1990) Statistical methods in soil and land resource survey. Oxford University Press, Oxford

Webster R, Oliver MA (2001) Geostatistics for environmental scientists. Wiley, Chichester

Wei M (1995) Soil moisture: report of a workshop held in Tiburon, California, 25–27 January 1994. NASA Conference Publication 3319

Western AW, Blöschl G (1999) On the spatial scaling of soil moisture. J Hydrol 217:203–224

Wu QB, Zhang TJ (2008) Recent permafrost warming on the Qinghai-Tibetan Plateau. J Geophys Res. 113:D13108. doi: 10.1029/2007JD009539

Xue ZP, Yang XW, Duan XS (2002) Spatial variability of soil nutrient and reasonable sampling number. Trans CSAE 18(4):6–9

Zhang CM, Wang GX, Wang JD (2007) The spatial heterogeneity of soil moisture after raining in representative Gully catchment of the alpine meadow. Res soil Water Conserv 14(6):10–14