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Full Length Research Paper

Variability of soil water-physical properties in a small catchment of the Loess Plateau, China

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Data from the Donggou small catchment, located in a typical wind-water erosion crisscross zone on the Loess Plateau of China, illustrate the spatial variability of soil water-physical properties of different soil depths. The results revealed that except for soil bulk density in the small catchment, saturated hydraulic conductivity and soil moisture presented moderate variability, and varied with land uses. All of the variables had moderate spatial autocorrelation. These results were consistent with the land use pattern of the catchment. The mixed land uses patterns developed by the spatial arrangement of different land uses could trap the runoff and sediments, which ultimately formed the plaque mosaic patterns of soil physical and chemical properties in the catchment. The study built the spatial multiple regression-prediction models of soil moisture. There were different variables entered to the prediction models, which meant that at different measured times and depths, there were different environmental factors that controlled the spatial variability of soil moisture.

Key words: Geostatistical analysis, regression analysis, rainfall season, land use pattern.

INTRODUCTION

Soil variability is a very important characteristic in hydrological modeling. Usually, we could subdivide the modeled area into homogeneous areas known as 'hydrological response unit' based on the soil variability (She et al., 2010). Therefore, specific considerations should be given on the magnitude of the soil variability, the spatial distribution patterns, and the various influencing factors and processes.

Variability of soil properties has been studied extensively based on remotely sensed and field-measured data (Famiglietti et al., 1998; Hu et al., 2008; She and Shao, 2009). One way of analyzing soil variability and establishing the spatial distribution pattern of soil properties is by the geostatistical method. Quantitative estimates of the geostatistical correlation structure are useful for the interpolation of spatial patterns from point data, the estimation of average catchment soil properties, and the prediction of runoff generation by distributed hydrologic modeling (Feng et al., 2004; She et al., 2010).

However, relatively less emphasis has been given to the changing spatial structures of soil properties over time and with soil depth, which are important for most hydrological processes such as the occurrence of subsurface runoff (Famiglietti et al., 1998; She et al., 2010). Furthermore, there have been contradictory conclusions related to the main structural parameters, such as the nugget, sill and the range values, for different studied areas (Fitzjohn et al., 1998; Mohanty et al., 2000). The spatial variability of soil properties results from many factors acting over a range of scales. These include variations in land use, topography, and intrinsic variations

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in soil characteristics (Famiglietti et al., 1998; She et al., 2010). Therefore, in order to assess the spatio-temporal structure of soil properties comprehensively, further investigation is required in various locations, for various soil depths, and over a large range of scales.

Re-vegetation is the principal mean for soil erosion control and ecosystem recovery on the Loess Plateau of China. Land use and vegetation cover changes have made the determination of the hydrological response units more complex due to the presence of multiple land uses that have increased soil variability. For example, vegetative soil cover plays an important role in the establishment of the spatio-temporal distributions of soil moisture, mainly by influencing infiltration rates, runoff intensity, and evapotranspiration (She et al., 2010). The evaluation of these distributions is helpful when modeling runoff generation, soil evaporation, and plant transpiration, and also further controlling soil erosion and improving land management practices (Fitzjohn et al., 1998; She et al., 2010).

The purpose of this present study was, thus, to investigate the spatial variability of the soil water-physical properties of different soil layers in a small catchment of the Loess Plateau. Specific objectives were (i) to detect the spatial variability of soil bulk density and saturated hydraulic conductivity; (ii) to analyze the soil moisture data collected in the small catchment, in order to determine temporal changes in the magnitude and spatial pattern of the soil moisture variability; (iii) to develop multiple-linear regression models for the prediction of soil moisture based on environmental and soil factors.

MATERIALS AND METHODS

Study site description

The study site was the Donggou catchment located on the Loess Plateau in Shenmu County, Shaanxi Province, China (38°46′-38°51′N, 110°21′-110°23′E). This is a typical wind-water erosion crisscross zone (Figure 1). The predominant soil is a loessal mein soil (Los-Orthic Entisol, Chinese Taxonomic System (Gong, 1999); Calcaric Regosol, WRB/FAO (WRB, 2006), which has developed over accumulated wind-deposited loessial parent material and has a sand loam texture. The loessal soil profile, showing non-stratified and unconsolidated characteristics, has developed immaturely. There are just two horizons, e.g. A horizon (0 - 20 cm) and C horizon (below 20 cm) along the soil profile, with no distinct division between them. The C horizon is homogeneous and highly porous (She et al., 2010). The climate is semi arid with a mean annual rainfall of 364 mm (measured locally between 2003 - 2007), about 73% of which falls between June and September, and a mean annual pan evaporation of 785.4 mm. During re-vegetation, cropland, fallowland, grassland, forage land, shrubland and orchard land consist of mosaic structure in the Donggou catchment. Major plant species found in these land use units were recorded in (She et al. (2010).

Sampling methods

Five transects were used to establish a total of 49 sampling locations (Figure 1). Each transect passed through one of five down-slope strips under typical land use patterns on adjacent hill slopes (She and Shao, 2009). Another group of sampling sites (21sites) spread throughout the catchment (Figure 1), making a total of 70 locations for which soil water-physical properties were determined. The slope gradients of most sites changed around 15°, which was a clear indicator of intensive erosion. Site slope direction, as well as altitude, longitude, and latitude, determined by portable GPS, were recorded. The percentage distributions and the number of sampling points for the different land uses are shown in She et al. (2010). Ten sets of soil samples were collected from each site for gravimetric soil moisture analysis, and were taken to a depth of 120 cm in 10 cm increments using an auger during the growing season from April to October, 2007, at approximately 20-day intervals.

In October 2007, undisturbed soil cores were removed in steel cylinders, 50 mm length and 50 mm in diameter, from the surface (0 - 20 cm) and subsurface (20 – 40 cm) layers from each sample site. Soil saturated hydraulic conductivity (K_s) was determined by the constant hydraulic head method (Li and Shao, 2006), and soil bulk density (B_d) was determined after oven-drying the cores at 105 - 110°C for 24 h following K_s measurements. An additional five disturbed soil samples were collected close to the soil moisture measurement points with a 5 cm diameter hand auger, down to the depth of 40 cm. These five replicate samples were homogenized using hand mixing and a subsample of about 1 kg was taken to the laboratory. Plant roots and shoots, as well as stones were removed. The remaining soil was air-dried, and then passed through 1.0 mm sieves for soil mechanical composition determination using a Malvern MasterSizer2000 laser particle size analyzer.

Statistical methods

Statistical analyses were carried out in three steps:

1. Normality testes were performed using Microsoft Excel (version 2003) and SPSS (version 13.0) software;
2. Construction of experimental variograms and modeling of spatial variability were carried out using Gstat software. The semivariogram, $\gamma(h)$, was estimated by:

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

where $N(h)$ is the number of pairs of observations [$z(x_i)$; $z(x_{i+h})$] separated by a distance h; and

(3) Relationships between soil moisture and land use, soil texture, and terrain-based attributes were determined by stepwise regression using SPSS software. Data from 50 sampling sites were randomly selected to develop regression models, while the data from the remaining twenty sites were used to validate them. A total of 13 explanatory variables (land uses, topographic variables, and soil textures) were used after making the following changes: Land use (Shrubland, Orchard, Grassland, Forage land, Fallow land and Cropland) was transformed into six independent "dummy" variables (0 for absence and 1 for presence); aspect, taken as a compass bearing, was transformed into Cosine (aspect); elevation was defined as relative to the outlet elevation (1051 m).

RESULTS

Variability of soil bulk density and saturated hydraulic conductivity

Land use, as an integrator of several environmental

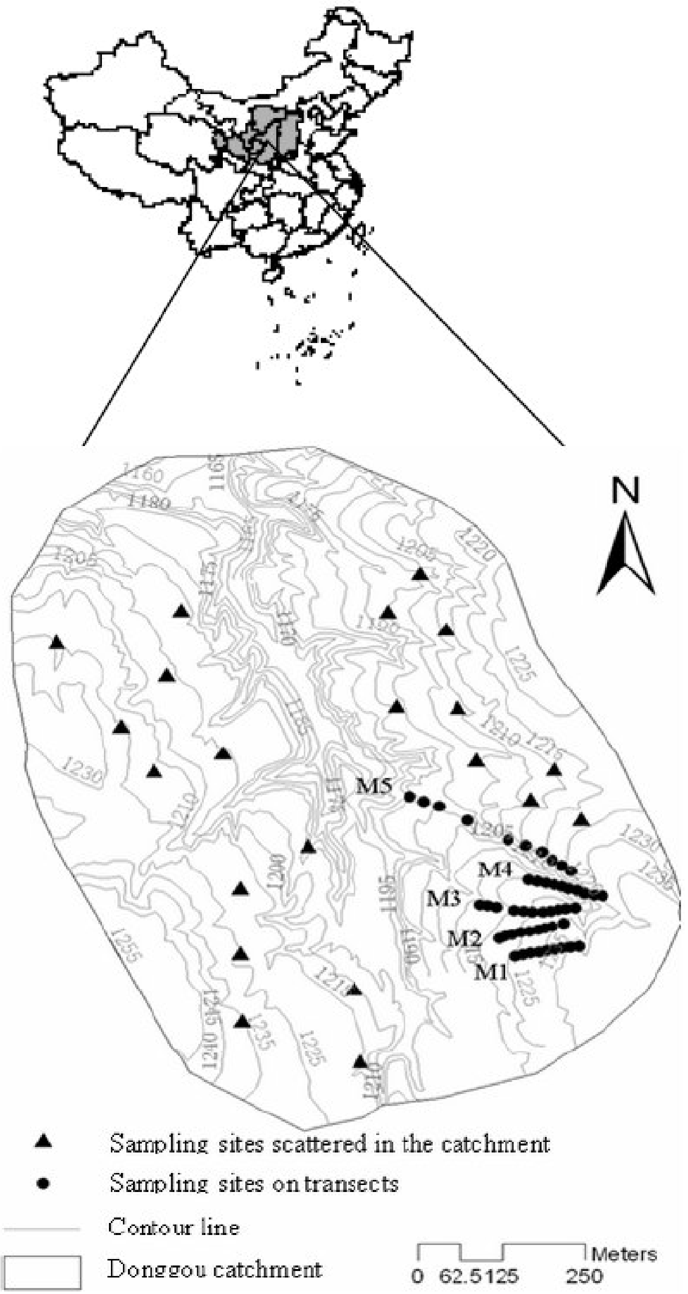

Figure 1. Location of the study area, distribution of sampling sites (M1, M2, M3, M4 and M5 refer to sampling transects).

attributes, influenced the changes of soil physical properties intensively. The ANOVA analyses followed the general linear model(GLM) procedure and showed that land use and soil depth affected soil bulk density (B_d) and saturated hydraulic conductivity (K_s) significantly ($p<0.05$) (Table 1). Among the six land uses, the grassland and forage land had the highest B_d for the 0 - 20 cm and 20 - 40 cm soil layer respectively. Some compaction in these land uses may be due to the drying of the soil caused by plant uptake of water (She et al., 2009). In contrast to B_d, the orchard had the highest mean K_s content for the two measured depths. The orchard was established on an abandoned form of cropland and re-vegetated with apricot about six years, which ameliorated the soil structure by the litter return to fields and plant root development (She and Shao, 2009). Basic statistical properties of B_d and K_s over the catchment are shown in Table 2. The one-sample Kolmogorov-Smirnov (K-S) test indicated that the spatial distribution of B_d and K_s remained normal for our catchment. No data

Table 1. Contents of soil bulk density (B_d) and saturated hydraulic conductivity (K_s) in relation to different land uses.

	Depth (cm)	Shrubland	Orchard	Grassland	Forage land	Fallow land	Cropland
B_d (g/cm^3)	0 - 20	1.36(±0.05)bc	1.23(±0.12)d	1.43(±0.09)a	1.36(±0.05)b	1.30(±0.09)cd	1.32(±0.05)bc
	20 - 40	1.37(±0.09)b	1.36(±0.06)b	1.39(±0.05)b	1.45(±0.07)a	1.39(±0.05)b	1.38(±0.06)b
K_s (mm/min)	0 - 20	1.95(±1.01)a	2.01(±0.53)a	1.22(±0.88)b	1.88(±0.50)a	1.95(±1.14)a	1.41(±0.41)ab
	20 - 40	1.62(±0.98)a	1.67(±0.62)a	0.76(±0.41)b	0.97(±0.43)b	0.96(±0.62)b	0.82(±0.34)b

Means with the same letter across rows are not significantly different (p=0.05) with respect to land uses, respectively at each depth.

Table 2. Descriptive statistics for soil bulk density (B_d) and saturated hydraulic conductivity (K_s).

	Depth (cm)	Mean	S.D(-)	C_v (%)	K-S value
B_d (g/cm^3)	0 - 20	1.36	0.01	6.6	0.51*
	20 - 40	1.40	0.01	4.9	0.54*
K_s (mm/min)	0 - 20	1.65	0.10	50.8	0.94*
	20 - 40	0.99	0.07	60.3	0.92*

K-S value: one-sample Kolmogorov-Smirnov value; * normal with 5% significance level.

transformation was performed before statistical analysis. Spatial variability of B_d and K_s as indicated by the coefficient of variation (C_v %) followed a trend that was the reverse of that of the mean. The C_v% of B_d was lower than 10%, indicating a weak spatial variability at the catchment scale. The K_s, which integrates several physical characteristics including B_d, porosity, soil particle composition and soil hardness, significantly decreased with soil depth ($p<0.05$). The variability of K_s was between 50.8 and 60.3% under different soil layers, and the data is thus defined as moderately variable.

The semi-varigograms for B_d and K_s of different soil depths are shown in Figure 2. Key parameters of these fitted semivariograms summarized in Table 3 were generated from the Gaussian models, which were the best fitting descriptors for this data set. The semi-variograms of B_d and K_s for same soil layer had similar tendencies, and there was a clear spatial structure for both variables in the different soil layers (Figure 2). The nugget for both B_d and K_s decreased with increasing soil depth, and all showed positive nugget effect, which comprises all unaccounted-for experimental errors and spatial variability at scales smaller than the sample spacing and random and inherent variability (Western et al., 1998). Apart from random factors, structural factors, such as the parent material and terrain, can codetermine the soil properties. The sill value included the nugget and structural variances; also showed decreasing tendencies with increasing soil depth, as the nuggets did. The ratio of nugget variance to sill variance is an important indicator of the spatial dependence of the variable being tested (Western et al., 1998). Usually, the variable is defined as having strong, moderate, or weak spatial dependence if the ratio is equal to or lower than 25%; between 25 and 75%; and when it is greater than 75%, respectively (Cambardella et al., 1994). In our study, the B_d and K_s all kept moderate spatial dependence. The ranges of spatial autocorrelations were 40 – 63 m and 25 – 43 m for B_d and K_s respectively, which was consistent with the land use pattern in our catchment.

Geostatistical analysis of soil moisture

The spatial distributions of soil moisture were determined to be normally distributed by a one-sample Kolmogorov-Smirnov (K-S) test ($P<0.05$) and, thus, no data transformation was required before the geostatistical analyses. The omnidirectional semivariograms for the 0 - 20 cm and 0 - 120 cm layer-averaged soil moisture for 10 different dates during the studied period are shown in Figure 3. Gaussian models were best-fitted to the experimental data for all of these dates, except for the data collected on July 31 and October 11 for the soil layer of 0 - 20 cm that was better fitted by Linear models. Key parameters of these fitted semivariograms are summarized in Figure 4. Trends were similar for all of the semivariograms (Figure 3), which indicated that the distribution of the soil moisture values in the field is consistent, since they exhibited clear sills and spatial structures.

The seasonal progression of the geostatistical structure is presented in Figure 4. All the measured sample semivariograms showed a nugget effect, ranging from 0.10 to 3.32%^{2} for the 0 - 20 cm soil depth and from 0.92 to 2.41%^{2} for the 0 - 120 cm soil depth. The nugget

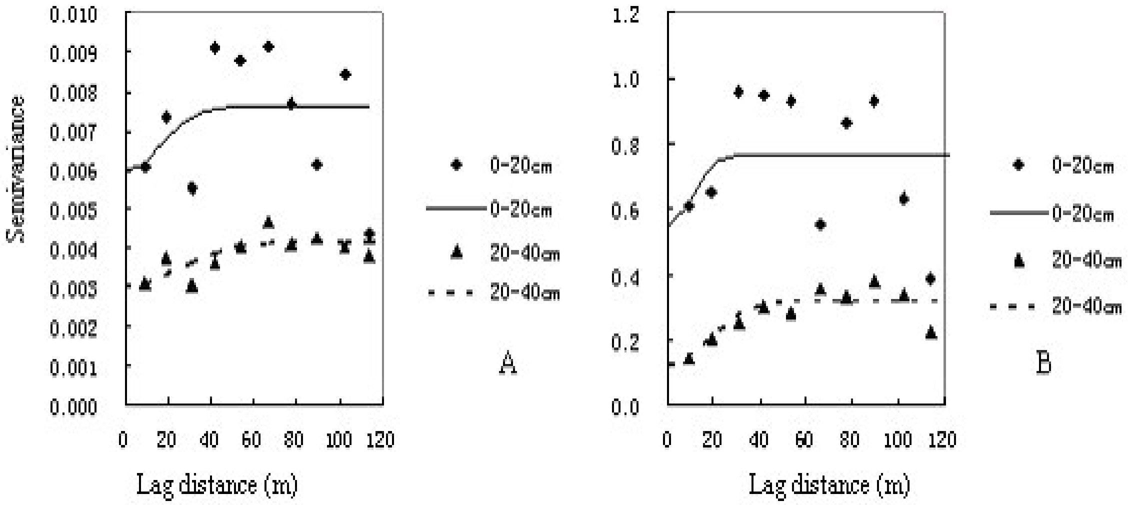

Figure 2. Experimental semi-variograms (symbols) and fitted models (lines) for (A) soil bulk density and (B) saturated hydraulic conductivity.

Table 3. Geostatistical analysis of soil bulk density (B_d) and saturated hydraulic conductivity (K_s).

	Depth (cm)	Class (model)	Nugget	Sill	Nugget/sill (%)	Range (m)
B_d (g/cm^3)	0 - 20	Gaussian	0.0060	0.0076	78.5	40
	20 - 40	Gaussian	0.0031	0.0042	73.0	63
K_s (mm/min)	0 - 20	Gaussian	0.5457	0.7651	71.3	25
	20 - 40	Gaussian	0.1200	0.3199	37.5	43

followed approximately the seasonal pattern of layer-averaged soil moisture, especially for the 0 - 20 cm soil depth. The sill value ranged from 2.72 to 10.60%^{2} for the 0 - 20 cm soil depth, and from 2.93 to 9.49%^{2} for the 0 - 120 cm soil depth. Trends in sill values would be related to the processes determining soil moisture patterns (Western et al., 1998). From April to August, the sill value was high due to the stronger influence of land use type and pattern over the relatively weaker effect of rainfall on soil moisture. These factors, possibly combined with their effect on evapotranspiration rates, resulted in greater soil moisture variability. However, with the increasing effect of greater amounts of rainfall occurring as the season progressed, which resulted in more uniformly wet soil conditions, the sill value exponentially decreased with increasing soil moisture (Figure 4). In our study, the nugget-to-sill ratio ranged from 0.04 to 0.74, and 0.13 to 0.38, for the 0 - 20 cm and 0 - 120 cm layer-averaged soil moisture semivariograms, respectively, indicating strong to moderate spatial dependence. The ranges of spatial dependence were 16 - 64 m and 33 - 54 m for 0 - 20 cm and 0 - 120 cm layer-averaged soil moisture, respectively (Figure 4). These spatial dependences may be affected by intrinsic variations in soil characteristics (e.g., texture, mineralogy and soil forming processes) and extrinsic variations (soil fertilization and cultivation practices).

Regression analysis

The previous analyses indicated that, in our catchment, the soil moisture spatial pattern was possibly influenced by vegetation cover type, soil texture and within-field variations of topographical attributes. To quantify and clarify these relationships, for both studied soil depths, we used stepwise multiple regression analysis for ten measurement dates. The intercept constants and the regression coefficients of the independent variables for the regression models of soil moisture at the two studied soil depths are presented in Table 4. All the regression models had high R^2 values, except for the 11-Oct measurement of the 0 - 20 cm soil moisture model, and most points in the plot of predicted values versus measured values (Figure 5) were close to the 1:1 line, indicating that they were usually accurate for soil moisture prediction in our study.

Significant explanatory variables that were found for the regression models differed with the date of measurement, which implied that the soil moisture variability under different moisture conditions were controlled by different

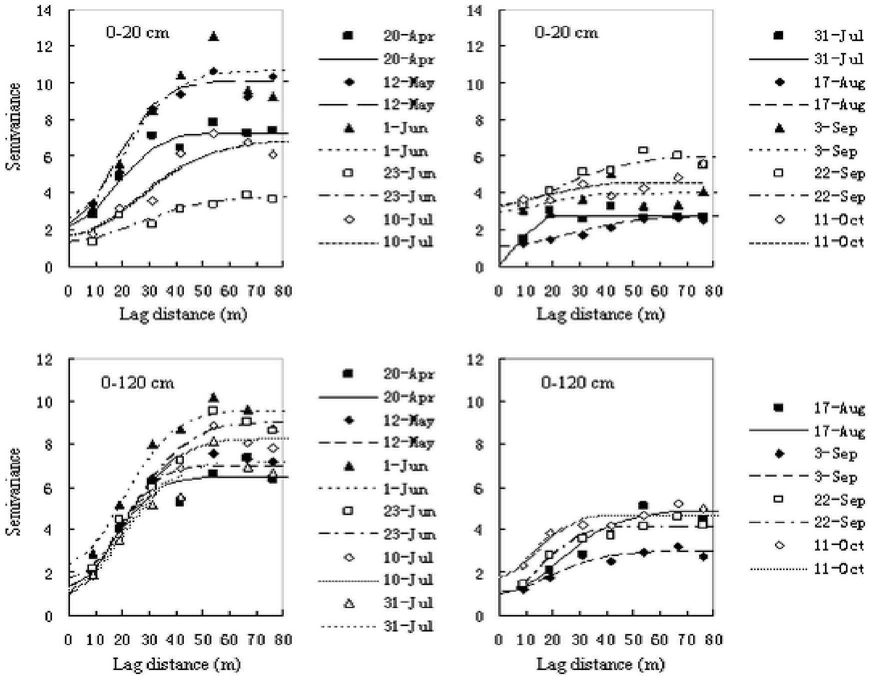

Figure 3. Experimental semi-variograms (symbols) and fitted models (lines) for mean soil moisture at the 0-20 cm and 0-120 cm soil depths.

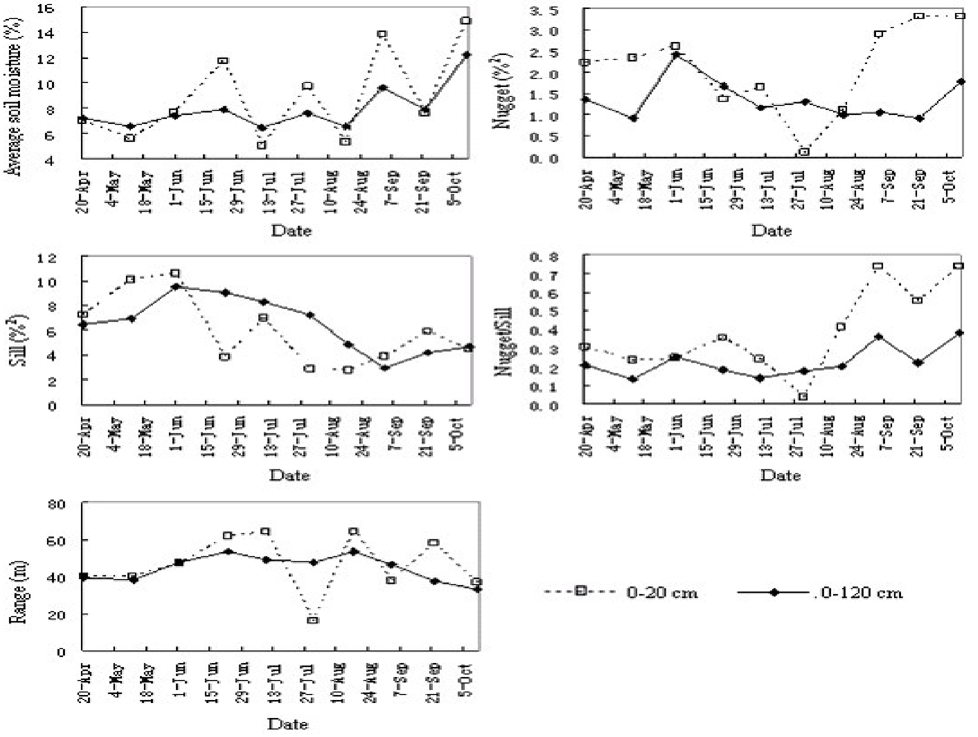

Figure 4. Seasonal changes in the geostatistical structure of the soil layer-averaged moisture content for the 0-20 cm and 0-120 cm soil layers.

factors. For example, the variables of Fallow and Crop land use types were in most of the models for the 0 – 20 cm soil layer and for all models in the 0 - 120 cm soil layer. The positive regression coefficients indicated that

Table 4. Regression analysis of soil moisture contents.

Depth	Date	Equations	R2
0-20 cm	20-Apr	M=1.17-1.48G+2.62F+2.88C+0.10S	0.80
	12-May	M=4.10-1.47H+4.65F+5.08C	0.96
	1-Jun	M=-0.09+5.30F+4.26C+0.12S+0.52A	0.89
	23-Jun	M=2.56+2.05F+1.87C+0.17S	0.59
	10-Jul	M=7.25+3.23F+4.02C-0.08D	0.64
	31-Jul	M=1.06-1.35R+0.18S	0.49
	17-Aug	M=2.41-1.46H-1.75G-1.47R+0.08S	0.65
	3-Sep	M=12.48-1.34R-0.17D+6.76B	0.61
	22-Sep	M=5.10-2.25H+3.11F+0.12S+1.04A-0.07E	0.61
	11-Oct	M=18.59-0.08D	0.10
0-120 cm	20-Apr	M=0.50-0.71G+2.64F+4.28C+0.12S	0.85
	12-May	M=1.63+1.55O+3.48F+5.56C+0.07S	0.87
	1-Jun	M=2.16+4.02F+5.51C+0.08S	0.91
	23-Jun	M=10.54+3.65F+6.02C-0.09D	0.86
	10-Jul	M=-0.98+4.14F+5.27C+0.12S	0.85
	31-Jul	M=0.80+2.88F+5.00C+0.11S	0.79
	17-Aug	M=2.76+2.65F+3.70C+0.11S-0.05E	0.71
	3-Sep	M=3.39+1.82F+2.23C+0.11S	0.62
	22-Sep	M=-2.96+3.43F+2.88C+0.0S+5.16B+0.37A-0.04E	0.78
	11-Oct	M=14.29+2.45F+3.37C-0.07D	0.58

M is soil moisture content, H is shrub land, O is the orchard land, G is grass land, R is forage land, F is fallow land, C is crop land, S is silt, D is sand, B is bulk density, A is Cos(aspect), E is relative elevation.

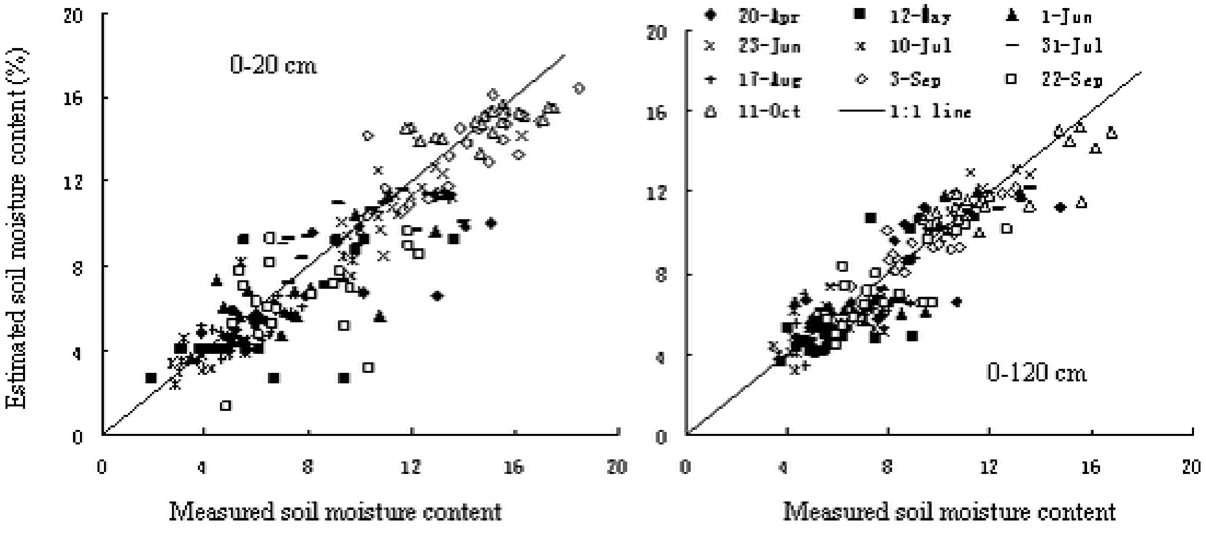

Figure 5. Average estimated and measured values of soil moisture for each sampling site of 0 – 20 cm soil layer and 0 – 120 cm soil layer.

the soils were generally wetter under these land uses compared with those under other land use types. In contrast, shrub, grass and forage land use types were in most of the models for the 0 - 20 cm soil depth but with negative coefficients suggesting comparatively drier soils. This indicates that land use results in differences in soil moisture, which are likely due to differing evapotranspiration rates from different vegetation types and in soil surface physical properties that are related to the vegetation type, such as infiltration capacity (Giertz et al., 2005; Zhang and Schilling, 2006; She et al., 2010). For most of the measured times, the soil moisture of both 0 -

20 cm and 0 - 120 cm soil layers were significantly and positively related to the soil's silt content and less frequently were negatively related to the sand content. Such reciprocal relations among environmental attributes had considerable influences on the stepwise regression. Clay content was not selected as a variable in any regression model because of the intrinsic correlation with the sand and silt contents.

Before August, most of the regression models selected only land use types and textural indices as entered variables, which together explained 48.6 - 89.0% of the 0 - 20 cm soil layer soil moisture variability and 78.7 - 86.5% of the 0 - 120 cm soil layer soil moisture variability (Table 4). The R^2 value gradually decreased with increasing soil moisture, which occurred from August to October, despite the addition of topographical attributes into the models. This indicated that the situation is more complex under wetter conditions and other factors may need to be considered.

DISCUSSION AND CONCLUSIONS

High variability in the soil physical and hydraulic properties may result in critical uncertainties for agricultural management. However, in terms of the ecological value of an area, soil variability may be beneficial, with distinct soil variations supporting a diversity of ecosystems and 'hydrological response unit'. This diversity of 'hydrological response unit' may create a self regulating system in which runoff producing areas are surrounded by buffer zones capable of reabsorbing the product of erosion (Fitzjohn et al., 1998). In this work, spatial variability of profile soil bulk density, saturated hydraulic conductivity and soil moisture measurements were conducted in 70 sampling points collected from the Donggou small catchment, located in a typical wind-water erosion crisscross zone on the Loess Plateau of China. The C_v% of soil bulk density was lower than 10%, indicating a weak spatial variability at the catchment scale. Saturated hydraulic conductivity and soil moisture presented moderate variability and spatial autocorrelation, and varied with land use. These results were consistent with the land use pattern of the catchment. The Loess Plateau is very seriously affected by soil erosion and water loss despite being one of the key regions for eco-environmental construction. Much effort on soil erosion control and ecosystem restoration has been made in recent years, especially by the project "Conversion of Farmland to Forest and Grassland Regeneration", which was initiated in 1999 and was carried out in 10 provinces including 363 counties located in mid- and western China. Extensive vegetation restoration was implemented and land use/cover has changed during the 11 years since this program started. Re-vegetation systems in the Donggou catchment were established in a patchwork or mosaic pattern of land uses (shrubland, orchard, grassland, forage land, fallow land and cropland), such as the five typical land use patterns (M1 - M5; Figure 1), which were detailed by She and Shao (2009). The mixed land uses patterns developed by the spatial arrangement of different land uses could trap the runoff and sediments, which ultimately formed the plaque mosaic patterns of soil physical and chemical properties in the catchment. The study built the spatial multiple regression-prediction models of soil moisture. The multiple regression models were developed based on the physical relationships between soil moisture and land use types, soil texture and the topographical attributes. There were different variables entered into regression models, which meant that at different measured times and depths, there were different environmental factors controlling the spatial variability of soil moisture. The spatial variability could be controlled by intrinsic variations in soil characteristics (texture, mineralogy and soil genesis processes) and extrinsic variations (soil fertilization and cultivation practices). Through our researches, we suggested that easing spatial variation of areal soil water-physical properties by land use arrangement could trap soil moisture and nutrients to stay in the ecosystem to improve the soil quality and control soil erosion effectively on the hilly area of the Plateau.

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