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ORIGINAL ARTICLE

Scale dependency of spatial variability of soil moisture in gravel-mulched field

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Abstract Knowledge of the scale dependency of the spatial variability of soil moisture is of paramount importance in the study of soil–atmosphere interactions and hydrological processes. We present a case study of the effects of sampling area and spacing on the spatial variability of soil moisture in a 32 × 32 m gravel-mulched field in an arid area of northwestern China. The coefficient of variation, correlation length and Moran's index, which are commonly used in spatial analysis, were applied to each scenario to characterise the degree of spatial variability of soil moisture. The spatial variability was weak at all sampling scales. All indices increased to various degrees with an increase in sampling area. The correlation length decreased with increasing sampling spacing, and neither the coefficient of variation nor Moran's index were significantly correlated with sampling spacing, indicating that sampling spacing had little effect on soil-moisture variability. The spatial distributions of soil moisture were irregular, with peaks and valleys at different sampling spacings but tending to gradually stabilise as sampling spacing increased. A sampling spacing of 8 m was reasonable, because it best-characterised the spatial distribution of soil moisture. This study also provides a theoretical reference for the establishment of optimal sampling schemes, which allow a considerable savings in both time and cost, and provides theoretical support for ecological agricultural production in gravel-mulched fields.

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Keywords Gravel-mulched field · Soil-moisture content · Spatial distribution · Scale dependency

Introduction

Soil moisture is a major factor restricting the growth of vegetation in the arid areas of northwestern China (He et al. 2003). Soil moisture affects many ecological processes, such as soil erosion, plant growth, and vegetation restoration (You et al. 2005; Ma et al. 2006; Wang et al. 2012a, b; Yao et al. 2012). The study of soil moisture is therefore important for environmental improvement and ecological reconstruction. Soil moisture varies spatially, so the analysis of its spatial distribution in a region is of great importance for its accurate monitoring. The effective management and use of water and soil resources will aid the monitoring and the establishment of reasonable sampling methods. The spatial variation of soil moisture has been studied at various sampling scales in different areas. Many studies have indicated that the degree of the complexity and heterogeneity of the spatial distribution of soil moisture varies with sampling scale (Blöschl and Sivapalan 1995; Western et al. 1998; Blöschl 1998; Wilson et al. 2003; Hu et al. 2005; Liu et al. 2010; Guo et al. 2013; Shi et al. 2014). Quantitative analyses of spatial variation of soil moisture and its scale dependency have therefore become important research topics in water-soil science.

Gravel mulching is a common and effective method to reduce evaporation and conserve water in the arid areas of northwestern China (Wang et al. 2010a, b, 2012a, b; Pang et al. 2012; Qiu et al. 2015). Gravel mulching can increase infiltration, reduce evaporation and erosion, and preserve heat (Mathur et al. 1983; Li et al. 2000; Tejedor et al. 2003; Li 2003; Chen et al. 2005; Wang et al. 2010a, b).

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Governments and farmers have recently paid increasing attention to gravel-mulch technology for resisting drought and water shortages in northwestern China. Identifying the factors influencing soil moisture and its spatial variability in gravel-mulched fields is thus of great importance for understanding the spatial distribution of soil moisture. Traditional field methods and laboratory procedures for determining soil-moisture content, however, are time-consuming, labour intensive, and expensive, and its determination on large scales at fine spatial resolutions is impractical. We thus conducted a field experiment with different sampling areas and spacings. We also measured three indices commonly used for spatial analysis, namely the coefficient of variation (CV), the correlation length, and Moran's index, to characterise the degree of spatial variability of soil moisture at the different scales. The results of the study can serve as a reference for constructing a reasonable sampling scheme that could save much time, labour, and cost and for providing a theoretical basis and support for ecological agricultural production in gravel-mulched fields.

Materials and methods

Study area

Jingtai County is located in the middle of the western portion of China's Gansu province; on the east side of the Hexi corridor; at the junction of provinces (regions) of Gansu, Ningxia, and Inner Mongolia; and at the transition zone of the loess plateau and Tengger desert (Fig. 1). According to the Chinese Soil Taxonomy System (Research Group of Chinese Soil Taxonomy System, 1995), the soil types in Jingtai County are mainly diluvium brown desert soil and sierozem. It is located in the transition zone between the monsoon and non-monsoon regions. Jingtai County has a continental climate, with an annual average precipitation of 185 mm, with nearly 61.4% falling between July and September. The average annual evaporation is 3038 mm, which is 16 times of the annual average precipitation. Solar thermal resources are rich with the annual sunshine time is about 2725 h and a sunshine percentage of 62%. The average annual solar radiation is approximately 147.8 kcal/cm^2. The average frost-free period is 141 days. The average annual temperature is 8.2 °C. The extreme maximum and extreme minimum temperatures are, respectively, 36.6 and −27.3 °C. The experiment area is located near the experimental base of Lanzhou University of Technology in Jingtai County.

Mulching fields using gravel is a farming technique indigenous to the semiarid loessial regions of northwestern China for conserving the sporadic and limited rainfall to increase crop production and may date from the Qing Dynasty, about 300 years ago (Wang and Sun 1986; Li 2000; Lü et al. 2013). Uniformly mixed gravel and sand were the mulching materials (Table 1), which were manually spread uniformly across the study area, at a cover density of 100% and a mulching depth of 10 cm, depending on local moisture and salinity.

Research method

A new gravel-mulched field (NGM) of less than 10 planting years covering an area of 32 × 32 m was used for the study. Rectangular sampling was performed for 1 × 1 m quadrats, with 4 m between the centres of the quadrats, for a total of 64 sampling points. The surface

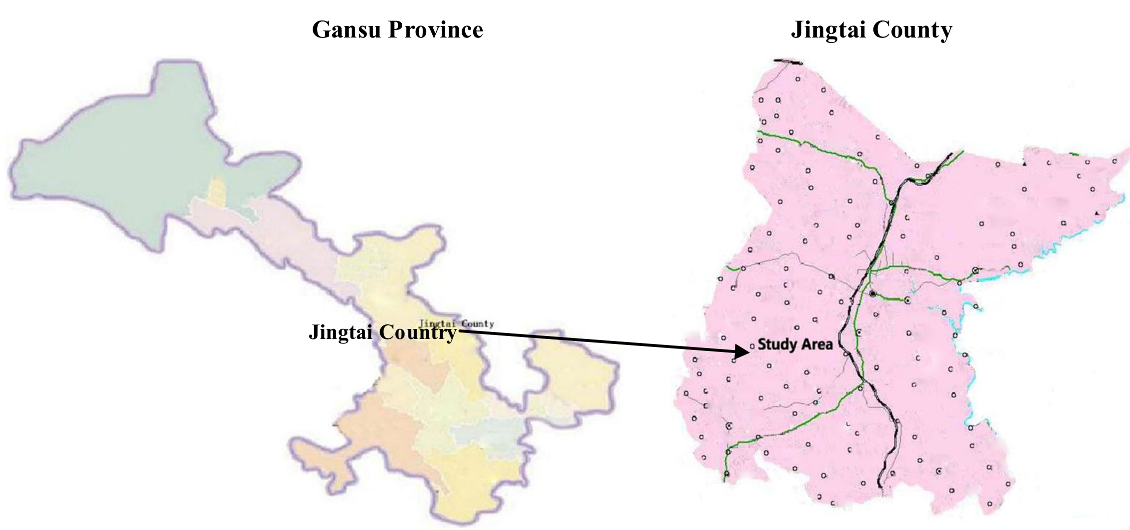


Fig. 1 Maps of Gansu province and Jingtai County

Table 1 Particle size distribution of gravel-mulched materials

<0.075 mm	0.075–0.5 mm	0.5–2 mm	2–5 mm	5–20 mm	>20 mm
0.8	9.5	22.5	26.2	29.4	11.6

sand and gravel were carefully removed, and soil samples weighing 60–70 g were collected from the 0–20 cm layer on 11 May 2013 using a soil drill. The soil-moisture content was determined by weighing the samples before and after drying. The sampling points were evenly distributed in the study area, and their distributions are shown in Fig. 2. According to the planting years, the gravel-mulched fields are divided into new gravel-mulched field (NGM) of less than 10 planting years, middle gravel-mulched field (MGM) of 25–30 years and old gravel-mulched field (OGM) of 45–60 years (Li 2003). Soil samples were collected on May 11, 2013.

M1: Sampling areas

All data were analysed using moving sampling-area windows of 32 × 32 m, 28 × 28, 24 × 24, 20 × 20, and 16 × 16 m from the northwest to the southeast corner of the study area. The CV, correlation length, and Moran's autocorrelation index were calculated for each moving window. The averages for the same size of moving window were used for the variations for the sampling scales.

M2: Sampling spacings

The spatial variability for all data was first analysed. The sampling density was varied by extracting sampling points from 1 to 2 points in the east–west and north–south directions, respectively, representing an increase in sampling spacing. All original data and the variation indices for each sample were calculated, and the averages for the same spacing were used for the variations for the sampling scales. The data in a geostatistical analysis will not be

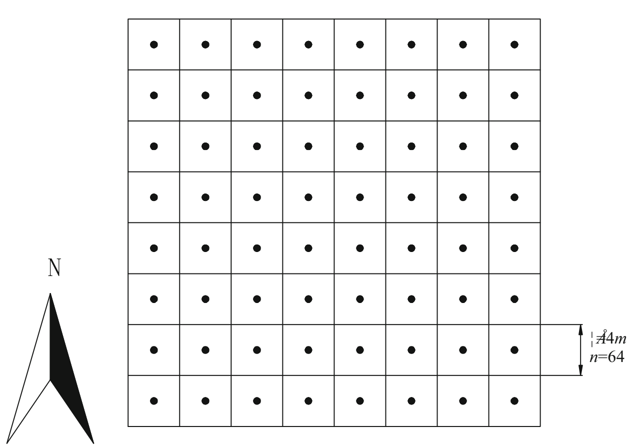


Fig. 2 Sampling point distribution map of soil moisture content

reliable if the spacing is too large, so we analysed only three sampling spacings (4, 8, and 12 m) for determining their effects on the correlation length and Moran's index.

Data analysis

D1: CV

CVs are commonly used in classical statistical analyses to determine the degree of variation. CVs ≤ 10% indicate weak variation, 10% < CVs < 100% indicate moderate variation, and CVs ≥ 100% indicate strong variation. The CV is calculated as:

$$\mathrm{CV} = \frac{S}{\bar{x}} \quad (1)$$

where S is the standard deviation, and $\bar{x}$ is the average.

D2: Correlation length

A semivariogram based on the regionalised variable theory and intrinsic hypothesis (Pham 2016) is described by:

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

where h is the spatial sampling interval, $\gamma(h)$ is the semivariance for interval h, $N(h)$ is the total number of sample pairs for the separation interval h, and $Z(x_i + h)$ and $Z(x_i)$ are measured samples at points $x_i + h$ and x_i, respectively.

GS + 9.0 (version 9.0, Gamma Design Software, Michigan, USA) was used to analyse the semivariograms and obtain the values of the nugget (C_0), sill ($C_0 + C$), and correlation length (a). Kriging was also used to decrease the adverse effects of the semivariogram-model selection in the interpolation survey.

D3: Moran's index

Moran's index (I) is similar to the correlation coefficient and ranges from −1 to 1. $I = 0$ indicates no correlation, $I > 0$ indicates a positive correlation, and $I < 0$ indicates a negative correlation. I is calculated as (Monica et al. 2010):

$$I = \frac{N \sum_{i=1}^{N} \sum_{j=1}^{N} \omega_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\left(\sum_{i=1}^{N} \sum_{j=1}^{N} \omega_{ij}\right) \sum_{i=1}^{N} (x_i - \bar{x})} (i \neq j) \quad (3)$$

where x_i and x_j are the observed values of spatial element x in spatial units i and j, respectively; $\bar{x}$ is the average x; ω_{ij} is the adjacent weight (binary weight is now commonly used; ω_{ij} is defined as 1 if adjacent sampling sites i and j are correlated, otherwise as 0); and N is the total number of spatial units. Changes in the spatial correlation can be determined for different scales by combining I with the lag-distance scale. Changes in spatial correlation along the sampling scale with changes in scale can then be acquired in a relation diagram of autocorrelation coefficient and scale.

Normality test

A *Q*–*Q* plot in SPSS (version 20, Predictive Analytics Software, IBM, USA) was used to test the normality of the original data for surface soil-moisture content (Fig. 3). The sample points were evenly distributed around the line $y = x$, indicating that the sample data for soil-moisture content in the 0–20 cm layer was normally distributed, so the original data did not require transformation for statistical analysis.

Results and analysis

The effect of sampling area on spatial variability

T1: The effect on CV

The spatial variability of soil moisture was investigated using spatial CVs as statistical descriptors, because they compare the variabilities of different sampling areas. The CV of soil moisture was low for the sampling areas between 16 × 16 and 32 × 32 m and ranged from 1.80 to 2.03% (Fig. 4), indicating weak variation. The CVs gradually increased with sampling area, and the rate of increase was higher for smaller than larger sampling areas. These results may have been due to the continuous introduction of new variables as the area increased. Some variables that can affect the spatial distribution of soil moisture may have a limited effect at a smaller scale but a large effect at a larger scale. The influences of the variables on the distribution of soil moisture thus became more apparent as the sampling area increased. The relationship between CV and sampling area was fitted by:

$$\begin{aligned} y &= -0.55\exp(-x/327.05) + 2.05 \\ R^2 &= 0.99932 \end{aligned} \quad (4)$$

where y is the CV, and x is the sampling area. The fitted results indicated that the CV increased with sampling area and then stabilised near 2.05%, because the variables affecting the variation cannot increase indefinitely within a research area. The CV first increased slowly and then remained quite constant, with an average of 2.05%, when the sampling area reached a certain size.

The true CV in the study area was very close to 2.05% (Fig. 4). Equation (4) was applied to determine the CVs and relative errors of the various sampling areas for identifying a reasonable sampling area that can represent the true variation with an allowable error. The relative errors for all measurements were smaller for sampling areas larger than 256 m^2 (Table 2). The CVs for the sampling areas of 784, 900, and 1024 m^2 could be used to indicate the true variation when the relative errors were 3, 2, and 1%, respectively. The area of the gravel-mulched field used in this study could thus indicate the true variation of surface soil moisture with an acceptable relative error of 1%.

T2: The effect on correlation length

The theoretical models of the semivariogram of soil moisture were fitted by a spherical model (Table 3). The

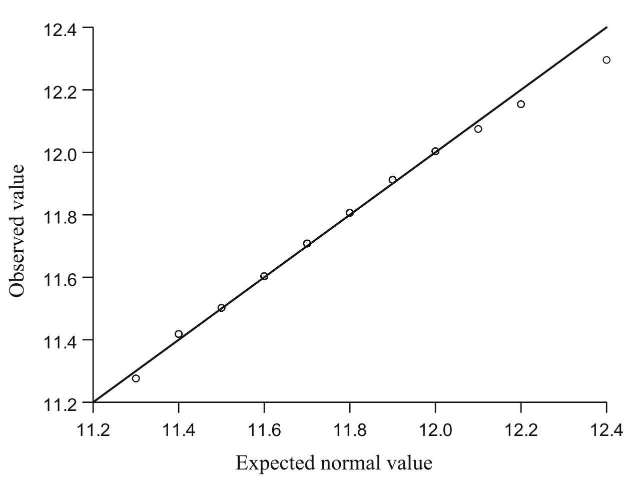


Fig. 3 *Q*–*Q* normal graph of surface soil moisture

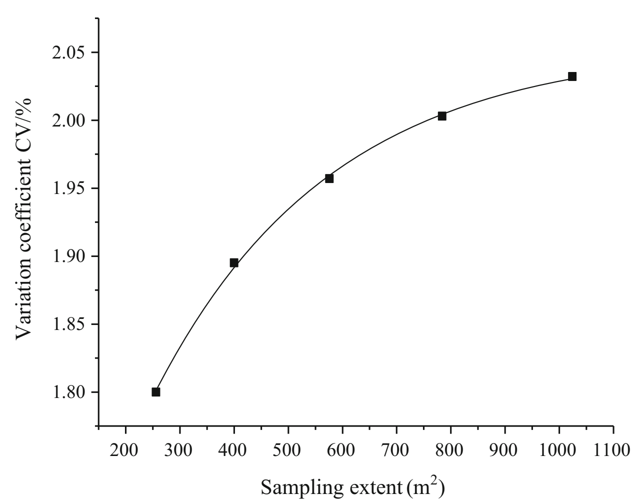


Fig. 4 Effect of sampling extent on variation coefficient

Table 2 Fitting values and its relative error of variation coefficient of soil moisture of different sampling extents

Sampling extent (m^2)	256	400	576	784	1024
Number of sampling dates	16	25	36	49	64
Variation coefficient (%)	1.80	1.89	1.96	2.00	2.03
Relative error (%)	12.19	7.80	4.39	2.44	0.98

nugget increased with sampling area, because the variation and the measurement error of the short range increased with sampling area. The sill was not correlated with sampling area, but *a* of the spatial variability of soil moisture tended to increase significantly, perhaps due to the nesting structure of the distributional pattern of soil moisture (Hu et al. 2005). The correlation of the variation with small areas was masked by the correlation of the variation with large areas.

T3: The effect on I

I was little affected by sampling area when lag distance was small but tended to increase with the lag distance, especially for the 16 × 16 and 20 × 20 m sampling areas (Fig. 5). *I* and *a* were positively correlated with sampling area. The positive correlation with surface soil moisture decreased as sampling area increased at lag distances between 23 and 28 m.

The effect of sampling spacing on spatial variability

T1: The effect on CV

The CVs of soil moisture irregularly ranged from 1.95 to 2.04%, with an average of 2.0%, for sampling spacings between 4 and 16 m (Table 4). The relative errors were 0.98, 0.49, 4.39, and 4.88%, respectively. The effect of sampling spacing on the CV was thus weak and could be ignored. This result agreed well with the results of previous studies; increasing sampling spacing did not decrease the number of variables that could affect the variation of soil moisture in a given sampling area. An appropriate increase in sampling spacing within a defined study area can thus also represent the true CV of soil moisture. A reliable indication of soil-moisture variation could also be obtained with fewer sampling points at a spacing of 8 m. A spacing of 8 m was the optimal sampling spacing in our study.

T2: The effect on correlation length

The semivariogram diagrams were similar for the 4, 8, and 12 m sampling spacings (Fig. 6). The nugget, which is the sum of the measurement error and the variation of the minimum sampling spacing, generally decreased as sampling spacing increased (Table 5). The increasing sampling spacing had little effect on the sill, but *a* decreased significantly as spacing increased.

T3: The effect on I

I varied irregularly as sampling spacing increased, indicating that the spacing had little effect on I (Fig. 7). The correlations of the environmental variables affecting the distribution of soil moisture were indicated by the correlations with soil moisture. Sampling spacing had little influence on the main factors affecting the variation of surface soil moisture in the gravel-mulched field in a limited study area.

T4: Spatial distribution of soil moisture

Kriging interpolation indicated that soil moisture was irregularly distributed, with peaks and valleys at different sampling spacings, which may have been due to the topography of the study field (Fig. 8). The distributional patterns tended to be "flat" as sampling spacing increased, with fewer peaks and a more uniform distribution. The patterns tended to flatten at a spacing of 8 m. The maps of spatial distribution were similar for spacings of 4 and 8 m, indicating that the map for the spacing of 8 m could better characterise the spatial distribution of soil moisture. The spatial distributions for the 12 and 16 m sampling spacings were, however, so flat that they could no longer well

Table 3 Effect of sampling extents on correlation length

Sampling extents (m^2)	16 m × 16 m	20 m × 20 m	24 m × 24 m	28 m × 28 m	32 m × 32 m
Theoretical model	S	S	S	S	S
Nugget C_0	0.0001	0.0005	0.0009	0.0014	0.0023
Sill C_1	0.062	0.0648	0.0641	0.062	0.0632
Correlation length *a* (m)	13.60	15.24	16.27	17.14	18.08
R^2	0.512	0.629	0.770	0.776	0.782

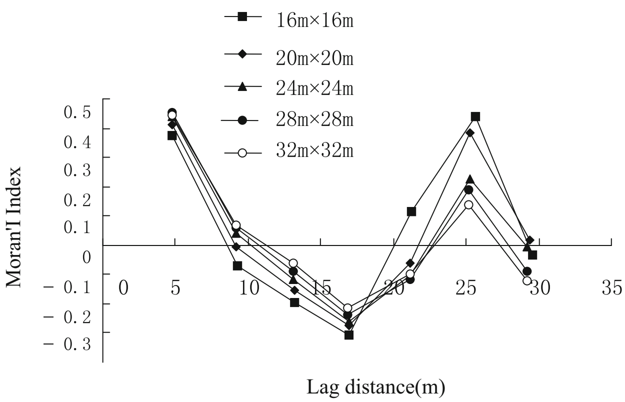


Fig. 5 Effect of sampling extent on Moran'I index

Table 5 Effect of sampling spacings on correlation length

Sampling extents (m)	4	8	12
Theoretical model	S	S	S
Nugget C_0	0.0023	0.0019	0.0001
Sill C_1	0.0632	0.0545	0.0601
Correlation length a (m)	18.08	13.93	11.47
R^2	0.782	0.59	0.598

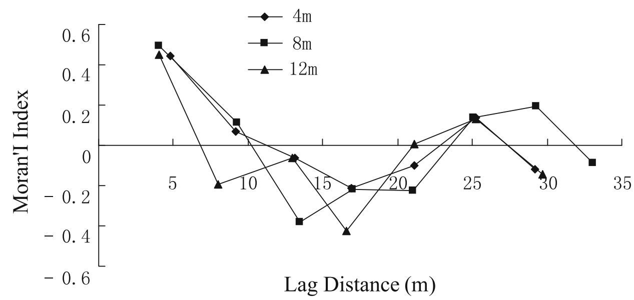


Fig. 7 The effect of spamling spacing on Moran'I index

Table 4 Effect of sampling spacings on variation coefficient

Sampling spacing (m)	4	8	12	16
Number of sampling dates	64	32	24	16
Variation coefficient (%)	2.03	2.04	1.96	1.95
Relative error (%)	0.98	0.49	4.39	4.88

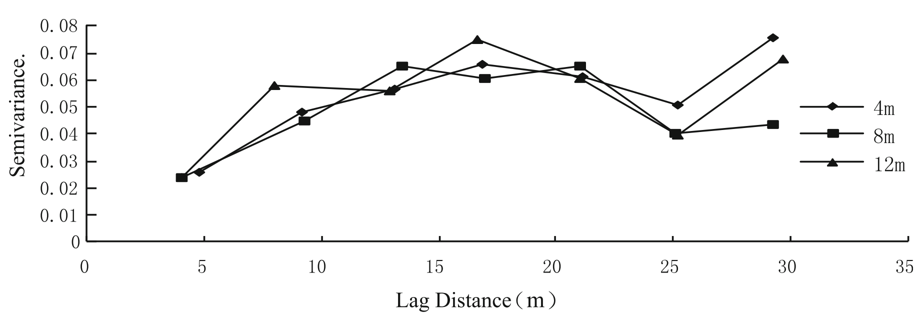
characterise the spatial variability of soil-moisture content. The most reasonable sampling spacing was thus 8 m, which could greatly reduce the workload of sampling.

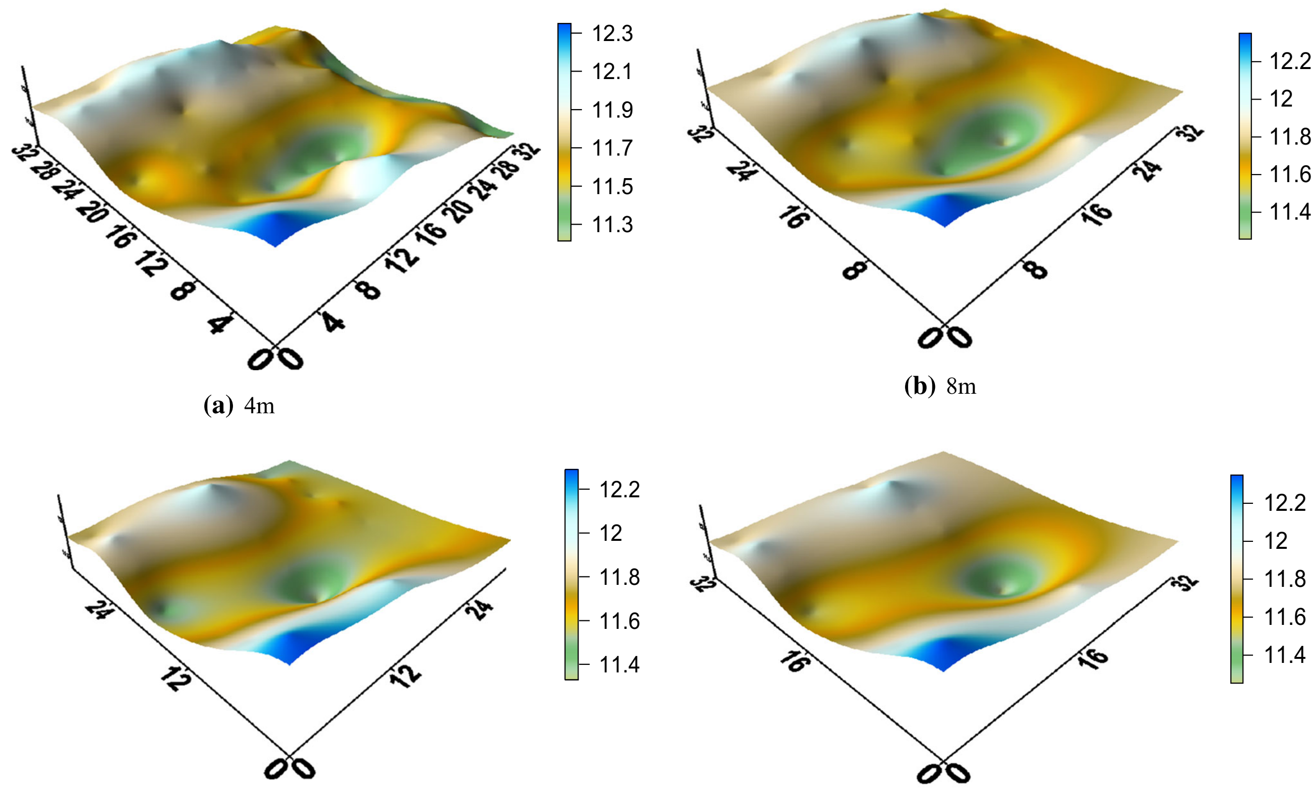
Discussion

Western and Blöschl (1999) reported that a very small spacing, a very large area, and a very small sampling volume were optimal, in which the apparent variance and the apparent a were similar to their true values. Sufficient sample data can well characterise the true variation of soil moisture in a study area, but sampling area and density cannot increase indefinitely in practical applications, because they are affected by human activity and are limited by material resources. We therefore analysed the spatial variation of soil moisture in various scenarios by varying sampling areas and spacings based on a field experiment to determine a reasonable sampling scale.

The variability of soil moisture typically increased with sampling area, in good accordance with previous studies (Hu et al. 2005; Guo et al. 2013; Li and Rodell 2013). This result may have been due to the increase in heterogeneity of the soil parental material and the climate as the area increased. Zhang et al. (2015) reported that an increasing area tended to increase the temporal stability of surface-soil moisture of the overall spatial pattern but to decrease the temporal stability at individual locations, indicating that the variability was also due to the limited study area. Sampling at different spatial areas is important for understanding how soil moisture varies with sampling area. Scaling (up or down) is needed between the measurement and modelling scales. Large areas can improve the soil classification system and improve the quality of soil survey and mapping, medium and small areas are foundation for

Fig. 6 Semi-variogram diagram of different sampling spacings





(a) 4m **(b)** 8m **(c)** 4m **(d)** 8m

Fig. 8 Spatial distribution of soil moisture under different sampling intervals

precise irrigation by reasonable layout of crops, improve the field management, increase efficiency of soil.

Larger sampling spacings had little influence on the CV and *I*, similar to the results reported by Hu et al. (2005), Guo et al. (2013), and Zhang et al. (2015). *a* decreased as the spacing increased, consistent with the results reported by Hu et al. (2005) but not with those reported by Western et al. (1999) and Guo et al. (2013), who observed a general increasing trend between *a* and sampling spacing. The similarities and differences of these results may be attributed to the different climates, soil textures, and optimal fitting models in these studies. A sampling spacing of 8 m was optimal in our study and could both accurately evaluate the spatial variability of soil moisture and allow a considerable savings in labour and resources.

Determining the spatial variability of soil moisture at different sampling scales is therefore crucial. The results can provide a clear indication of an optimal sampling scheme for determining soil-moisture content in the gravel-mulched fields in the arid areas of northwestern China and in similar regions of the world and for reaching general conclusions for hydrological and other applications. Our data set was restricted to the surface soil, so the generalisation and application of the results are limited. Further study is needed to assess the distribution and variation of moisture in deeper soil profiles. The reasonable sampling spacing of 8 m we obtained will help to greatly reduce the workload of sampling, because increasing sampling spacing from 4 to 8 m decreases the number of sampling points for each soil layer from 64 to 16. Reasonable sampling areas can also be determined for specific research purposes and accuracy requirements.

Conclusions

Measurements of surface soil-moisture content in a gravel-mulched field in an arid region of northwestern China were used to investigate the spatial variability of soil moisture. Based on the statistical analyses of spatial variability, the following conclusions can be drawn:

1. The CV of soil-moisture content first increased and then remained quite constant, approaching 2.05%, and ranged between 1.80 and 2.03% with increasing sampling area. *a* and *I* increased with sampling area to different degrees.

2. Increasing sampling spacing had little influence on the CV and *I*, but *a* decreased as the spacing increased. Reasonably increasing the sampling spacing can therefore provide reliable estimates of spatial variation in soil moisture, which could save a lot of time, labour, and resources.
3. The spatial distributions of soil moisture were irregular, with peaks and valleys at different sampling spacings, but tended to gradually stabilise as sampling spacing increased. A spacing of 8 m was the most reasonable spacing, because it best-characterised the spatial distribution of soil moisture.

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