

Field-scale spatial distribution characteristics of soil nutrients in a newly reclaimed sandy cropland in the Hexi Corridor of Northwest China

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Received: 28 June 2012 / Accepted: 25 February 2013
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Abstract Conversion of native desert to irrigation cropland often results in the changes of soil processes and properties. The objective of this study was to investigate the changes of soil nutrients and their spatial distribution characteristics of a newly reclaimed cropland at the initial stage of the conversion using statistical and geo-statistical methods. Soil samples were collected at regular intervals from a cropland of 0.24 ha, and their nutrient indicators determined. The mean contents of soil organic carbon (SOC), total nitrogen (TN), available nitrogen (AN), available phosphorus (AP), available potassium (AK), and pH value in this newly reclaimed sandy cropland were averaged at 4.45 g kg^{-1} , 0.49 g kg^{-1} , 19.99 mg kg^{-1} , 21.08 mg kg^{-1} , $121.60 \text{ mg kg}^{-1}$, and 8.98, respectively. The ranges were less than 20 m for the semivariogram of SOC, TN, and pH, but exceeded 20 m for AN, AP, and AK. The ratios of nugget-to-sill were less than 10 % for the

semivariogram of SOC, TN, and pH, but exceeded 25 % for AN, AP, and AK. There were similar distribution characteristics for SOC, AN, and pH, with different sizes of patches present; such distribution patterns were related to the regular planting of orchard and the interval application of manures. There were big-sized patches in the distributions of AN, AP, and AK. Topography was the main factor causing the spatial heterogeneity of available N, P, K, and the 4 years (2001–2004) of cropping affected the distribution patterns of these nutrient variables. The conversion of native desert to irrigation cropland caused significant increases in soil nutrients, but their spatial distributions had large variations. This study identified the main factors affecting the spatial distribution of each soil nutrient variable, including the environment factors and anthropogenic management practices. There is a great potential to improve the productivity and soil fertility for the newly reclaimed sandy cropland, only if the appropriate and sustainable soil management practices are adopted.

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Keywords Spatial variability · Soil nutrient · Newly reclaimed · Sandy cropland · Geostatistics · Soil organic carbon

Abbreviations

SOC	Soil organic carbon
TN	Total nitrogen
AN	Available nitrogen
AP	Available phosphorus
AK	Available potassium
SD	Standard deviation
CV	Coefficient of variation
BD	Bulk density
EC	Electrical conductivity
CEC	Cation exchange capacity

Introduction

Conversion of natural ecosystems to cropland may increase land availability for agriculture, but such an action often results in significant modifications to soil processes and properties, and therefore affecting soil functionality (Beheshti et al. 2012; Dawson and Smith 2007; Walker and Desanker 2004). Changes in land use influences soil fertility and soil quality by altering abiotic (moisture, temperature) and biotic factors (vegetation, biodiversity), and also it may reduce soil organic matter stabilization (Birch-Thomsen et al. 2007; Grünzweig et al. 2003; Raiesi 2007). Soil nutrients are the major determinants of soil quality and are the essential reflectors for the plant growth and development. In agricultural ecosystems, soil nutrients play a crucial role in increasing crop yield and achieving sustainability of agricultural ecosystems. The status of soil nutrients are closely related to agricultural land use types and the associated land management practices (Agbede 2010; Chen et al. 2011; Kong et al. 2006; Wang et al. 2010). For example, the adoption of long-term, improved agricultural management practices increased soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) significantly in low soil nutrient areas (Dawson et al. 2008; Sainju et al. 2008; Zhang and He 2004). However, due to limited field observations and soil spatial heterogeneity, the change and distribution of soil nutrients in the arid regions of northwest China remain largely uncertain. Extensive field soil surveys are expected to provide improved assessments of the effect of land use changes on soil nutrients.

Soil nutrients exhibit a complex variability in both spatial and temporal scale (Cao et al. 2011; Stutter et al. 2004; Zhang et al. 2007; Zhao et al. 2008), and such variability is observed at multiple scales, ranging from point measurements to global scales (Garten et al. 2007). A better understanding of the spatial variability of soil nutrients at a field scale is important for improving cropland management practices and providing a valuable base upon which subsequent and future measurements can be evaluated (Huang et al. 2007a). It also assisted land managers and researchers to improve the understanding of the soil evolution under the processes of land use and ecosystems conversion.

Over the past several decades, increases in human population and food demands have caused intensive land transition from desert to arable soil; this is particularly the case in the arid regions of northwest China (Huang et al. 2007b; Li et al. 2009; Luo et al. 2003). Some works have been conducted to determine the effects of this land conversion process and associated land management on the changes of soil properties in temporal scale (Li et al. 2009; Su et al. 2010). Topography and vegetation conditions are multiplex in sandy desert ecosystems, and often there exist

larger soil variations in the newly reclaimed cropland. However, spatial variations of soil properties caused by this conversion have received a little attention by far. There is a lack of knowledge and accurate assessments of soil fertility established on the basis of the spatial distribution characteristics of soil nutrients. Therefore, the objectives of this study were to (1) investigate the field-scale spatial distribution characteristics of soil nutrients in the newly reclaimed sandy cropland area of northwest China and (2) identify the main factors influencing the spatial variability of soil nutrients and to provide theoretical guidelines for sustainable development and rational management of newly reclaimed sandy cropland.

Study area

The study was conducted on the marginal oasis of Linze county in the middle of Hexi Corridor region, Gansu Province, Northwest China (39°24'N, 100°21'E, altitude, 1,380–1,385 m) (Fig. 1). It was alongside the diluvial-alluvial plains of Qilian Mountain and bordered with Badajilin Desert in northeast. The area has a typical desert climate according to Köppen climatic classification (BWk) and is characterized by cold winters and dry hot summers with a mean annual precipitation of 117 mm. Mean annual evaporation measured by evaporation pan is 2,390 mm. Average annual temperature is 7.6 °C. Mean annual wind velocity is 3.2 m s⁻¹. Gales with wind velocity above 17 m s⁻¹ occur 15 or more days per year (Su et al. 2010). The zonal soil is Calci-Orthic Aridosols derived from diluvial-alluvial materials according to Chinese Soil Taxonomy, which is equivalent to the Calciorthis in the USDA soil taxonomy classification (Zhang 2001). Due to long-term encroachment of drift sand from Badanjin Desert and deposition of aeolian sand, Psamments were developed in some areas and sandy lands formed. Since 1960s, sandy lands have been gradually developed for agricultural production to mitigate the pressure of population growth (Su 2007). The land use distribution of Linze county in 2000 was an example of the desert–cropland conversion occurring in the study area (Fig. 2), according to the data set provided by “Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China” (<http://westdcwestgis.ac.cn>).

Materials and methods

Soil sampling

The experiment site was established in the field with an area of 0.24 ha, which is a 40 m by 60 m regular rectangle

Fig. 1 Map of the study area located at Linze county, Gansu Province of China

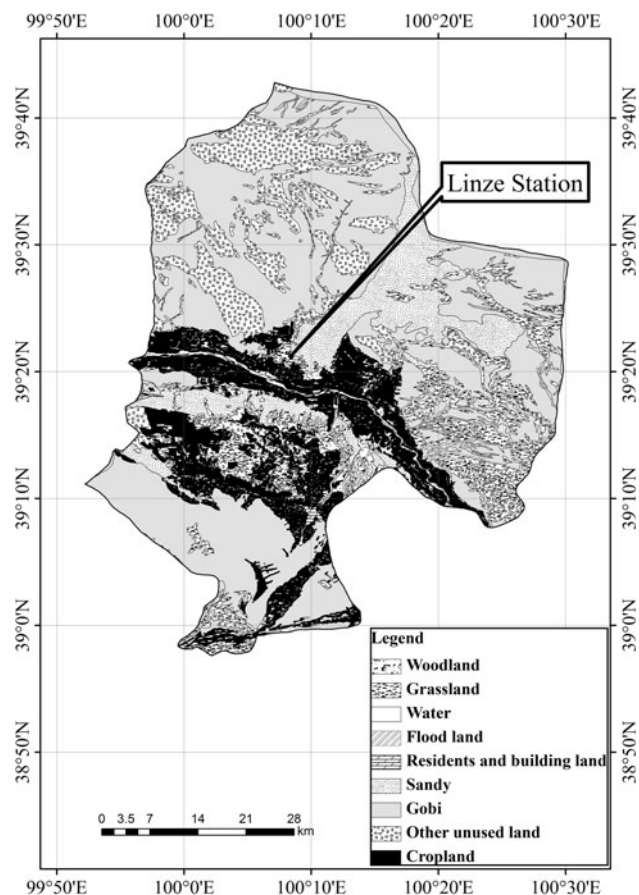
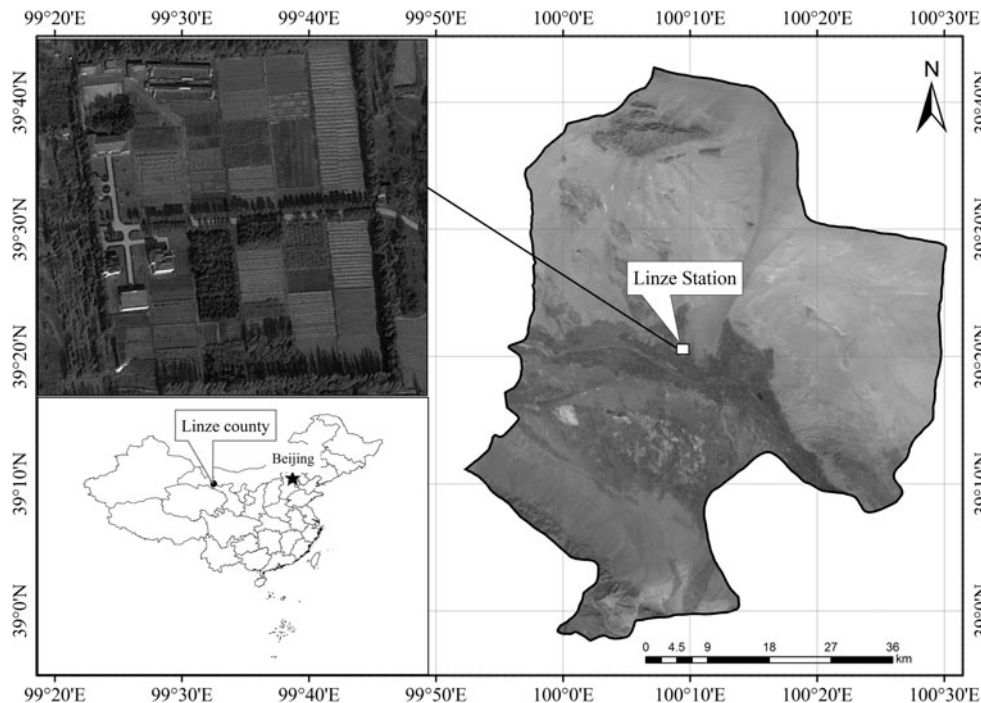


Fig. 2 Land use map of Linze county in 2000

area. It was reclaimed as orchard from mobile sand dunes in 1975 and was replaced by crops in 2001. From 2001 to 2004, main crops grown on the field were maize (*Zea mays* L.)-wheat (*Triticum aestivum* L.) intercropping, watermelon (*Citrullus lanatus*), soybean (*Glycine max*), and maize. The characteristics of some selected soil properties including soil bulk density (BD), electrical conductivity (EC), and cation exchange capacity (CEC) were presented in Table 1. In late October 2004, sampling points were marked in 6-m intervals from east to west and in 7-m intervals from south to north (Fig. 3). For each sampling point, five soil cores that were randomly distributed within 1 m range from the central position were taken using a 7-cm diameter soil column cylinder auger and were homogenized by hand mixing. Sixty-three soil samples were collected, each being approximately 500 g. Soil samples were sieved to 2 mm after being air-dried at room temperature. Before being analyzed for SOC, TN, AN, AP, AK concentrations, and pH, samples were further ground to pass a 0.25-mm sieve.

Soil analysis

Soil organic carbon was determined by dichromate oxidation of Walkley–Black (Nelson and Sommers 1982). Total nitrogen was measured by micro-Kjeldahl procedure (Bremner and Mulvaney 1982). Available nitrogen (AN) was determined by the alkalizable diffusion method,

Table 1 Characteristics of some selected soil properties

Soil layer (cm)	BD ^a (g kg ⁻¹)	Texture ^a			EC ^a (ms cm ⁻¹)	CEC ^b (mmol kg ⁻¹)
		Sand (%) 1–0.05 mm	Silt (%) 0.05–0.002 mm	Clay (%) <0.002 mm		
0–20	1.43 (0.020)	82.28 (3.78)	14.19 (3.83)	3.01 (0.081)	0.093 (0.007)	56.99 (1.45)
20–40	1.55 (0.039)	90.64 (2.19)	6.11 (1.77)	2.84 (0.023)	–	–
40–60	1.56 (0.017)	94.11 (0.13)	3.45 (0.17)	2.83 (0.11)	–	–
60–100	1.55 (0.0090)	93.13 (0.57)	3.56 (0.28)	2.96 (0.061)	–	–

^a The values of variable were measured in 2005

^b The values of variable were measured in 2010

^c “–”, no measured this variable

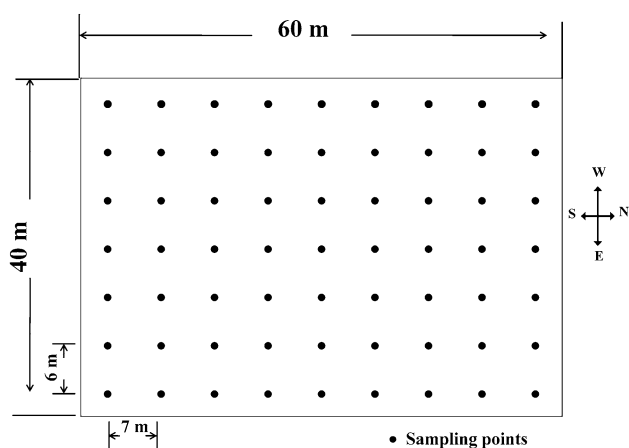


Fig. 3 Illustration of sampling points with a 6 m × 7 m grid between individual samples

available phosphorus (AP) by the Olsen method, and available potassium (AK) by the colorimetric method with NH₄OAc extraction (Institute of Soil Sciences CAoS 1978). Soil pH was measured by a pH meter with a soil: water ratio of 1:2.5 (Institute of Soil Sciences CAoS 1978).

Statistical analysis

Mean, median, standard deviation (SD), and coefficient of variation (CV) were determined for all data sets. The distribution of the data was tested for normality using the Kolmogorov–Smirnov (K–S) test. These statistical parameters were determined using SPSS software package (SPSS19.0, Chicago, Illinois, USA).

Spatial patterns of soil nutrients for the data sets were determined using geo-statistical analysis. Data that were not normally distributed were logarithmically transformed. Semivariograms were calculated using the GS + software package (Version 7.0; Gamma Delta, Plainwell, Michigan) as follows:

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

where $Z(x_i)$ represents the measured value for soil property at location of x_i , and $\gamma(h)$ is the variogram for a lag distance h between observations $Z(x_i)$ and $Z(x_i + h)$, and $N(h)$ is the number of data pairs separated by h .

Several standard models are available to fit the experimental semivariograms (spherical, exponential, Gaussian, liner and power models) (Burrough 1995). Based on the regression coefficients of determination (R^2), the fitted exponential model, spherical model, and liner model were used in this study, which were defined as follows:

$$\gamma(h) = C_0 + C(1 - e^{-ha}) \text{ (exponential model)} \tag{2}$$

$$\gamma(h) = \begin{cases} C_0 + \left[\frac{3h}{2a} - \frac{1}{2} \left(\frac{h}{a} \right)^3 \right] & (0 < h < a) \\ C_0 + C & (h \geq a) \end{cases} \text{ (spherical model)} \tag{3}$$

$$\gamma(h) = \begin{cases} C_0 + bh & (0 < h < a) \\ C_0 + C & (h \geq a) \end{cases} \text{ (liner model)} \tag{4}$$

where C_0 is nugget value, C is the partial sill, $C + C_0$ is the sill, and a is the spatial correlation distance (or Range). These models quantify the scale of heterogeneity and the parameters for spatial prediction by ordinary kriging: (1) the nugget value (C_0) represents spatial variability arising from the random components like measured errors and micro-scale processes; (2) the sill ($C + C_0$) provides an estimate of total population variance, and the partial sill (C) indicates the spatially dependent predictability of the variable (structural variance); and (3) the range (R) established the spatial correlation distance (Webster and Olive 2000). The models fitted to the semivariogram allow for interpolation, providing unbiased estimates of non-sampled points. The resulting maps provide visualizations of the patterns.

Table 2 Descriptive statistics of soil nutrient parameters and their normal distribution tests

Item	SOC (g kg ⁻¹)	TN (g kg ⁻¹)	AN (mg kg ⁻¹)	AP (mg kg ⁻¹)	AK (mg kg ⁻¹)	pH
Mean	4.45	0.49	19.99	21.08	121.60	8.98
Median	4.18	0.47	19.28	18.52	107.90	9.02
SD	1.09	0.10	6.66	12.05	43.16	0.21
CV (%)	24	20	33	57	35	2
Minimum	2.66	0.31	9.14	7.38	74.70	8.19
Maximum	6.90	0.75	39.59	73.04	298.80	9.30
Skewness	0.46	0.66	0.62	1.82	2.30	-2.00
Kurtosis	-0.71	0.001	0.01	5.29	6.22	4.66
K-S <i>p</i>	0.00	0.00	0.00	0.00	0.00	0.00
Distribution	Logarithmic normal	Logarithmic normal	Logarithmic normal	Logarithmic normal	Normal	Normal

Table 3 Pearson correlation coefficients of soil nutrients

Variable	SOC	TN	AN	AP	AK	pH
SOC						
TN	0.97**					
AN	0.53**	0.58**				
AP	0.44**	0.43**	0.25*			
AK	0.42**	0.42**	0.24	0.57**		
pH	-0.27*	-0.25	-0.17	-0.43**	-0.36**	

** Correlation is significant at $p = 0.01$ (two-tailed), * Correlation is significant at $p = 0.05$ (two-tailed), $n = 63$

Results

Statistical description and correlation analysis

The mean values of SOC, TN, AN, AP, and AK content were 4.45 g kg⁻¹, 0.49 g kg⁻¹, 19.99 mg kg⁻¹, 21.08 mg kg⁻¹, and 121.60 mg kg⁻¹, respectively (Table 2). The mean value of soil pH was 8.98 at the experimental site. The one-sample Kolmogorov–Smirnov test confirmed the normal distribution of AK content and pH ($K-S p < 0.05$) while rejecting this model for the SOC, TN, AN, and AP contents. However, the log-transformed data of SOC, TN, AN, and AP contents have passed the one-sample Kolmogorov–Smirnov normal distribution test ($K-S p < 0.05$), implying that the SOC, TN, AN, and AP contents in this experimental field generally follow a log-normal distribution.

Coefficient of variation (CV), as an index of overall variation, reflects the heterogeneity of soil properties, ranging from 0.02 to 0.57 (Table 2). The CV of AP content (57 %) was particularly high, suggesting dissimilarity of AP content among the samples. The CV of SOC, TN, AN, and AK contents (24, 20, 33, and 35 %, respectively) was moderate, indicating the variation of these variables are smaller than that of AP content. The lowest CV of pH (2 %) suggested that this variable has a weak variation.

The Pearson correlation coefficients and their significance levels between variables were presented in Table 3. There were significant, positive correlations between SOC and TN content, and the derived correlation coefficient was 0.97 ($p < 0.01$). A similar pattern was found among SOC, TN, AN, AP, and AK contents ($p < 0.05$); however, the correlation between AN and AK contents was not significant. In this newly reclaimed sandy cropland, the contents of SOC, TN, AN, AP, AK were negatively correlated with soil pH, although the correlation was not always significant.

Geo-statistical variability

The raw data of AK content and pH values followed a normal distribution, whereas the log-transformed data of SOC, TN, AN, AK, and AP content exhibited normal distribution. Therefore, experimental semivariograms were calculated upon the raw data of AK content and pH, and upon the log-transformed data of SOC, TN, AN, and AP contents.

The parameters of theoretical semivariogram models are summarized in Table 4. For the data of SOC and AK contents and pH value, an exponential model provided a significant fit to the semivariograms. The spherical model provided a best fit to the semivariograms of TN and AP contents, and the liner model was the optimal theoretical model for the semivariogram of AN content. The regression coefficients of determination (R^2) for theoretical semivariogram models were all greater than 0.9. The residual sums of squares (RSS) for the semivariograms of SOC, TN contents, and pH were close to zero, and the RSS for the semivariograms of AN and AP contents were 6.48 and 21.29, respectively. However, the RSS for the semivariogram of AK was especially large. Nugget values (C_0) were less than 1 for the semivariograms of SOC, TN contents, and pH, but were 23.44 and 47.00 for the semivariograms of AN and AP contents, respectively. The C_0 for the semivariogram of AK was also large. The ratios of

Table 4 Semivariogram (γ) models and parameters

Variable	Model	Nugget (C_0)	Sill ($C + C_0$)	$C_0/(C + C_0)$	Range (m)	RSS	R^2
SOC	Exponential	0.13	1.28	0.10	18.24	1.31×10^{-3}	0.98
TN	Spherical	0.00035	0.011	0.03	12.92	1.50×10^{-7}	0.97
AN	Linear	23.44	49.77	0.47	32.64	6.48	0.98
AP	Spherical	47.00	137.60	0.34	21.29	21.9	0.98
AK	Exponential	1,111.00	2,921.00	0.38	132.33	1.46×10^4	0.95
pH	Exponential	0.00090	0.043	0.02	17.52	6.03×10^{-6}	0.93

nugget-to-sill for SOC, TN contents, and pH were all higher than 90 %, but for AN, AP, and AK it ranged from 53 to 62 %. The ranges for the semivariograms of soil nutrients varied from 12.92 to 132.33 m. The range for SOC, TN, AP contents, and pH value was roughly 2–3 times that of the sampling intervals (12–17 m to 18–21 m). However, the ranges of AN and AK were greater than 30 m which was the half of the long side of rectangle sampling field. The range of AK was greater than the maximal distance of sampling (72 m, the diagonal of the rectangle sampling field).

Spatial distribution maps

According to the parameters obtained above, the distribution maps of soil nutrients were drawn (Fig. 3). These maps illustrated the comparable spatial distribution patterns of these variables and also differentiated the zones with nutrient deficiency from the zones with nutrient abundance. There was a strong heterogeneity in this newly reclaimed sandy cropland. There were four zones with greater soil fertility than the other zones, and one zone had the lowest soil fertility. Four high-fertility zones were distributed in the southwest corner, the northeast corner, the middle of eastern edge, and the northerly areas of western edge. One low-fertility zone was distributed in the southerly areas of western edge. All the variables presented patchy distribution in this rectangular sampling site, with patch sizes and densities differed among variables. The distribution maps of SOC content and pH showed smaller patch sizes and a large number of patch quantity, followed by TN content. Available nutrients showed an adverse distributing characteristic, with large patch sizes and a small number of patch quantity (Fig. 4).

Discussions

Variogram analysis

The variogram analysis, a traditional geo-statistical tool commonly used in ecology, was an effective method for describing spatial data (Robertson 1987; Rossi et al. 1992).

Also, the variogram analysis played an important role in understanding the relationship between the heterogeneity of soil properties and its pedogenesis (Cobo et al. 2010; Lacarce et al. 2012; Sollitto et al. 2010; Tesfahunegn et al. 2011; Trangmar et al. 1986). In the present study, the variogram analysis was used to describe the spatial variation in soil nutrients distribution in a field-scale cropland which was reclaimed in recent years. Three parameters were used to interpret the spatial dependence of each variogram. The nugget variance (C_0) of soil nutrient variables ranged from 0.00035 to 1,111.00, and the sill variance ($C + C_0$) ranged from 0.011 to 2,921. A high nugget variance indicates that most variance occurs over short distances (Schlesinger et al. 1996), and a sill variance presents the biggest degree of spatial heterogeneity. However, the nugget and sill were shown to provide an incomplete, even misleading statistics in comparing the difference of random variation and the degrees of spatial heterogeneity between different regional variables because they were often impacted by the magnitude of different variables (Wang 1999). The ratio of nugget-to-sill served as an indication of a random pattern among the data.

The ratio of nugget-to-sill for SOC content indicated that 10 % of the variation is found at a scale <6 m (minimal sampling distance), but the remaining variance is found over an 18.24-m range of autocorrelation. Only 3 and 2 % of the variation were at a scale <6 m for TN content and pH, and the distance of autocorrelation were 12.92 and 17.52 m, respectively. Different patterns were found in AN, AP, and AK contents, with ranges of autocorrelation being far from that of SOC, TN content, and pH value. The ratio of nugget-to-sill also can be regarded as a criterion for classifying the spatial dependency of soil properties. If the ratio is <25 %, the variables have strong spatial dependence. If it is between 25 and 75 %, the variables have moderate spatial dependence. With a ratio greater than 75 %, the variables show weak spatial dependence (Cambardella et al. 1994). The ratio of nugget-to-sill for SOC, TN content, and pH value exhibited strong dependence within the distance of range. Moderate spatial dependence was shown for AN, AP, and AK content within the distance of range, with the ratio of nugget-to-sill

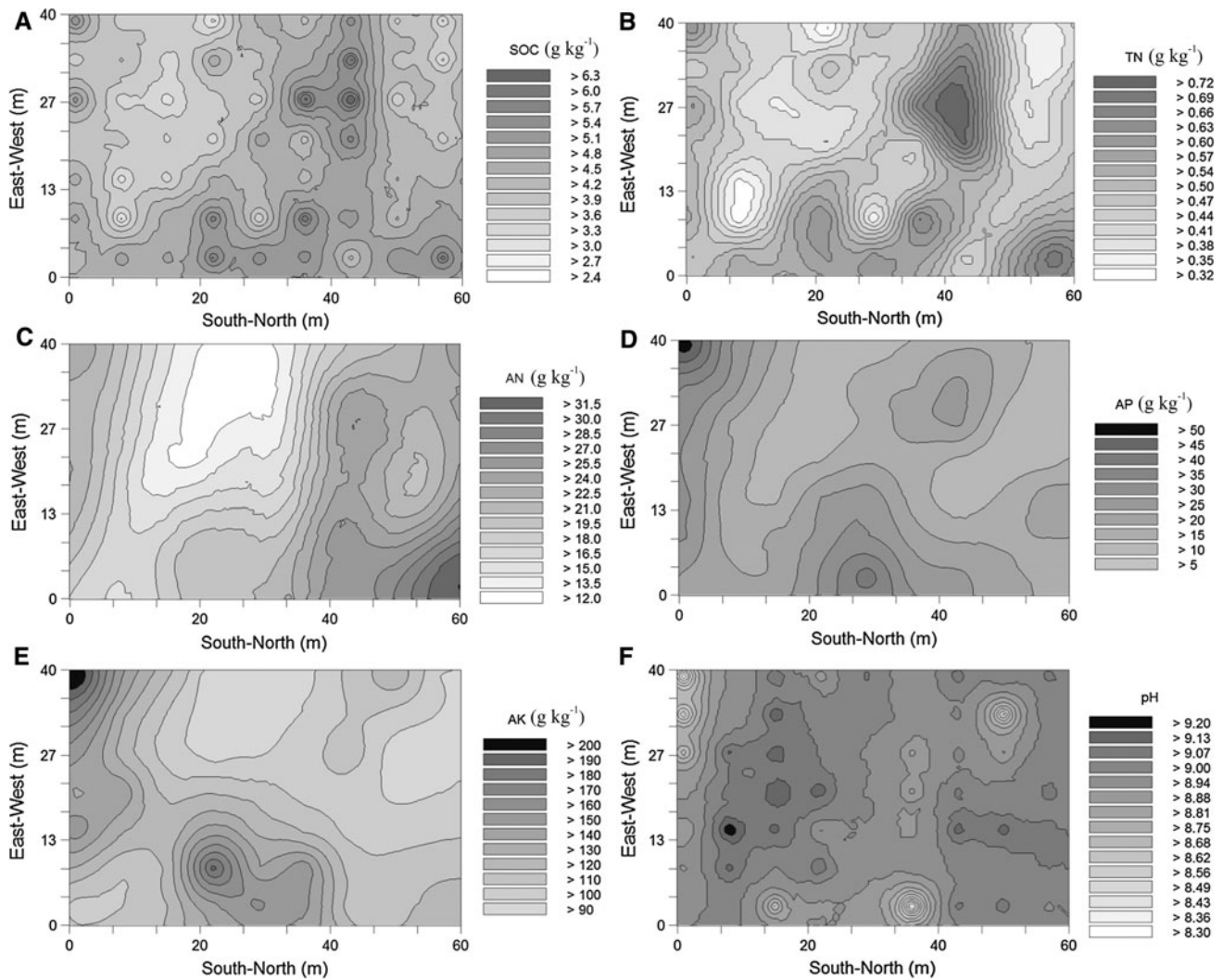


Fig. 4 The spatial distribution maps of **a** SOC, **b** TN, **c** AN, **d** AP, **e** AK, and **f** pH measured at Linze Station, China

between 25 and 75 %. The variogram analysis allowed the determination of the scale of spatial dependence in the distribution of soil nutrients. The analysis showed that AN, AP, and AK nutrients have a longer distance of autocorrelation, but weaker spatial dependence than the SOC, TN contents, and pH value in this newly reclaimed sandy field.

Spatial distribution and impact factors

The exponential model showed that the semivariograms of variables had the same variation in different directions, which occurred in all scales. The spatial distribution map comprising different sizes of the patches was accorded to this kind of model (Goovaerts 1997). The exponential model provides a best fit to the semivariograms of SOC, AK contents, and pH value. Similar spatial distribution patterns between SOC content and pH value can be seen from Fig. 3 where there were many patches with different

sizes and regular shape. The different spatial distribution pattern for AK content may be related to the high nugget and range value leading to the big-sized patches. The spherical model indicated that the changes of semivariograms were different in different direction. The spatial pattern of this kind of model showed irregular patches distributing randomly (Goovaerts 1997). The spherical model provided a good fit to the semivariograms of TN and AP content, but the nugget and range value for AP content were higher. The liner model indicated that the semivariograms of variables rises with the increase of distance and the rate of changes also increase with the increase of distance. There was a gradient variation for these variables. The distribution of AN content followed this kind of spatial pattern (Fig. 3).

Both intrinsic (such as soil parent material, soil texture) and extrinsic factors (such as fertilizer and irrigation application, cropping history) control the spatial variability

of soil properties in agriculture ecosystems (Buschiazzo et al. 2001; Cambardella et al. 1994; Urioste et al. 2006; Zhao et al. 2008). The strong correlations among the content of soil nutrients (Table 2) indicated that six variables of soil nutrients came from the same soil parent material, climate, and vegetation. Scale effect should be considered when analyzing the spatial heterogeneity of variables (Li and Reynolds 1995). In the present study, the ranges of SOC, TN content, and pH value were all <20 m. This indicated that the main variance is over distances from 6 to 20 m, which is likely to be related to the planting pattern of orchard in this moderate spatial scale. The ranges of AN, AP, and AK contents all exceeded 20 m, indicating that the impact factors of soil heterogeneity should be considered in a large spatial scale. This field was reclaimed from sand dunes; thus, the topography should be the main factor causing the spatial heterogeneity of the three variables.

Usually, a strong spatial dependence of soil properties can be attributed to intrinsic factors such as soil texture and mineralogy, and a weak spatial dependence can be attributed to extrinsic factors such as fertilizer application, tillage, and other soil management practices (Cambardella et al. 1994). Available nutrients have a weaker spatial dependence compared with the SOC, TN contents, and pH value, indicating that the effect of fertilizer and irrigation management for crops planted from 2001 to 2004 on spatial distribution is greater for the available nutrients than for the SOC, TN contents, and pH value in this newly reclaimed sandy field.

Soil fertility change and its impact factors in a newly reclaimed sandy cropland

The natural desert soil exhibits loose structure and very low nutrient contents, because the soil-forming processes are quite weak under extremely arid environments. With continuous cropping, agricultural practices including irrigation, tillage, and fertilization may have altered soil-forming processes, thus influencing soil structure and fertility (Su et al. 2010). Other researchers have pointed out that the topsoil still showed typical characteristics of desert soil even after conversion of native sandy soil to irrigated cropland in a relatively short-term period (Liu et al. 2011; Garten et al. 2007). In the present study, the mean contents of SOC, TN, AN, AP, and AK were 4.45 g kg⁻¹, 0.49 g kg⁻¹, 19.99 mg kg⁻¹, 21.08 mg kg⁻¹, and 121.60 mg kg⁻¹, respectively. These values were particularly lower than those reported by Liu et al. (2011) at a regional level. Through 287 soil samples collected from Linze county, Liu et al. (2011) reported that the mean contents of SOC, TN, AN, AP, and AK were 13.8 g kg⁻¹, 0.81 g kg⁻¹, 64.4 mg kg⁻¹, 32.3 mg kg⁻¹, and 199 mg kg⁻¹, respectively. Nevertheless, the soil fertility of

the newly reclaimed cropland has been improved obviously compared with native sandy desert, in which SOC, TN, AN, AP, and AK content were 0.90 g kg⁻¹, 0.11 g kg⁻¹, 12.0 mg kg⁻¹, 1.5 mg kg⁻¹, and 94.1 mg kg⁻¹, respectively (Su et al. 2010). In addition, the soil of this newly reclaimed sandy cropland are partial alkaline, with an average value of 8.89 in soil pH. After several years of farming, the soil acidity is expected to increase due to fertilization (Robson and Foy 1990).

The increase in SOC and soil nutrients following the conversion to agriculture was attributed mostly to irrigation and fertilization because they increased plant productions, and in turn, increased input to soils via increased litter and root mass (Entry et al. 2004). Furthermore, irrigation water from the river contains more than 38 g L⁻¹ of fine particles (silt and clay) in the study region, indicating that the input of silt and clay is over 380 kg ha⁻¹ with an irrigation volume of 10,000 m³ ha⁻¹. Silt and clay content play an important role in the process of SOC and nutrient accumulation and retention in desert soil cultivation (Su et al. 2010). The changes in the concentration of available N, P, and K could be related to the application of chemical fertilizers. The application of manure was another factor to cause the increase of SOC and soil nutrients (Huang et al. 2007a). It contributed to the spatial distribution of SOC in this study field. A large quantity of manure has been applied to the site where orchard was planted, which caused the regular patch distribution of SOC.

After 39-year cropland management, soil structure and soil fertility were improved, but they are still at a level insufficient to support sustainable crop production. Agriculture production still relies mostly on the high input of chemical fertilizers along with large volume of irrigation water. In newly cultivated farmlands, wind erosion is serious in winter and spring seasons due to loose soil structure. To minimize wind erosion and accelerate soil quality enhancement to ensure long-term sustainability of the farming system on these sandy lands, land managers may consider the adoption of improved farming practices, such as conservation tillage (no-till or minimum tillage), retaining standing stubble or crop residue cover on soil surface, rotating crops and grasses, and returning the part of marginal newly cultivated lands to perennial grasslands (Su 2007; Li et al. 2006).

Conclusions

In this newly reclaimed sandy cropland, the soil fertility was apparently improved, however, it was still lower compared with the regional averages. The increased SOC and soil fertility were mainly due to the input of plant residues and roots, the application of fertilizers, and

irrigation. The changes in the concentrations of available N, P, and K could be mainly due to the application of chemical fertilizers. There were similar distribution characteristics for SOC, AN, and pH, with different sizes of patches present, which would be related to the regular planting of orchard and the interval applications of the manures. The big-sized patches were observed in the distributions of AN, AP, and AK contents. The topography may be the main factor causing the spatial heterogeneity of available N, P, K, whereas 4 years of crop planting (2001–2004) affected the distribution of these soil nutrients. The continuous applications of chemical fertilizer significantly affect the concentration and distribution of available nutrients, but the efficacy was low on the change of SOC, AN, and pH value. The newly reclaimed sandy cropland has the potential to improve the productivity and soil fertility only if the appropriate and sustainable soil management practices are adopted. However, land use change and their influences on soil nutrients are complicated processes deserving further investigation.

Acknowledgments This research was supported by the National Natural Science Foundation of China (41201284), National Natural Science Fund for Distinguished Young Scholars (41125002), and the Open Foundation of Key Laboratory of Arid Land Crop Science in Gansu Province.

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