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ORIGINAL ARTICLE

Catchment scale spatial variability of soil salt content in agricultural oasis, Northwest China

Yugang Wang · Yan Li · Duning Xiao

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Abstract Soil salinization is a serious environmental problem in the world, especially in arid and semi-arid regions. Therefore, estimating spatial variability of soil salinity plays an important role in environmental sciences. Aiming at the problem of soil salinization inside an oasis, a case study was carried out at the Sangong River catchment in Xinjiang province, northwest China. Methods of classical statistics, geostatistics, remote sensing (RS) and geographic information system (GIS) were applied to estimate the spatial variability of soil salt content in the topsoil (0–20 cm) and its relationship with landscape structure at catchment scale. The objective of this study was to provide a scientific basis to understand the heterogeneous of spatial distribution of soil salt content at a large scale. The results revealed that (1) elevation of landform was a key factor for soil salt content's spatial variability, and soil salt content had a strong spatial autocorrelation, which was mainly induced by structural factors. (2) Mapping of soil salt content by Kriging and comparing it with landscape maps showed that area of soil salinization in old oasis was smaller than that in new oasis, and degree of soil salinization in old oasis was also lower than that in the new one. Among all landscapes, cropland was mostly affected by salinity, with 38.8% of the cropland in new oasis moderately affected by soil salinity, and 8.54% in old oasis.

Y. Wang · Y. Li (✉)
Xinjiang Institute of Ecology and Geography,
Chinese Academy of Science, 40-3 South Beijing Road,
Urumqi, Xinjiang 830011, People's Republic of China
e-mail: liyan@ms.xjb.ac.cn

D. Xiao
Shenyang Institute of Applied Ecology,
Chinese Academy of Science,
Shenyang 110016, People's Republic of China

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Introduction

Soil salinization is a serious environment problem in the world, especially in arid and semi-arid regions. Therefore, estimating spatial variability of soil salinity plays an important role in environmental sciences. Salt accumulation has a direct impact on soils and crop growth. Usually, salt tends to concentrate in the surface and near-surface layers of soil. Excessive soil salinity may cause the decrease of the crop's field, the loss of land productivity, and possibly, land degradation (Thomas and Middleton 1993; Lesch et al. 1995). On the global scale, it is estimated that naturally occurring salt-affected soils cover about a billion hectares (Flowers and Flowers 2005), and nearly 50% of the irrigated land in arid and semi-arid regions has some degree of soil salinization problem (O'Hara 1997). Every year about 4×10^4 ha of land becomes unfit for agricultural use because of salinization problem throughout the world (Lamsal et al. 1999). The mitigation and control of soil salinity is one of the main challenges in the agriculture of the twenty-first Century (Amezketa 2006). This requires efficient and accurate quantification of soil salinization (Wang 1998; Benyamini et al. 2005).

The spatial variability of soil physical and chemical properties has been a topic of major concern to soil scientists (Webster 1985; Hillel 1991; Sylla et al. 1995; Jordán et al. 2003). The spatial heterogeneity is one of the main characters in soil property. Usually two reasons result in the heterogeneity of soil properties, one is the intrinsic factors (e.g., soil formation factors, such as soil parent materials), and another is the extrinsic factors (e.g., soil management practices, fertilization, irrigation, and crop rotation). Understanding the spatial variability of soil properties is a key in understanding of the landscape-scale processes of soils (Corwin and Lesch 2005). In previous studies on spatial variability of soil salinity, limited attention had been paid on catchment scale. Most of the studies were directed towards the characterization of field scale patterns in soil salinity (Lesch 2005). Assessments of salinization in the literature are often based on indirect estimation, small-scale studies, or poorly defined periods of time (Herrero and Pérez-Coveta 2005). However, Characterizing spatial and temporal variability of soil properties at larger scales is extremely important for various agronomic and environmental concerns (Corwin et al. 2006). Therefore, the specific characteristics of soil salt content should be used to identify the spatial variability of soil salt content and its relationship with landscape structure at larger scale.

Arid and semi-arid regions occupy more than 30% of the Earth's land surface (Okina et al. 2006), and oases are unique intrazonal landscapes in these regions (Zhang et al. 2003). In China, oases are mainly distributed in the deserts and gobies between the Helanshan–Wuqiaoling Mountains and western Border of China. Economically and socially speaking, oasis is the most important part in arid zones of northwest China. Although they occupy only 4–5% of the total area of the region, over 90% of the population and over 95% of social wealth are concentrated within the oases (Han 2001). Soil salinization is a major environmental problem in the arid region of northwest China; and its development has been an important factor to threaten the safety and stability of oases due to improper land use and management (Liu et al. 2001; Guo and Liu 2002). Soil salinization is no doubt a key issue affecting the sustainable development of the oases (Zhao et al. 2004; Li et al. 2007).

In this study, a typical agricultural oasis in Xinjiang province, northwest China named Sangong River catchment was chosen as a case study at catchment scale. The combination of methods in classical statistics, Geostatistics, remote sensing (RS) and geographic information system (GIS) were applied to quantitatively study the spatial characteristics of soil salt content in the topsoil (0–20 cm) and its relationship with landscape structure at catchment scale. The objective of this study was to provide a scientific basis in understanding the heterogeneous of spatial distribution of soil salinity at a large scale.

Materials and methods

Description of the studied area

Sangong River catchment is located at the north of the Tianshan Mountains and the south of the Guerbantonggute Desert in north-west China (Fig. 1), and extents from 87°47′ to 88°17′E and from 44°09′ to 44°29′N. The catchment covers at the south the mountainous region, in the middle the oasis region, and at the north the desert region, which is a mountain-oasis-desert landscape pattern typical to the region, with a terrain slope downward from the south to the north. The current study is mainly on the oasis area, which is 969.11 km^2. It is a typical agricultural oasis. The dominant land use types are agricultural, while urban area occupies a small portion of the study area. Land use has a history of hundreds of years in the upper (south) old oasis, but only less than 50 years in the lower (north) new oasis. Distance from north to south and east to west of the region are 36.97 and 37.65 km, respectively. This region has a slope of 2–2.5% downwards from south to north. The elevation of the region is between 450 and 680 m. The climate is an arid continental climate, with annual precipitation of 106.1–337.33 mm and annual pan evaporation of 1,533–2,240 mm. The mean annual temperature is about 7.3°C (average maximum 25.75°C in July and average minimum −15.7°C in January). The predominant soils are gray desert soil, characterized by 7.66% clay, 71.11% silt and 21.23% sand, including luvic yermosole and meadow solonchaks. Natural vegetation of the studied area is characterized by different types of halophyte communities dominated species including *Tamarix ramosissima*, *Haloxylon ammodendron* and *Reaumuria soongorica* etc. Crops include cotton, wheat, hops, grape, and corn inside the oasis.

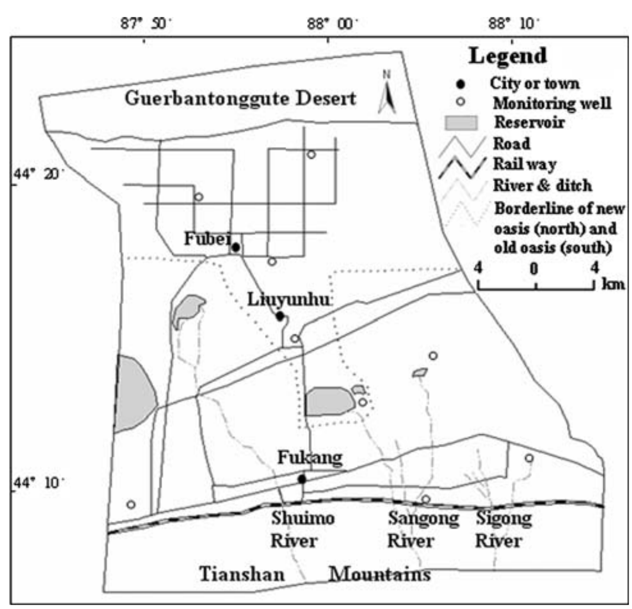

Fig. 1 Location map and borderline of new oasis and old oasis in the studied area

Soil sampling and measurements

The surface soil had been disturbed dramatically by cultivation in this catchment since 1960, especially when native vegetations were demolished completely for agriculture use in the north of the catchment and/or near the edge of Gurbantunggut Desert. The studied area is a typical agricultural landscape, where cropland occupies the major part. The 0–20 cm depth of the soil is the plowed layer for agricultural practice in this region, and in this layer soil salinization is important factor influencing crop growth. Considering that, only the soil at 0–20 cm depth was samples and analyzed. A total of 308 soil samples were collected in different landscape types throughout the catchment oasis in October 2005. The sample sites covered various landscape patch types including crop land, shrub land, grassland, etc. As many as 137 sampling were done in old oasis (64 in cropland, 5 in planted forest, 18 in scrub, 14 in grassland, 13 in construction land, 8 in reservoir/flood land, 9 in saline alkali land, 6 in bald land) and 171 in new oasis (77 in cropland, 21 in planted forest, 17 in scrub, 24 in grassland, 15 in construction land, 4 in reservoir/flood land, 8 in saline alkali land, 5 in bald land). The design allowed a comprehensive investigation into the impact of landscape types on soil salt content in the topsoil (0–20 cm). The sampling locations were recorded by the global position system (GPS). Soil samples from these sites were obtained by hand soil auger and analyzed in the laboratory. Samples were air dried and crushed to pass through a 2-mm mesh. The soil salt content, pH and SOM were measured.

Obtaining of the landscape types data

In the current study, the landscape types data were obtained from remote sensed image, topography map and field investigations. A topographic map at the scale of 1:50,000 was used to drive the image on the scale of 1:50,000. In 2004 spot imagery (June with10 × 10 m resolution) was geo-referenced to Universal Transverse Mercator projection with a root mean square (RMS) error of 0.45 pixels. In order to obtain the map of landscape types in 2005, landscape types were investigated in June 2005 according to the maps of spot imagery, topography and field. Visual interpretations of landsat imagery have been demonstrated to be useful tools in land cover and vegetation mapping (Valle et al. 1998; Bocco et al. 2001; Wilson and Sader 2002). According to the land use situations, landform, and vegetation, the landscape types in the study area were divided into eight types, namely farmland, planted forest, scrub, grassland, construction land, reservoir/flood land, saline alkali land and bald land (Fig. 2). Linear features such as roads or undeveloped desert were not included.

Geostatistical and GIS analysis

Geostatistical methods, which have been used in soil science for more 20 years (e.g., Campbell 1978; Webster. 1985; Zhang et al. 1995; Sepaskhah et al. 2005), considered the spatial–temporal variation of soil properties as a random process (Goovaerts 1999). Geostatistical data coming from the spatial random sampling in the studied area were used to analyze the natural phenomenon of spatial variability and spatial pattern. The method of Geostatistical is proved effective in studying spatial variability and spatial pattern (Li et al. 1998). An important contribution of geostatistics is the assessment of the uncertainty on unsampled point values, which usually takes the form of a map for soil properties (Castrignano et al. 2002). The main tool in geostatistics is the semvariogram, which gives an indication on the spatial dependence of each point on its neighbor. The semvariogram, $\gamma(h)$, can be defined as one-half the variance of the difference between the attribute values at all points separated by a distance h. The semi-variance γ for lag h is given by

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

where $z(x_i)$ is the value of the variable z at location of x_i, $z(x_i + h)$ is the value of the variable z at location of $x_i + h$, h is the lag distance, and $N(h)$ is the number of pairs separated by lag h (Wang 1999).

The soil salt content data were elaborated by geostatistical tools in order to study the spatial structure and to predict values of the property at unsampled positions, thereby providing the variance of the estimated value. A GS+5.3.2 program (Robertson 2000) designed by Gamma

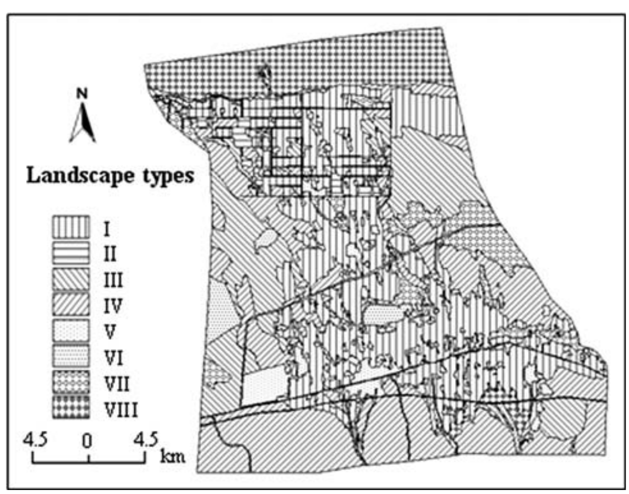

Fig. 2 Map of landscape types in the studied area (*I* Cropland, *II* Planted forest, *III* Scrub, *IV* Grassland, *V* Construction land, *VI* Reservoir/flood land, *VII* Saline alkali land, *VIII* Bald land)

Design Software was used for geostatistical analysis. The ordinary Kriging estimator, $z(x_0)$, of an unsampled site is a linear sum of weighted observations within a neighborhood:

$$z(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \quad (2)$$

where $z(x_0)$ is the value to be estimated at the location of x_0, λ_i is the weight assigned to the ith observation, $z(x_i)$ is the known value at the sampling site x_i and n is the number of sites within the search neighborhood used for the estimation. The number n is based on the size of the moving window and is defined by the user.

Cross-validation is used to evaluate the accuracy of predicted map quality of soil salt content. In this process, every known point is estimated using the values at the neighborhood around it, but not itself. Reduced Kriging variance and correlation between estimated and actual values should be as close to unit as possible. Two indices were calculated to assess the effectiveness of the predicted map. They are the mean error (ME) and the root mean square error (RMSE). With this as a basis, the superposition calculations were done using the map of land use of the studied area and then analyzed the relationship between distribution of soil salt content in the surface and land use patterns.

Obtaining of the groundwater data

Since 1976, characteristic of groundwater has been monitoring by the Hydrology Survey Bureau of Fukang in the Sangong River catchment. Today, nine monitoring wells of shallow groundwater are kept on working. Among them, four monitoring wells located in the upper (south) old oasis in the Sangong River catchment, and five monitoring wells located in the lower (north) new oasis (Fig. 1). In order to gain enough sample data to analysis the relationship between soil salt content in the topsoil (0–20 cm) and shallow groundwater table, ph, and shallow groundwater mineralization degree, 16 pumped wells with seven pumped wells in old oasis, and nine in new oasis were investigated according to situation in oasis and hydrological geology in the studied area. This added 25 groundwater wells in analyzing the relationship between soil salt content and groundwater in the studied area.

Statistical analysis

Data analyses were carried out with SPSS v. 11.5 statistical packages. Classical descriptive statistics (e.g., mean, standard deviation, Kurtosis) assumes implicitly that observations are independent of one another regardless of their location in the sampled area. Pearson correlation was used to analyze the relationships between soil salt content and elevation of landform, shallow groundwater table, shallow groundwater mineralization degree, values of pH in groundwater, landscape types, and SOM.

Results and discussion

Classical statistical analyses of the data on soil salt content

Table 1 lists the descriptive classical statistics of soil salt content data, including mean, standard deviation (SD), coefficient of variation (CV), minimum, maximum, skewness, kurtosis, and Kolmogorov–Smirnov (K–S). CV is the most important factor in describing the variability of a soil property. CV lower than 0.1, indicates low variability while CV higher than 1.0 indicates great variability. The high value for CV in the present analysis indicated great variability of the soil salt content at the surface soil of the studied area. The classical statistics of the data suggest that soil salt content is a normally distributed variable by a one-sample K–S test ($P < 0.05$) and could therefore, be directly used in the analysis of variation function of geostatistics (Table 1).

Oasis is a complex depositional environment in Sangong River catchment, exhibiting considerable spatial heterogeneity in hydrological and sedimentological characteristics, often at very local scales. Such spatial variability in the fundamental characteristics that influence groundwater and drainage will certainly influence soil salinity. If the groundwater table rises above a certain critical depth, soil salinization may occur. The rising groundwater table will then accelerate soil deterioration through increases in soil salinity (Mahmood et al. 2001). Changes in landscape, depending on type, intensity, shape, and so on, can change infiltration ratio and then affect the soil salt content (Fang et al. 2005). In the current study, Pearson coefficient analysis of relationships between soil salt content in surface soil and shallow groundwater table, shallow groundwater

Table 1 Statistical assessment of data of the soil salt content

Sample	Mean (%)	SD	CV	Minimum (%)	Maximum (%)	Skewness	Kurtosis	*K–S* value
308	0.9344	1.23	1.53	0.01	6.24	1.84	3.37	4.228

Table 2 Results of the Pearson test for soil salt content at different factors

Elevation of landform	Shallow groundwater table	Shallow groundwater mineralization degree	pH	Landscape type	SOM
−0.804**	−0.284	−0.097	0.267	0.11	−0.649**

** Correlation is significant at the 0.01 level

mineralization degree, pH, and landscape type revealed only weak correlations (Table 2). However, the correlation between soil salt content in surface soil and elevation of landform was significant ($P < 0.01$). In addition, the correlation between soil salt content and SOM was significant too ($P < 0.01$, Table 2). The landform is undulating plain with gentle but extended slopes. The slop is only 2–2.5% downwards from south to north in the studied area. The spatial variability of soil salinity is generally high, and the average levels often reflect topography (Utset and Borroto 2001). Thus, these results indicate that elevation of landform is the main factor in controlling the variability of soil salt content in the surface layer.

Geostatistical analysis of spatial pattern in soil salt content

The semivariogram analysis of the standard geostatistical techniques was performed to understand the structure and the spatial variability of the soil salt content patterns in the surface soil. The semivariogram was computed using all pairs separated by lags up to 15,000 m and Eq. (1) was used to compute the sample semivariogram. Semivariogram models and best-fitted model parameters are given in Table 3 and Fig. 3. The optimal theoretical model of soil salt content was exponential model. The determining coefficient (R^2) was 0.758; the residual sum of square (RSS) was small and the F test for R^2 reached a highly significant level ($\alpha = 0.01$). This indicated that the theoretical model efficiently reflected the spatial structural characteristics of soil salt content in the surface soil of the studied area. The ratio of nugget and sill (Co/Co + C) reflects the spatial autocorrelation (Li and Reynolds 1995) with values of <0.25, 0.25–0.75 and >0.75 indicating strong, moderate and weak spatial autocorrelation, respectively (Chien et al. 1997). The low value for nugget/sill in the present analysis indicated strong spatial autocorrelation of the soil salt content in the surface soil of this catchment. The value for nugget/still of soil salt content was less than 0.25. Spatial dependence of soil salt content was mainly structural factors. The possible cause for this spatial variability of soil salt content was elevation of the landform. This is in agreement with the conclusion from classical statistics that elevation of landform is the main factor to control the variability of soil salt content in the surface soil of the studied area. The range of this influence is considered as the distance beyond which observations are not spatially dependent. Points within the range can be considered spatially auto correlated; points outside the range are spatially independent. The semivariogram in this study has a lag of 1,500 m, which is within the range. In such situations, the use of geostatistics is appropriate (Barbizzi et al 2004).

Kriging interpolation result

The prediction map of soil salt content (Fig. 4) was created with GS+ program by a 15 × 15 m grid. Kriged contour map indicated that surface soil with lower soil salt content was distributed in the southern part of the studied area, where there are more cropland and construction land in old oasis with hundreds of years of land use history. Cross-validation was carried out to test the effectiveness of the prediction maps, and the scatter plots between the actual and predicted values are demonstrated in Fig. 5. The result of cross-validation showed the smoothing effect of the spatial prediction, and the scatter plots showed a near 1:1 correspondence between observed and predicted soil salt content values. ME was −0.0005, very close to 0. RMSE was 1.081, i.e., it is small enough to meet the accuracy requirement of the prediction. These indicate that the predicted map of soil salt content from Kriging is reliable.

Distribution of soil salt content in landscape types

Kriging interpolation can help to identify the spatial patterns (Zhang and McGrath 2004). The predicted map of soil

Table 3 Correlation parameters and F test of theoretical variogram models of soil salt content

Theoretical model	Co	Co + C	Co/Co + C	Rang (km)	R^2	RSS	F test
Exponential	0.0233	0.27052	0.093	2.49	0.758	0.0011	103.71**

** F test significance at $\alpha = 0.01$

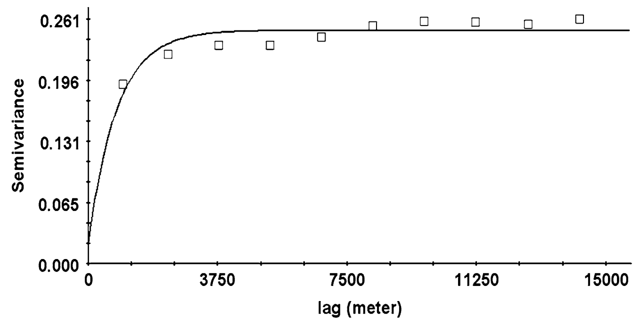

Fig. 3 Empirical semivariograms of soil salt content (*open square*) and the fitted models (*lines*) of soil salt content

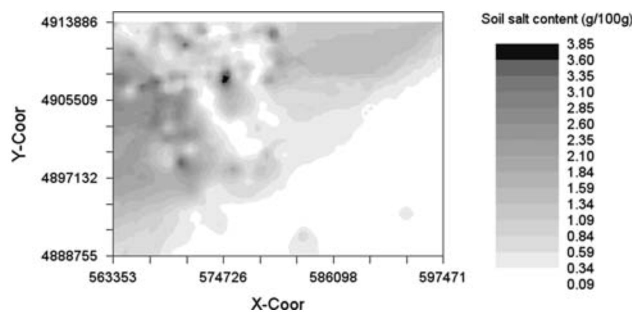

Fig. 4 Predicted map of distribution of soil salt content in the surface soil of the studied area

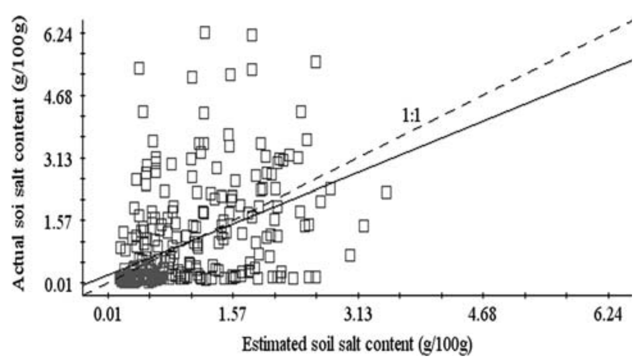

Fig. 5 Kriging interpolation accuracy of soil salt content (g/100 g) was evaluated with cross-validation

salt content was obtained from Kriging map, with boundary covering of the studied area. Soil salt content was reclassified into lower than 0.2% without salt hazard to crop growth, 0.2–1.0% with lower salt hazard to crop growth, 1.0–2.0% with moderated salt hazard to crop growth, highter than 2.0% with great salt hazard to crop growth (Fig. 6). The Kriging map of the spatial distribution of soil salt content was superimposed on the map of landscape patch type for 2005, and then the distribution of soil salt content in the surface soil on various landscape types was obtained (Table 4). In entire oasis, 73.76% land was subject to soil salinization, with 4.02% graded as great salt hazard,

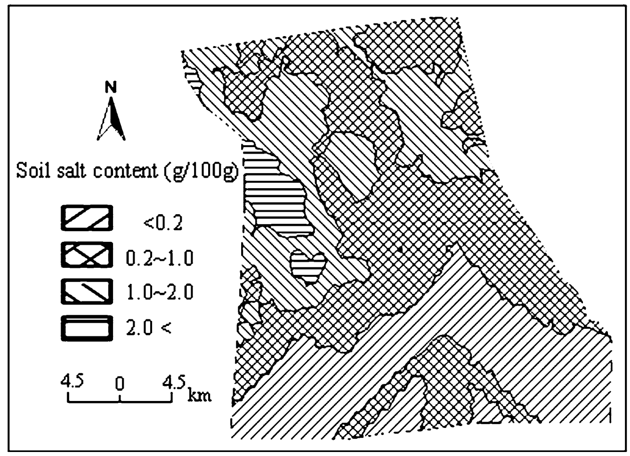

Fig. 6 Cut and reclassified distribution map of soil salt content in the surface soil of the studied area

and then 26.23% graded as no salt hazard. Area of soil salinization was smaller in southern old oasis than in northern new oasis, and the degree of soil salinization was also lower in southern old oasis than in northern new oasis. In old oasis, 44.67% of the land graded as salt hazard, and 39.21% of the land graded as low salt hazard area. In new oasis, all area was subject to soil salinization, and 36.81% of land was graded as moderate or great salt hazard. For the area graded as no salt hazard, 35.66% was cropland, and 40.46% was grassland. For the area graded as great salt hazard, 59.63% was scrub and 30.25% was grassland. Area with great salt hazard was mainly distributed around reservoir (Fig. 6), especially in old oasis. Thus, area with great salt hazard within scrub was 89.19% in old oasis, only 10.81% in new oasis. 70.2% cropland in entire oasis was subject to soil salinization, and area of soil salinization in cropland was larger than in other landscape types. Among all landscapes, cropland was mostly affected by salinity, with 38.8% of the cropland in new oasis moderately affected by soil salinity, and 8.54% in old oasis. High evaporation rates in arid lands usually result in high near-surface salinity (Weisbrod and Dragila 2006). Distribution different of soil salinization in cropland might be attributed to surface–water irrigation in old oasis, groundwater in new oasis, particularly the rising groundwater mineralization degree and soil salinization (Gu et al. 2003; Yan et al. 2006). The irrigation water mainly came from two sides, one was from surface-water in the Sangong River, and the other was pumped groundwater in the studied area. Irrigation in old oasis mainly came from surface–water in Sangong River, which accounts for 82.19% of the water consumption, only 17.81% from groundwater. But in new oasis, the water consumption from surface–water was only 41.24, 58.76% from groundwater. Land use has a history of hundreds years in old oasis, but only less than 50 years in new oasis. Though agricultural practices, excessive water

Table 4 Distribution of soil salt content in the surface soil on various landscape types (unit: × 10^2ha)

Landscape type	Oasis position	<0.2%	0.2–1.0%	1.0–2.0%	>2.0%
Cropland	Entire oasis	87.45	142.16	62.27	1.55
	Old oasis	87.45	63.8	12.76	1.37
	New oasis	0	78.36	49.51	0.18
Planted forest	Entire oasis	0.46	2.6	11.9	0.04
	Old oasis	0.46	0	0	0
	New oasis	0	2.6	11.9	0.04
Scrub	Entire oasis	12.32	59.08	32.13	23.22
	Old oasis	12.32	16.63	23.51	20.71
	New oasis	0	42.45	8.62	2.51
Grassland	Entire oasis	102.88	128.6	42.06	11.78
	Old oasis	102.88	88.52	17.5	6.04
	New oasis	0	40.08	24.56	5.74
Construction land	Entire oasis	34.69	19.12	5.02	0.11
	Old oasis	34.69	7.4	1.14	0.07
	New oasis	0	11.72	3.88	0.04
Reservoir/flood land	Entire oasis	5.18	12.89	5.81	2.24
	Old oasis	5.18	5.92	5.34	2.24
	New oasis	0	6.97	0.47	0
Saline alkali land	Entire oasis	3.08	45.11	11.81	0
	Old oasis	3.08	39.56	1.02	0
	New oasis	0	5.55	10.79	0
Bald land	Entire oasis	8.2	66.38	28.97	0
	Old oasis	8.2	1.36	0	0
	New oasis	0	65.02	28.97	0

and fertilizer applications can cause soil salinity. Water-use between cropland of old oasis and in cropland of new oasis was significant different. The groundwater table in new oasis had risen by 0.09 m per year from 1983 to 2005, and the mineralization of water in wells in this area was rising at a rate of 0.12 g l^{-1} year^{-1}. The rising groundwater table in new oasis could directly cause soil salt accumulation in the surface soil, then indirectly lead to increase in soil salt accumulation per unite area (Wang et al. 2007). However, the groundwater table in old oasis had dropped by 0.47 m per year from 1983 to 2005, and the mineralization of water in wells in this area was rising at a rate of 0.03 g l^{-1} year^{-1}. These factors could cause different distribution of soil salt content at various landscape types of different region.

Conclusion

The agricultural oasis in Sangong River catchment, northwest China provides a natural laboratory to examine the spatial variability of soil salinity in the topsoil (0–20 cm) and its relationship with landscape structure at catchment scale by classical statistics, geostatistics, remote sensing (RS) and geographic information system (GIS). Classical statistical analysis indicated great variability of soil salt content in the surface soil. Elevation of landform was the most important factor for its spatial variability. Geostatistics analyses showed that strong spatial autocorrelation of soil salt content, which was mainly induced by structural factors. The possible cause for the strong spatial autocorrelation of soil salt content was elevation of landform. Soil salt content increased gradually with decrease of elevation from south to north. Among all landscapes, cropland was mostly affected by salinity. Area of soil salinization in old oasis was smaller than that in new oasis, and degree of soil salinization in old oasis was also lower than that in new one. This conclusion and illustration may guide policy-makers to set up the priority to mitigate and control soil salinity's programs at a large scale for maintenance of oasis agricultural sustainability in this region.

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