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ORIGINAL ARTICLE

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Temporal–spatial change in soil degradation and its relationship with landscape types in a desert–oasis ecotone: a case study in the Fubei region of Xinjiang Province, China

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Abstract Desert–oasis ecotone is an interactive area between desert and oasis ecosystems which plays an important role in ensuring oasis ecological security and maintaining oasis internal stabilization. The studied region had experienced dramatic landscape change and soil degradation during the 20th century, especially in the last two decades. To document the status and evaluate this degradation process, geostatistics and GIS map algebra were used to quantify the temporal–spatial changes in landscape pattern and soil degradation from 1983 to 2005. The results showed that: (1) the change of landscape pattern due to human activities was the key reason responsible for the increasing of landscape diversity and fragmentation; (2) the extent of soil degradation was higher near desert ecosystem than oasis, and human activities were the major driving forces in ameliorating the soil properties; and (3) soil degradation is weaker in regions of bad soil quality than regions of good soil quality due to both human activities and natural processes.

Keywords Soil degradation · Landscape pattern · Desert–oasis ecotone · Xinjiang of China

Introduction

Soil degradation is a long-standing environmental issue in the world. As a major issue concerning environmental change, it has recently received wide attention (Feddema 1999; Fairhead and Scoones 2005). Recent studies at many areas of the world (Barros et al. 2004; Rodrıguez et al. 2005) have emphasized the need for monitoring the degree of soil degradation. Soil degradation is a major environmental threat to the sustainability and the productive capacity of agriculture. Soil degradation, which is associated with long-term changes in ecosystem functions, changes physical structure and chemical component of soils, reduces soil nutrients, declines land productivity, biodiversity, and diminishes economic viability (Melegy 2005). The conversion of grasslands and forests to agricultural land has dramatic impact on the direction and degree of soil quality changes in time and space. These changes usually contribute to accelerate soil deterioration (Meyer and Turner 1992). In previous studies on land-use changes, limited attention had been paid to soil degradation following these changes (Jamalam et al. 1998).

Landscape structure and composition evolves continuously in space and time. Landscape pattern impacts the physical, chemical, and biological processes of soil. These impacts contribute significantly to the complex interactions between natural environment and human activities and cause changes of individual element in the soil system and the spatial variations of the soil properties (Sveistrupa et al. 2005). The spatial distribution of soil properties and compaction are typical examples. Soil degradation is a widespread serious problem in the modern world and it is hard to be restored through low levels of external inputs (Koning and Smaling 2005). Since soil degradation is incompatible with sustainable development (Paza et al. 2006), it is important to evaluate it on a regional scale. Few studies had focused on the soil degradation in the course of land-use (Fu et al. 2003). Therefore, the specific characteristics of the area in different periods would allow us to identify the degraded areas, evaluate the degradation state, and especially, estimate the impact of human activities on soil productivity.

Oases are unique intrazonal landscape in arid and semi-arid regions of the world. In China, they are mainly distributed in temperate desert areas between the west of the Helan Mountain in Ningxia Hui Autonomous Region and the south of Qinghai-Tibet Plateau. A unique phenomenon is that some oasis exists in desert in the northwest drought climate area (Pan and Chao 2003). Although oases take up only 4–5% of the total area of this region, over 90% of the population and over 95% of social wealth are concentrated within these areas (Han 2001). Oases evolution in arid and semi-arid regions has two opposite processes: one is oasification, and the other is desertification (Jia et al. 2004; Zhang et al. 2003a, b). Desert–oasis ecotone is an interaction area between desert and oasis ecosystems, and plays an important role in arid region. Oasis evolution and oasis exploitation usually starts at desert–oasis ecotone. Maintaining the stability of desert–oasis ecotone could effectively prevent land from being barren and soil from being salinized in internal oasis (Pan 2001).

The objectives of this research are to: (a) evaluate the soil degradation on a regional scale; (b) estimate the dynamics of soil degradation pattern in accordance with different land-use patterns; and (c) identify the courses of soil degradation development.

Materials and methods

Description of the study area

Fubei region of Xinjiang Province is located in the northern Tianshan Mountains and southern edge of the Guerbantunggute Desert in north-west China (Fig. 1), and ranges from 87°47′30″ to 88°01′15″E and from 44°17′30″ to 44°22′30″N with a total area of 169 km^2. It is a typical desert–oasis ecotone. Distance from north to south and east to west of the region are 19.2 and 8.8 km, respectively. This region has a slope of 0.17% downwards from south-east to north-west. The elevation of the region is between 454.3 and 485.4 m. The climate is an arid continental climate, and its annual precipitation ranges from 88 to 246 mm. The mean annual temperature is about 6.6–7°C (average maximum 42.6°C in July and average minimum −41.6°C in January). The accu-

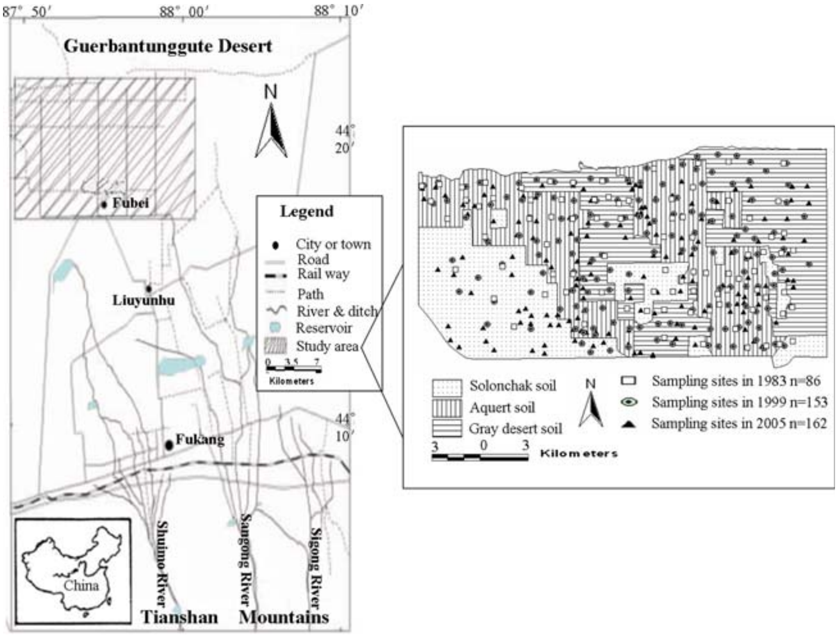

Fig. 1 Location map, soil sampling sites, and soil types in the studied area

mulated active (≥ 0°C) temperature is 3,949°C and ≥ 10°C is about 3,257°C. The latest soil survey showed that the soil types of this area include Gray Desert soil, Solonchak, and Aquert which covers 28.1, 37.3, and 34.6% of the region area, respectively. Natural vegetation of the study area is characterized by different types of xeromorphic formations, including desert *Tamarix ramosissima*, *Haloxylon ammodendron*, and *Reaumuria soongorica* scrubs. Crops include cotton, wheat, hops, grape, and corn inside the oasis. The total area of cropland is 7,285.65 ha and the total population of the area is 12,000.

Landscape data set

Basic maps for this study came from land-use maps at 1:10,000 scale for 1983 and 1999, and Spot imagery (with 10 m × 10 m resolution) of 2005. The area measurements of the paper maps in the study were made with the statistics function of GIS, according to the details of the satellite image processing methodology and procedures (Bocco et al. 2001; Chen et al. 2002; Del Valle et al. 1998). The compilation of landscape maps was done with map generalization method. The paper maps were digitized, and the Spot imagery was classified and digitized as well. The landscape maps of studied area were compiled with the land-use map using GIS software ArcView 3.2a (ESRI, Environmental Systems Research Institute Inc., Redlands, CA, USA). We reclassified the landscape into seven major landscape categories in accordance with their properties such as landform, land-use type, and constructive plant species (Table 1), based on the major features of the studied area. No linear features such as roads or undeveloped desert were included.

The following landscape categories were distinguished:

(i) Residential area;
(ii) Artificial forest;
(iii) Cropland;
(iv) Orchard land;
(v) Shrubbery land;
(vi) Saline alkali land; and
(vii) Grassland.

Figure 2 shows the landscape map of the studied area. The map was further amalgamated into two cover types according to the degree of influence by human activities, artificial (i–iv), and natural (v–vii) landscape.

Soil data

Soil data including soil organic, available N, available P, available K, and total salt in 1983, 1999, and 2005 mainly came from two sources: one was the soil sampling taken in 2005 by the authors; the other was from Fubei Land Resources Administration, which includes the soil data of 1983 and 1999. There are 86 and 153 soil samples in the 1983 and 1999 soil data, respectively. These two sets of soil data were part of the Chinese national soil survey carried out during these two years, and the sample depth was 0–20 cm. In October 2005, soil samples were collected randomly within each landscape type and soil type in the studied area. The sampling depth was 0–20 cm following the national survey, and the sampling locations were recorded using GPS. This added another 162 soil samples for all landscape types investigated in the study. Soil type data came from the 1:10,000 soil type map of 1983.

Description of soil degradation index (SDI) in space and time

Based on land degradation index (Dumanski and Piere 2000) and soil quality index (Adejuwon and Ekanade 1998), we developed a soil sample degradation index to quantify the soil degradation state. SDI is a measurement of soil degradation that takes the sample mean of a soil property as the reference value in a soil type of a landscape type, and then calculate the deviation of each soil sample to the reference value, finally calculate the weighted average of all soil properties by taking the

Table 1 Landscape categories in study area

Patch ID	Patch type	Patch type meaning
i	Residential area	Including city, town and traffic land
ii	Artificial forest	Including man-made forest and shelter belt
iii	Cropland	Area with crops such as cotton, wheat and corn
iv	Orchard land	Area with hops and grapes
v	Shrubbery	Area with shrubs densities, such as *Tamarix ramosissima, Haloxylon ammodendron*, and *Reaumuria soongorica*
vi	Saline alkali land	Areas with few natural vegetation, saline alkali grasslands, and saline alkali shrubs
vii	Grassland	Grassland with vegetation coverage more than 5%; area with natural vegetation and scattered shrubs

reference values as weights (Eq. 1). The following is the SDI equation:

$$\mathrm{SDI} = [(p_1 - p'_1)/p'_1 + (p_2 - p'_2)/p'_2 + (p_3 - p'_3)/p'_3 + \cdots + (p_n - p'_n)/p'_n]/n \tag{1}$$

where $p'_1, p'_2, \ldots, p'_n$ are measured sample means of soil property 1, 2, 3,..., n under a reference landscape type in the same soil type; p_1, p_2, ..., p_n are soil sample values of each soil property under all landscape types in the same soil type. SDI could be a positive number, or a negative number. Relative to a reference mean of a soil property of a soil type, a positive SDI indicates that the soil is improved; the higher the SDI value, the higher quality of the soil type. Conversely, a negative SDI value indicates soil degradation; the smaller the value, the more serious the soil degradation.

In the current study, considering the oasis–desert ecotone landscape structure, vegetative cover, soil type, and land exploitation history, we use soil sample mean of shrub land as a reference value in calculating SDI by Eq. 1. In many other studies, the reference type was usually chosen as nature forest (Li et al. 2003; Adejuwon and Ekanade 1998) since land exploration started from cutting forest. But in desert–oasis ecotone, exploration usually started from is the cultivation of the original desert shrub land. Hence, it is reasonable to select natural shrub land as the reference type. In order to evaluate soil quality in the same quantified factors from 1983 to 2005, soil properties selected include soil organic, available N, available P, available K, and total salt to calculate SDI. The position of sample points in 1983, 1999, 2005, from which SDI was calculated, are shown in Fig. 1: 86 points in 1983, 153 in 1999, and 162 in 2005.

Geostatistical analysis

The theoretical basis of geostatistics used in the current study was described in several studies (e.g., Campbell 1978; Holawe and Dutter 1999; Trangmar et al. 1985; Matheron 1963). The main tool in geostatistics is the variogram, which gives an idea of the spatial dependence of each point on its neighbor (Curran 1988). An important contribution of geostatistics is the assessment of the uncertainty about unsampled points, which usually takes the form of a map of the probability of exceeding critical values for soil quality (Castrignano et al. 2002). The variogram, $\gamma(h)$, can be defined as one-half the variance of the difference between the attribute values at all points separated by h as follows:

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

where $z(x)$ is a measured sample at point x, $z(x + h)$ is a measured sample at point $x_i + h$, and $N(h)$ is the number of pairs separated by lag h (Wang 1999). The SDI data were elaborated by using geostatistical tools in order to study the spatial structure and predict values of the property at unsampled locations, providing the variance of the estimated value. A method of Ordinary Kriging in ARCGIS's the geostatistical analysis module was used to make three periods (1983, 1999 and 2005) SDI maps. SDI maps were overlaid on soil type map from which the SDI distribution in different soil types was obtained. Different period digital SDI maps were superimposed (1983 + 1999, 1999 + 2005) from which the temporal–spatial changes in SDI were obtained. SDI maps were overlaid with landscape patch type maps to obtain SDI changes at different landscape patch types.

Results and discussion

Character of landscape pattern in study area

In recent decades, landscape structure changed greatly due to human activities, such as reclamation, grazing, and traffic construction, etc. Such activities, on one hand, change the land cover, and on the other hand, lead to the land degradation. Table 2 presents the change of landscape metrics in different periods (1983, 1999, and 2005). Landscape patterns in each period are shown in Fig. 2. It can be seen that (Table 2; Fig. 2), from 1983 to

Table 2 Changes of landscape patterns in the studied area

Landscape patch type	1983		1999		2005		Area change (%)	
	Area (ha)	Percent (%)	Area (ha)	Percent (%)	Area (ha)	Percent (%)	1983–1999	1999–2005
Cropland	5,658.08	35.63	6,355.2	40.02	5,333.32	33.58	12.32	−16.08
Artificial forest	145.10	0.91	198.97	1.25	986.20	6.21	37.13	395.65
Grassland	5,271.73	33.20	3,668.15	23.10	2,693.05	16.96	−30.42	−26.58
Orchard land	140.23	0.88	123.05	0.77	1,952.33	12.29	−12.25	1,487.00
Saline alkali land	2,977.65	18.75	3,668.82	23.11	3,284.25	20.68	−23.21	−10.48
Residential area	375.29	2.36	580.32	3.65	597.77	3.76	54.63	3.01
Shrubbery land	1,312.92	8.26	1,286.49	8.10	1,034.03	6.52	−2.01	−19.62

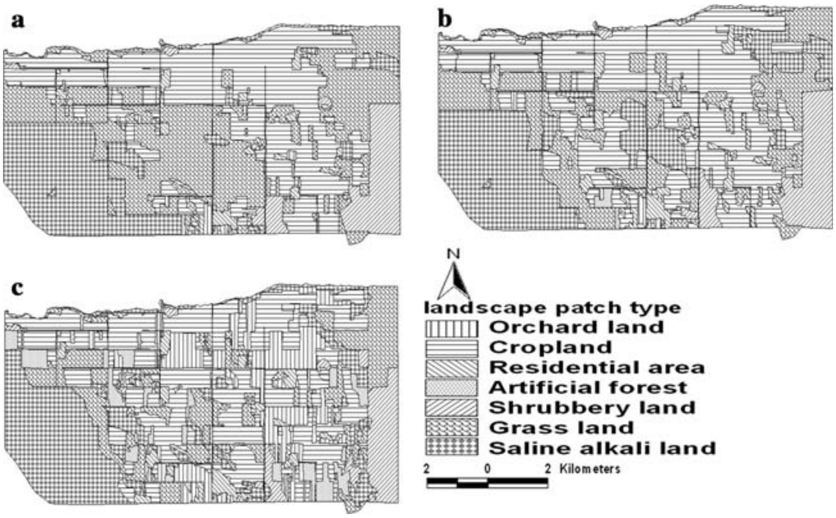

Fig. 2 Map of landscape patch types in different periods (*a* = 1983; *b* = 1999; *c* = 2005)

2005, the landscape change was mainly characterized by the increasing multiplicity and fragmentation. Areas of nature landscape, including grassland and shrub land, decreased continuously, especially the grassland area, which reduced from 33.2% in 1983 to 16.96% in 2005. Saline alkali land showed an increasing trend, 2.13% higher in 2005 than in 1983. The percentage of artificial landscape increased, which was clearly the result of intensified human activities on the landscape in the study area. At the same time, percentage of cropland increased in the first period (1983–1999) and decreased in the latter period (1999–2005).

Socioeconomic processes are the primary drives for landscape pattern changes (Jenerette and Wu 2001). Human activities have great impact on the landscape evolution, such as improvement of economic benefits or land exploitation which leads to landscape change (Lu et al. 2003). Oasis development in desert–oasis ecotone had altered the composition and configuration of the regional landscape between 1983 and 2005. Areas of artificial landscape types had increased, while areas of nature landscape types had decreased. These structural changes can affect ecological processes in various ways. Fragmentation of patches reduced landscape connectivity thereby breaking a full landscape matrix into several types of patch, and landscape diversity increased. Therefore, the change of landscape pattern induced by human activities was the key factor that resulted in the increasing of landscape diversity and the fractionizing of the landscape.

Geostatistical and statistical analysis of SDI in different landscape pattern

The geostatistical methods consider the spatio-temporal variation of soil properties as a random process depending on both the time and space (Goovaerts 1999). Geostatistics can characterize and quantify spatial variability, perform rational interpolation, and estimate the variance of the interpolated values. Geostatistical data from spatial random sampling can be used to analyze the natural phenomenon of spatial variability and spatial pattern, and the method of Geostatistical has been proved to study spatial variability and spatial pattern effectively (Li et al. 1998). In general, the variograms assumed that the data is in intrinsic stationarity and should be in normal distribution, where the variance of sample properties or variables between each sampling point is only related to their spatial separation. To ensure the data fit this criterion, one-sample Kolmogorov–Smirnov (K–S) method was used to test normal distribution in SPSS software 11.5a. The mean, standard deviation (SD), coefficient of variation (CV), the maximum value, minimum value, Skewness, Kurtosis, and K–S test value of the SDI properties in 1983, 1999, and 2005

Table 3 Results of SDI for descriptive statistics and K–S test

Time	Sample	Mean	SD	CV	Minimum	Maximum	Skewness	Kurtosis	Value of K–S
1983	86	−0.0871	0.2770	0.0909	−0.8210	0.5770	0.14	−0.47	0.93
1999	153	−0.0557	0.2482	0.0808	−1.1390	0.5300	−1.02	1.38	0.46
2005	162	0.0726	0.2990	0.08982	−0.7340	0.5650	−0.64	−0.22	0.77

are listed in Table 3. SDI values were proved to be in normal distribution in three periods, and mean and CV% is lower in 1983, 1999, and 2005 samples. The results in descriptive statistics and normal distribution test for 1983, 1999, and 2005 proved that the variograms can be directly used in the analysis of SDI spatial variability.

SDI spatial structure

Variogram of geostatistics is used to quantify the spatial variation of a regionalized variable. Experimental variogram estimator is asymptotically unbiased for any intrinsic random function. The fitted function to the experimental variogram provides the input parameters for spatial prediction by kriging to analysis variogram structure depend on the parameters of the variogram model (Wang 1999; Li et al. 1998). Theoretical variogram models include spherical model, Gaussian model, exponential model, and linear model. To select the best-fitted model by comparing each parameter of the variogram model, attempts were made to get the minimum values of Residual Sum of Squares (RSS), Range and Nugget (Co) and maximum value of Coefficient of Determination (R^2). Value of R^2 determines the actual significance when performing F-test on variogram model. If it is not significant at $\alpha = 0.01$ or 0.05 level, variogram model is not applicable.

In this study, the variogram analysis on the point soil measurements, employing standard geostatistical techniques, was performed to understand the structure and the spatial variability of the SDI patterns in space and time. The sample variograms were computed using all pairs separated by lags up to 8,900 m, and Eq. 2 was used to compute the sample variograms. Variogram models and best-fitted model parameters were given in Table 4 and Fig. 3. These were generated from the spherical model (Table 3) which was the best fitting descriptor in these data sets. Values of R^2 were higher than 0.8; RSS was small (0.0005 in 1983, 0.0001 in 1999, and 0.0002 in 2005); and similarly F-test was significant at $\alpha = 0.01$ level. All SDI showed positive nugget, which might be explained by sampling error, short-range variability, random, and inherent variability. The nugget-to-sill ratio can be used to classify the spatial dependence of properties of estimator of a model. The variable is considered to have a strong spatial dependence if the ratio is less than 25%, and has a moderate spatial dependence if the ratio is between 25 and 75%; otherwise, the variable has a weak spatial dependence (Zhang et al. 2003a, b; Chang et al. 1998; Chien et al. 1997). In our case, the nugget-to-sill ratio showed a moderate spatial dependence for SDI in 1983, 1999, and 2005, which might be attributed to the strong natural and human impact on the processes in soil in this region, especially, soil degradation and soil salinization (Gu et al. 2003). The range of influence is considered as the distance beyond which observations are not spatially dependent. Points within the range can be considered spatially autocorrelation; points outside the range are spatially independent. For these three periods, Range were smaller than 3.8 km which were within studied area (distance from north to south and east to west of the region are 19.2 and 8.8 km); these suggested that the Range is effective in the variation of SDI on the studied scale. All of these variograms have a lag of 890 m, which were in agreement with the recommendation of Webster (1985) who recommended that lags should not exceed 1/5 to 1/3 of the transect length.

Kriging of spatio-temporal changes of SDI in soil type

The spatial–temporal changes of soil properties can be modeled by multivariate spatial random processes when the soil properties are measured in a large area at few sampling times; the spatio-temporal changes of soil properties can be simplified by multivariate spatial random processes (Papritz and Flühler 1994; Sepaskhah et al. 2005; Sun et al. 2003). We used co-kriging to estimate the temporal changes of SDI in the same area. The kriging maps of the SDI in 1983, 1999, and 2005 (Fig. 4) show high-quality soils distributed in the south of the oasis area, and low-quality soil distributed in the north near the desert part. The soil degradation degree increased gradually form south to north. The nearer to the desert, the more serious the soil degradation was. In the different periods, the soil degradation degree was different among different soil types (Table 5). In the 23 years from 1983 to 2005, the degradation area of Gray Desert soil increased by 527.37 ha, which was much more serious than those of Solonchak soil and Aquert[0] soil. In this period, the soil degradation area of Solonchak soil and Aquert soil were decreased by

Table 4 Correlation parameters and F-test of theoretical variogram models of SDI

SDI	Theoretical model	Nugget	Sill	Nugget/sill	Range	Dimension	R^2	RSS	F-test
1983	Spherical	0.0350	0.0980	0.643	3.78	1.89	0.808	0.0005	34.46**
1999	Spherical	0.0478	0.0957	0.501	3.54	1.926	0.889	0.0001	127.25**
2005	Spherical	0.0415	0.0863	0.519	2.96	1.921	0.891	0.0001	123.43**

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

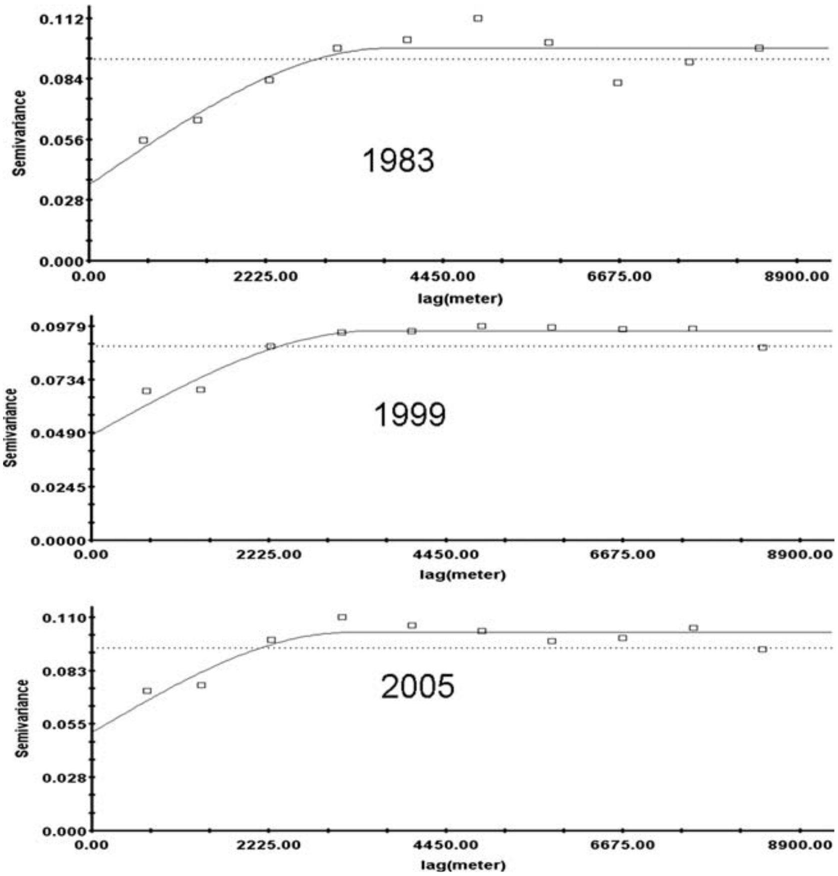

Fig. 3 Empirical and the fitted models (*lines*) of soil degradation index; *blank squares* represent the empirical semi-variograms of soil degradation index measured in 1983, 1999, and 2005

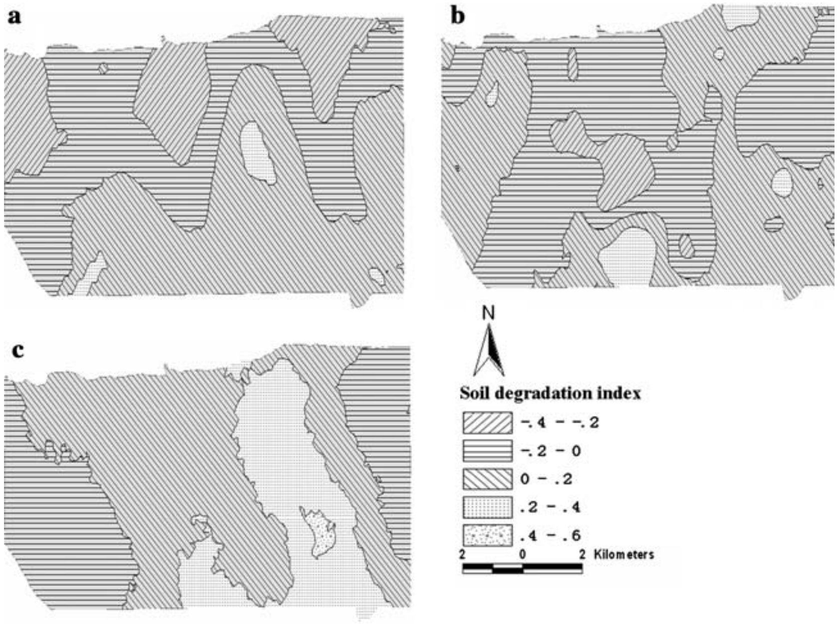

Fig. 4 Interpolated soil degradation index of the studied area in different periods (a = 1983; b = 1999; c = 2005)

3,053.93 and 1,712.40 ha, respectively. These results showed that human activities influenced soil properties not only by degrading the soil qualities, but also improving them in some cases. The soil qualities of Solonchak soil and Aquert soil were improved by human activities, while the quality of the Gray Desert soil was degraded by these activities. Although changes of land-use patterns might affect the soil properties, the impact might not be the same for different soil properties (Sabrina et al. 2004). Overall, areas of soil degradation decreased by 49.15% from 1983 to 2005, which show that human activities played an important role in ameliorating soil quality.

Dynamic patterns of soil degradation development

During the period from 1983 to 2005, the spatial change in the SDI within every landscape type indicated a dynamic variation of soil degradation development. Tables 6 and 7 show the spatial changes in the periods of 1983–1999 and 1999–2005 in soil degradation at different regional landscape types, respectively. When SDI maps superimposed on regional landscape types, the areas of SDI > 0 in landscape types show two ways of transition: one is transferring to higher class, which means soil quality improvement in the progress of land-use. Since 1983, areas of soil quality improvement in cropland and orchard land were 2,095.38 ha, and artificial forest and saline alkali land were 679.80 ha, which were mainly caused by the utilization and amelioration of Solonchak soil and Aquert soil (Table 5: in 23-year, area of Aquert soil without degradation increased by 1,712.41 ha and area of Solonchak soil without degra-

Table 5 Soil degradation areas in different soil types and in different periods

Soil type	1983		1999		2005	
	D (ha)	UD (ha)	*D* (ha)	UD (ha)	*D* (ha)	UD (ha)
Gray desert soil	2,052.47	2,414.16	2,123.75	2,342.88	2,579.84	1,886.79
Solonchak soil	3,315.09	2,601.51	2,598.96	3,317.64	261.15	5,655.45
Aquert soil	3,247.40	2,250.37	3,500.82	1,996.95	1,534.99	3,962.78
Total (ha)	8,624.96	7,266.04	8,233.53	7,657.47	4,385.98	11,505.02

D means area of soil when value of SDI < 0, *UD* means area of soil when value of SDI > 0

Table 6 The area of change of SDI between 1983 and 1999 at various landscape types

SDI	−0.4 to −0.2		−0.2 to 0			0 to 0.2			0.2 to 0.4	
	C (ha)	UC (ha)	*C* (ha)		UC (ha)	*C* (ha)		UC (ha)	*C* (ha)	UC (ha)
Cropland	1,386.75	156.08	584.12	−34.51	626.14	198.22	−1,144.52	2,071.02	−153.84	0.00
Artificial forest	24.97	30.52	29.10	0.00	46.62	31.11	−21.14	7.93	−7.58	0.00
Grassland	722.89	62.66	304.93	0.00	1,117.53	140.43	−1,288.36	8.71	−22.74	0.00
Orchard land	0.00	0.00	7.80	0.00	0.00	55.41	0.00	49.84	−10.00	0.00
Saline alkali land	458.60	0.00	949.65	0.00	600.75	255.28	−884.55	219.59	−300.40	0.00
Residential area	63.25	0.00	132.04	0.00	0.00	136.01	−134.60	107.00	−7.42	0.00
Shrubbery land	682.13	0.00	0.00	0.00	81.83	0.00	−484.98	0.00	−37.55	0.00
Total (ha)	3,338.59	320.15	2,007.64	−34.51	2,472.87	816.46	−3,958.15	2,464.09	−539.53	0.00

C means area of soil change, *UC* means area of soil unchanged

Table 7 The area of change of SDI between 1999 and 2005 at various landscape types

SDI	−0.4 to −0.2		−0.2 to 0		0 to 0.2			0.2 to 0.4	
	C (ha)	UC (ha)	*C* (ha)	UC (ha)	*C* (ha)		UC (ha)	*C* (ha)	UC (ha)
Cropland	429.29	0.00	2,582.33	101.62	1,153.98	−221.02	685.51	−82.05	77.52
Artificial forest	85.52	0.00	378.87	93.69	271.74	0.00	130.76	−2.87	22.75
Grassland	211.62	0.00	768.06	874.98	274.25	−79.95	446.31	−9.41	27.47
Orchard land	21.68	0.00	710.93	0.00	687.77	−14.95	256.14	−2.05	258.81
Saline alkali land	67.99	0.00	486.37	2,227.06	121.67	−157.34	220.52	0.00	3.30
Residential area	20.39	0.00	114.34	0.00	142.62	−76.73	168.97	−15.16	59.53
Shrubbery land	11.61	0.00	147.61	214.94	87.08	−242.59	313.73	0.00	16.47
Total (ha)	848.10	0.00	5,188.51	3,512.29	2,739.83	−792.58	2,221.94	−111.54	465.85

C means area of soil change, *UC* means area of soil unchanged dation increased by 3,053.94 ha). The other is transferring to lower class, which means that soil quality decreased in land-use process. There was about 5,401.80 ha, the area of soil degradation from 1983 to 2005. Especially in cropland and grassland, soil degradation area was larger than any other landscape patch type.

Areas of SDI < 0 in landscape patch types had a trend of increase in SDI, and decrease in the area of soil degradation from 1983 to 2005. Especially, areas of soil degradation in the 23 years from 1983 to 2005 decreased 10,382.80 ha. Among them, the decrease in the 7 years from 1999 to 2005 was only 690.96 ha. Over the whole period from 1983 to 2005, temporal changes in increasing area of soil degradation occurred only in 34.51 ha.

Conclusions

The Fubei region provides a natural laboratory to examine the relationship between changes in soil properties and landscape evolution in the desert–oasis ecotone. In the recent 23 years, the change of landscape pattern induced by human activities (e.g., land-use, land exploitation, abandoned land) was the key factor that resulted in the increasing of landscape diversity and the fractionizing of the landscape.

Soil degradation is a very complicated process involving a variety of natural processes and human economic activities. It is difficult to quantify the degree of soil degradation since the mechanism and process of soil degradation still remain random on a region scale (Sun et al. 2003). A combination of geostatistics and GIS map calculation provides a useful tool for the study of tempore-spatial changes in soil properties and landscape pattern. The spatial changes of soil degradation in different landscape of the study area were visualized with a GIS and thus showed clear spatial patterns. The levels of the differences of soil degradation were evaluated with kriging maps to show areas with significant differences. A significant increase in degree of soil degradation was observed near desert resign, and a decrease further inside the oasis. Human activities were important in ameliorating soil properties. Human activities influence on soil type of Solonchak soil and Aquert soil was to improve soil quality, while the influence on Gray Desert soil was to degrade the soil quality. In the areas of SDI lower than 0, the degree of soil degradation is weaker (10,382.80 ha of soil quality improvement and 34.51 ha of soil degradation), while in areas of SDI higher than 0, the degree of soil degradation is stronger (5,301.80 ha of soil degradation and 3,558.29 ha of soil quality improvement). Dynamic of soil degradation development was weaker where the soil quality was low, and stronger where the soil quality was high, due to both human activities and natural processes. The result of the current study demonstrated that a combination of geostatistics and GIS map calculation provides a useful tool for quantifying and characterizing the dynamic change patterns of soil degradation.

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References

Adejuwon JO, Ekanade OA (1988) Comparison of soil properties under different land use types in a part of the Nigerian concoa belt. Catena 15:319–331

Barros E, Grimaldi M, Sarrazin M, Chauvel A (2004) Soil physical degradation and changes in macrofaunal communities in Central Amazon. Appl Soil Ecol 26:157–168

Bocco G, Mendoza M, Velazquez A (2001) Remote sensing and GIS-based regional geomorphological mapping: a tool for land use planning in developing countries. Geomorphology 39:211–219

Campbell JB (1978) Spatial variation of sand content and ph with in single contiguous delineation of two soil mapping units. Soil Sci Soc Am J 42:460–464

Castrignano A, Maiorana M, Fornaro F, Lopez N (2002) 3D spatial variability of soil strength and its change over time in a durum wheat field in Southern Italy. Soil Tillage Res 65:95–108

Chang YH, Scrimshaw MD, Emmerson RHC, Lester JN (1998) Geostatistical analysis of sampling uncertainty at the Tollesbury Managed Retreat site in Black water Estuary, Essex, UK: kriging and cokriging approach to minimize sampling density. Sci Total Environ 221:43–57

Chen W, Xiao D, Li X (2002) Classification, application, and creation of landscape indices. Chin J Appl Ecol 13(1):121–125

Chien YJ, Lee DY, Guo HY, Houng KH (1997) Geostatistical analysis of soil properties of mid-west Taiwan soils. Soil Sci 162:291–297

Curran PJ (1988) The semi-variogram in remote sensing: an introduction. Remote Sens Environ 24:493–507

Del Valle HF, Elissalde NO, Gagliardini DA, Milovich J (1998) Status of desertification in the Patagonian Region: assessment and mapping from satellite imagery. Arid Soil Res Rehabil 12:95–122

Dumanski J, Pieri C (2000) Land quality indicators: research plan. Agric Ecosyst Environ 81:93–102

Fairhead J, Scoones I (2005) Local knowledge and the social shaping of soil investments: critical perspectives on the assessment of soil degradation in Africa. Land Use Policy 22:33–41

Feddema JJ (1999) Future African water resources: interactions between soil degradation and global warming. Clim Change 42:561–596

Fu BJ, Liu ShL, Lu YH, et al (2003) Comparing the soil quality changes of different land uses determined by two quantitative methods. J Environ Sci 15(2):167–172

Goovaerts P (1999) Geostatistics in soil science: state-of-the-art and perspectives. Geoderma 89:1–45

Gu FX, Zhang YD, Pan XL (2003) Interaction of land use change and spatial dynamics of soil moisture and salinity in and temporal arid land. Acta Geogr Sin 58(6):845–853

Han DL (2001) Artificial Oases of Xinjiang. Chinese Environmental Sciences Press, Beijing, pp. 21–32

Holawe F, Dutter R (1999) Geostatistical study of precipitation series in Austria: time and space. J Hydrol 219:70–82

Jamalam L, Tamaluddin S, Hiroyo N, et al (1998) Deterioration of soil fertility by land use changes in South Sumatra, Indonesia: from 1970 to 1990. Hydrol Process 12:2003–2013

Jenerette GD, Wu JG (2001) Analysis and simulation of land-use change in the central Arizona-Phoenix region, USA. Landsc Ecol 16:611–626

Jia BQ, Zhang ZhQ, Ci LJ (2004) Oasis land-use dynamics and its influence on the oasis environment in Xinjiang, China. J Arid Environ 56:11–26

Koning N, Smaling E (2005) Environmental crisis or ‘lie of the land’? The debate on soil degradation in Africa. Land Use Policy 22:3–11

Li HB, Wang ZhQ, Wang QCh (1998) Theory and methodology of spatial heterogeneity quantification. J Appl Ecol 9(6):651–657

Li YB, Gao M, Wei ChF (2003) Effects of land use on soil quality in Karst Hilly Area. J Mt Sci 21(1):41–49

Lu L, Li X, Cheng GD (2003) Landscape evolution in the middle Heihe River Basin of north-west China during the last decade. J Arid Environ 53:395–408

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

Melegy AA (2005) Relationship of environmental geochemistry to soil degradation in Helwan catchment, Egypt. Environ Geol 48:524–530

Meyer WB, Turner BL (1992) Human population growth and global land-use/cover change. Annu Rev Ecol Syst 23:39–61

Pan XL (2001) A preliminary study on the stability of oasis ecosystem in arid area. Quaternary Sci 21(4):345–350

Pan XL, Chao JP (2003) Theory of stability, and regulation and control of ecological system in oasis. Glob Planet Change 37:287–295

Papritz A, Flühler H (1994) Temporal change of spatially autocorrelated soil properties, optimal estimation by ckriging. Geoderma 62:29–43

Paza JD, Sánchezb J, Visconti F (2006) Combined use of GIS and environmental indicators for assessment of chemical, physical and biological soil degradation in a Spanish Mediterranean region. J Environ Manage 79:150–162

Rodrıguez AR, Mora JL, Arbelo C, Bordon J (2005) Plant succession and soil degradation in desertified areas (Fuerteventura, Canary Islands, Spain). Catena 59:117–131

Sabrina B, Paolo DZ, Maria B (2004) Characterisation of a reference site for quantifying uncertainties related to soil sampling. Environ Pollut 127:131–135

Sepaskhah AR, Ahmadi SH, Shahbazi AR (2005) Geostatistical analysis of sorptivity for a soil under tilled and no-tilled conditions. Soil Tillage Res 83:237–245

Sun B, Zhou Shl, Zhao QG (2003) Evaluation of spatial and temporal changes of soil quality based on geostatistical analysis in the hill region of subtropical China. Geoderma 115:85–99

Sveistrupa TE, Haraldsenb TK, Langohrc R, Marcelinoc V, Kværner J (2005) Impact of land use and seasonal freezing on morphological and physical properties of silty Norwegian soils. Soil Tillage Res 81:39–56

Trangmar BB, Yost RS, Uehara G (1985) Apply of geostatistics to spatial studies of soil properties. Adv Agron 38:44–94

Wang ZhQ (1999) Geostatistics and its application in ecology. Chinese Science Press, Beijing, pp. 150–189

Webster R (1985) Quantitative spatial analysis of soil in the field. Adv Soil Sci 3:1–70

Zhang H, Wu JW, Zheng QH, Yu YJ (2003a) A preliminary study of oasis evolution in the Tarim Basin, Xinjiang, China. J Arid Environ 55:545–553

Zhang ShJ, He Y, Fang H (2003b) Spatial variability of soil properties in the field based on GPS and GIS. Trans CSAE 19(2):39–45