Environ Earth Sci
DOI 10.1007/s12665-014-3171-3

ORIGINAL ARTICLE

Changes in soil quality in the critical area of desertification surrounding the Ejina Oasis, Northern China

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Received: 17 July 2013 / Accepted: 19 February 2014
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Abstract The critical area around an oasis where desertification occurs determines the ecological security and stability of the oasis. In this study, the soil quality in the critical area of desertification surrounding the Ejina Oasis was evaluated by using a soil quality index (SQI). The soil surface moisture content was related to vegetation cover; it remained high to a distance of 600 m from the oasis, decreased at distances of 600 to 1,700 m, and then gradually increased to a distance of 1,900 m. The sand content and soil bulk density gradually decreased to a distance of 300 m from the oasis; however, the silt and clay contents, soil pH, soil organic matter (SOM), and total and available nutrients increased away from the oasis. From 300 to 1,900 m, the sand content and soil bulk density increased; however, values of other soil properties decreased. Thus, a distance of 300 m from the edge of the oasis represents an obvious demarcation point for soil properties. SOM and the clay content were the key factors that determined soil quality. SQI increased from 0.284 at the edge of the oasis to 0.793 at 300 m, decreased to 0.262 at 1,400 m, and then decreased further to 0.142 at 1,900 m. SQI was lowest at distances of 1,400–1,900 m. The area beyond 300 m from the oasis was most vulnerable to desertification, and is thus the area where desertification control measures should be strengthened.

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Keywords Soil quality index (SQI) · Soil physical properties · Soil chemical properties · Principal components analysis · Critical area of desertification · Ejina Oasis

Introduction

Oases are a unique intrazonal landscape in the world's arid and semi-arid regions (Wang et al. 2007a). The peripheral regions around an oasis are in direct contact with areas of primary desert, where an ecological "fault zone" arises, with lower environmental quality than in either the desert or the oasis (Jia et al. 2001, 2002). Interactions in this area lead to rapid material recycling, energy conversion, and transmission of information between the desert and oasis ecosystems (Zhao et al. 2001). The ecological environment of such peripheral regions is fragile, sensitive to disturbance, and highly variable. Because this area is the region near an oasis that is most vulnerable to desertification, it can be referred to as the "critical area of desertification". This area plays an important role in ensuring the ecological security and stability of the oasis (Pan 2001; Wang et al. 2007a).

The evolution of oases in arid and semi-arid regions is influenced by two opposite processes: oasification (an increase in the size or stability of the oasis) and desertification (Zhang et al. 2003; Jia et al. 2004). The rate of oasis desertification depends on the desertification that develops in the critical area (Su et al. 2007). The critical area typically contains a high concentration of nebkha dunes (also referred to as nabkhas, coppice dunes, or vegetated dunes), composed of wind-borne sediment trapped within or around plants. Nebkha dunes have ecological functions, such as sand fixation and protection of biodiversity, as well

Published online: 13 March 2014

as water and nutrition enrichment (Du et al. 2010). However, nebkhas are an unstable geomorphologic feature, and if erodible sediments become exhausted, the surfaces of nebkhas become degraded (Seifert et al. 2009). Therefore, the occurrence and development of desertification in the critical area are closely related to the evolution of nebkha dunes. Nebkha evolution is controlled mainly by the characteristics of the vegetation community, wind activity, and local hydrogeological conditions (Tengberg 1995; El-Bana et al. 2002; Yue et al. 2005). For example, nebkhas may become degraded in response to a lowering of the groundwater table, as most plant roots can not acquire deterioration of moisture condition, leading to the death of the vegetation (Lang et al. 2013). In turn, this leads to the degradation and collapse of the nebkhas. Degradation of the nebkhas results in destruction of the crust on the soil surface and reduces vegetation cover (Du et al. 2010). Wind activity is important in the transport and accumulation of the sediment that makes up nebkhas; however, wind also erodes nebkha surfaces when vegetation cover is below a certain threshold (14 % in most regions) (Lang et al. 2013). Therefore, one consequence of nebkha evolution and an obvious visual indicator of nebkha degradation is spatial variations in vegetation communities (Li et al. 2008). Soil is the basic substance that sustains vegetation growth, and is therefore one of the main environmental factors that affect the composition and coverage of vegetation communities (Robertson et al. 1993; Jafari et al. 2004). The evolution of plant communities is governed by interactions between plants and the soil (Zuo et al. 2009). The process of vegetation degradation is often accompanied by declining soil quality, which inhibits the growth and development of plants (Jiao et al. 2009). Thus, in the present study, a quantitative analysis of soil quality was performed to determine the extent of desertification in the critical area.

Soil quality represents the capacity of a specific kind of soil to sustain biological productivity; to accommodate, degrade, and purify pollutants; to maintain ecological balance; to promote plant and animal health; and to support human health and habitation (Doran and Safley 1997). Soil quality is a complex parameter that is affected jointly by soil physical, chemical, and biological properties, and that reflects the processes that lead to the formation of these soil properties (Schoenholtz et al. 2000; Nortcliff 2002). The objective of soil quality assessment is to understand the changes that occur in soil quality, and the impact of management measures on soil quality, by studying the soil's physical and chemical properties (Adolfo et al. 2007). From the perspective of protecting oases against degradation and ensuring sustainable utilization of the soil, it is necessary to protect or improve soil quality. The critical area of desertification in the peripheral regions around an oasis has critical threshold characteristics, and is therefore a region in which soil quality is particularly important (Zhao et al. 2001). Quantitative identification of the critical conditions for desertification, based on an assessment of soil quality, and using this knowledge to control or predict desertification, are important problems both from scientific and land management perspectives. They require insights from ecology, geography, soil science, hydrology, and other disciplines. However, in recent years, numerous intensive studies have focused on the spatial heterogeneity of vegetation characteristics and soil properties (Ma et al. 2009; Qiu et al. 2010, 2011; Wang et al. 2007a, b), but very few have focused on the comprehensive quantitative studies of soil quality changes in the critical area of desertification. So the significant additional research is necessary to understand the evolution of soil quality in this area.

The Ejina oasis is a typical hyper-arid desert oasis in the lower reaches of the Heihe River in northwestern China (Fig. 1). It is also a natural ecological screen that protects the Hexi Corridor region and parts of northwestern and northern China from sand dust. In recent decades, the combined effects of a continuous decrease in the discharge of the Heihe River, unsustainable growth of human and animal populations, increased socioeconomic activity, and climatic warming have caused a marked deterioration of the ecological environment of the oasis. The size of the oasis is decreasing and its ecological function is declining, resulting in a series of ecological and environmental problems, including lowering of the groundwater table, the degeneration of vegetation, natural oasis withering, land desertification due to rapid development, the sand source becoming exposed in the oasis interior, and degradation of the oasis due to sandstorms. With the worsening of the ecological environment of the Ejina Oasis, nebkhas in the ecotone between the oasis and desert may become degraded, leading to the fixed dunes becoming semi-mobile or mobile. Given that activation of fixed dunes would cause desertification of the critical area, this topic has attracted increasing attention from researchers and land managers.

This study examined the soil properties in the critical area of desertification in the Ejina Oasis, and assessed their relative importance in determining soil quality. The objectives of this research were to: (1) investigate the causes of the degradation, (2) reveal the evolution of soil quality in the desert–oasis ecotone, and (3) provide an empirical and theoretical basis for further study on the critical condition of oasis desertification, to improve protection of the oasis and support ecosystem management in the critical area of desertification. The results are expected to have high scientific significance both from a theoretical perspective and from the perspective of protection and restoration of the ecological environment of the oasis.

Materials and methods

Study area

The Ejina Oasis (Fig. 1) lies in the northwestern part of China's Inner Mongolia Autonomous Region, in the lower reaches of the Heihe River (40°20′N–42°41′N, 97°36′E–102°08′E; elevation, 900–1,100 m a.s.l.). The oasis is bordered by the Badain Jaran Desert to the south and east, by the Dingxin Basin of Gansu Province to the southwest, by the Mazong Mountains to the west, and by the border between China and Mongolia to the north. The total area of the oasis is 5.99×10^4 km^2. The region has a typical continental arid climate. Long-term climate data (from 1957 to 2011) recorded at the Ejina Meteorological Station indicate a mean annual temperature of 8.77 °C, and mean maximum and minimum temperatures in July and January of 26.3 and −12.2 °C, respectively. The mean annual precipitation is <39 mm, of which 84 % falls during the growing season from May to September; the mean annual pan-evaporation is greater than 3,390 mm, which is much higher than the annual precipitation. The mean annual wind velocity is 3.7 m s^{-1}, and the mean annual number of gale days (wind speed >8 m s^{-1}) is around 70.

The zonal soil types in the area are grey desert soils and grey–brown desert soils; however, there are also saline-alkaline soils and swamp soils in the lake basins and lowlands. The main vegetation species are xerophilous arbors, shrubs, and grasslands with high tolerance of saline and alkaline conditions, and these are located mainly along the banks of the Ejina River and in lacustrine plains. The main trees are *Populus euphratica* Oliv. and *Elaeagnus angustifolia* L. The main shrubs are *Tamarix ramosissima* Ledeb. and *Haloxylon ammodendron* (C.A. Mey.) Bge., followed by *Lycium ruthenicum* Murr., *Nitraria tangutorum* Bobr., and *Alhagi sparsifolia* Shap. ex Kell. et Shap. Herbaceous vegetation is dominated by *Sophora alopecuroides* L., *Phragmites communis* Trin., *Achnatherum splendens* (Trin.) Nevski, and *Peganum harmala* L.

Soil sampling

The field sampling site was located in the northeastern part of the Ejina Oasis (Fig. 1), in the Badao Qiao area about 22 km east of Dalaikubu Town, the capital of Ejina. Badao Qiao lies near the border of the Ejina Oasis, adjacent to the Badain Jaran Desert. The region is a critical area for desertification control and provides a good example of a typical oasis–desert ecotone. The total area of the sampling site is 38 ha (1,900 m from west to east and 200 m from south to north). The natural vegetation in the study area is primarily *Nitraria tangutorum*, *Tamarix ramosissima*, and

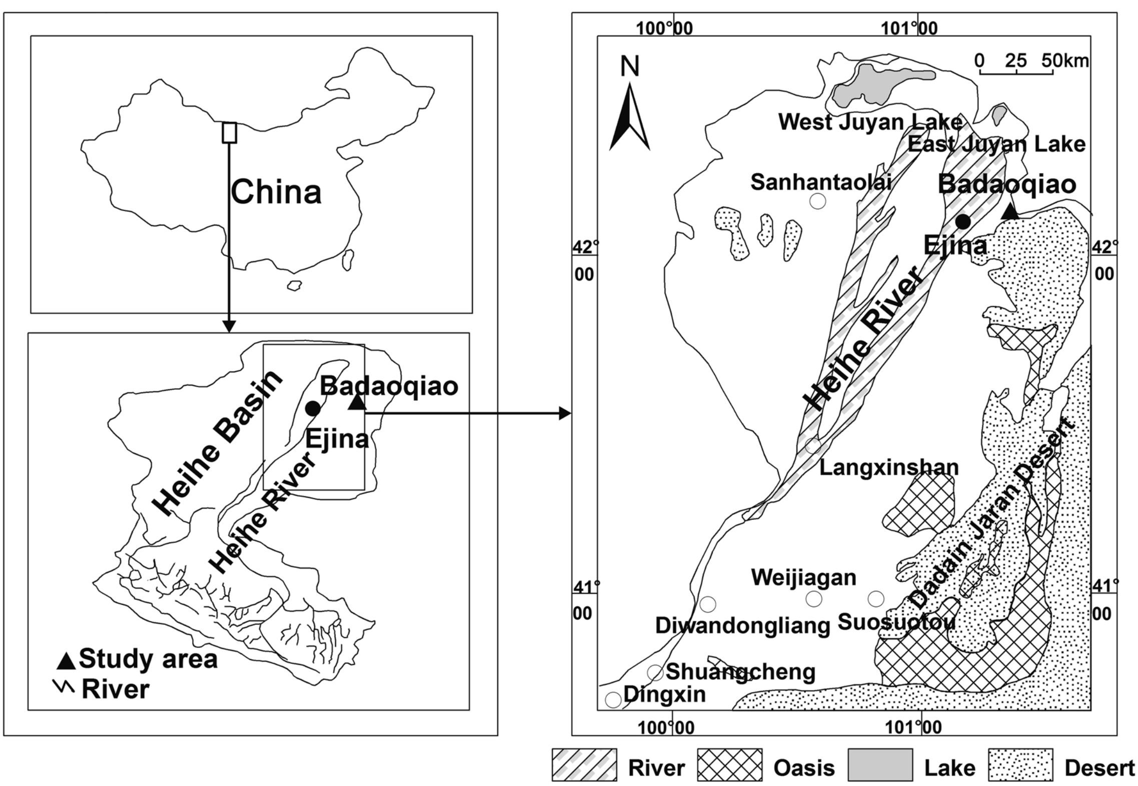


Fig. 1 Location of the study area in China

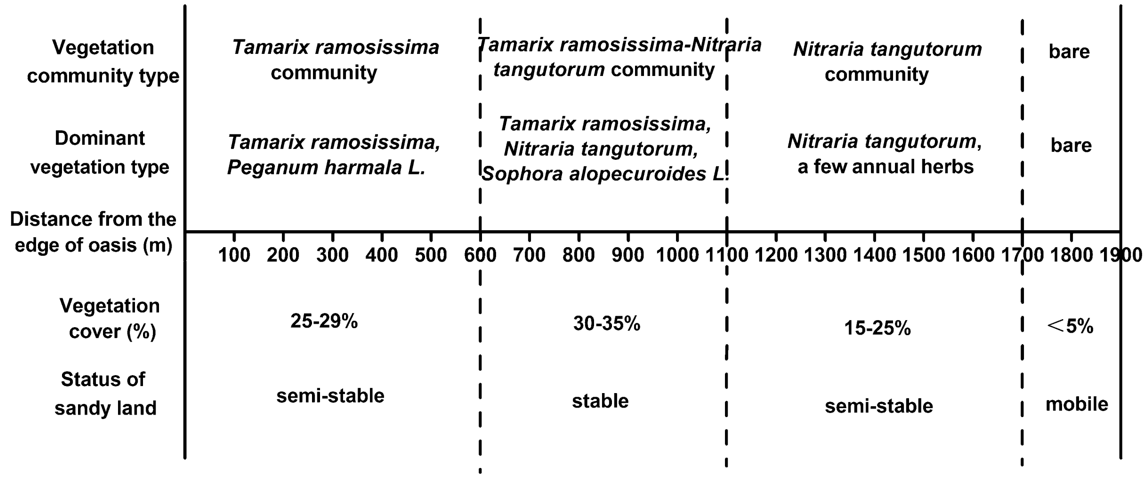


Fig. 2 Spatial trends in the vegetation and surface characteristics in the critical area of desertification

Peganum harmala L. The vegetation cover shows a continuous gradient in the sampling area, decreasing from west to east (Fig. 2).

The field research was based on linear transects established in mid-August of 2012, during the most vigorous period of plant growth. Three parallel sampling lines were established, spaced 100 m apart and oriented south–north. Each line started at the edge of the oasis and ended 1,900 m from the edge. Along each line, 20 sampling points were established; each sampling point was located 100 m from the next, oriented west–east, making a total of 60 sampling points. At each sampling site, a composite sample of about 2 kg of soil was collected from 0 to 20 cm depth within a 3 m radius of the plot center. The samples were stored in sealed plastic bags until analysis. Three additional soil samples were obtained at the same depth using a cutting ring (volume 100 g/cm^3) to measure the bulk density. Soil samples were air-dried and hand-sieved through a 2 mm screen to remove roots and other debris. A portion of each air-dried sample was finely ground to pass through a 0.25 mm sieve before chemical analysis.

Soil analysis

Soil water content was measured by drying the soil for 8 h at 105 °C to constant weight before weighing. The soil particle-size distribution was determined using the pipette method in a sedimentation cylinder, using sodium hexametaphosphate as the dispersing agent (Gee and Bauder 1986). Soil pH was determined in a soil–water suspension at a soil/water ratio of 1:5 (w/w), and was measured with a glass pH electrode. Soil chemical properties were determined following standard laboratory methods. Soil organic matter (SOM) was determined by the Walkley–Black $K_2Cr_2O_7$–H_2SO_4 oxidation method (Nelson and Sommers 1982). Total nitrogen (total N) was determined using the semi-micro Kjeldahl procedure (UDK140 Automatic Steam Distilling Unit, Automatic Titroline 96, Italy) (ISSCAS 1978), and total phosphorus (total P) was determined using a UV-2450 spectrophotometer (Shimadzu, Kyoto, Japan) after H_2SO_4–$HClO_4$ digestion (ISSCAS 1978). Available nitrogen (Avail. N) was determined using the alkaline diffusion method (ISSCAS 1978), available phosphorus (Avail. P) was determined using the Bray method (ISSCAS 1978), and available potassium (Avail. K) was determined by means of flame spectrometry, after extraction with 1 M NH_4OAc (ISSCAS 1978).

Data analysis

All statistical analyses were carried out using SPSS 17.0 software for Windows. One-way ANOVA was used to compare the soil properties of the different sampling lines, followed by least-significant-difference tests when the ANOVA results revealed a significant difference. Principal components analysis (PCA) was applied to identify the most important soil parameters in the critical area of desertification. For all analyses, statistically significant differences were set at $P < 0.05$.

Results

Soil physical properties

Soil water

The soil water content to a depth of 20 cm reached a maximum value at 400 m from the edge of the oasis, and a minimum value at 1,600 m (Fig. 3). The soil water

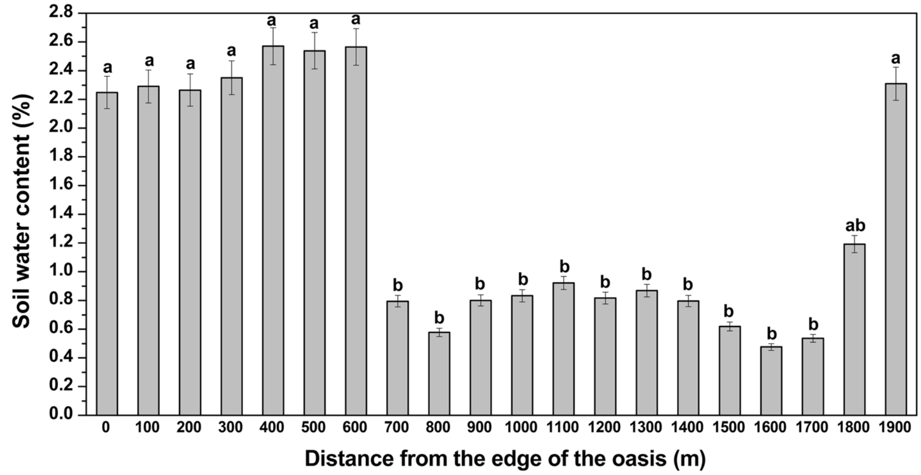


Fig. 3 Changes in soil water content to a depth of 20 cm in the critical area of desertification (*bars labeled with the same letter* are not significantly different at $P < 0.05$.)

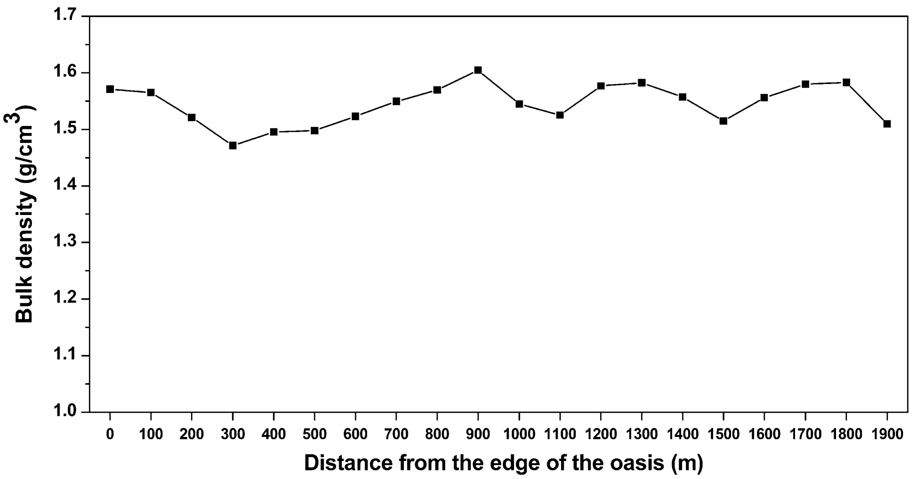


Fig. 4 Changes in soil bulk density in the critical area of desertification

content along the transect can be divided into three sections within which soil water content did not differ significantly: from 0 to 600, 600 to 1,700, and 1,700 to 1,900 m. The soil water contents from 0 to 600 m and from 1,700 to 1,900 m were significantly higher than those from 600 to 1,700 m.

Bulk density

The soil bulk density can be divided into three sections: 0–300, 300–900, and 900–1,900 m (Fig. 4). It decreased to 1.47 g/cm^3, its minimum value, at 300 m, then increased to a maximum (1.60 g/cm^3) at 900 m; subsequently fluctuated between 1.51 and 1.58 g/cm^3 without a irregular trend from 900 to 1,900 m.

Particle size distribution

The sand content exceeded 66 % along the entire transect (Fig. 5). The clay content ranged between 3.2 and 5.3 %, and did not change significantly with increasing distance from the oasis. The silt content ranged from 1.0 to 27.7 %. The sand and silt contents can be divided into two sections: from 0 to 300 m, where sand contents decreased rapidly while silt contents increased, and from 300 to 1900 m, where the opposite trend occurred. Therefore, the soil texture became finer with increasing distance from the edge of the oasis to 300 m, and then became coarser at greater distances from the edge of oasis.

Soil chemical properties

pH

Soil pH is an important factor that affects nutrient availability, and therefore determines nutrient uptake by plants (Li et al. 2007). Spatial trends in soil pH can be divided into two sections from the edge of the oasis to the desert (Fig. 6): from 0 to 300 m, pH increases; and from 300 to 1,900 m, pH decreases.

Fig. 5 Changes in the soil particle size distribution in the critical area of desertification

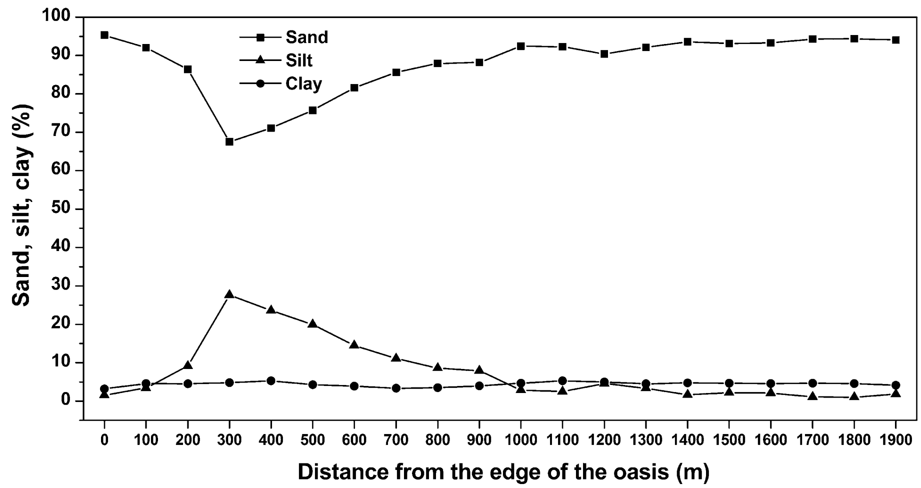
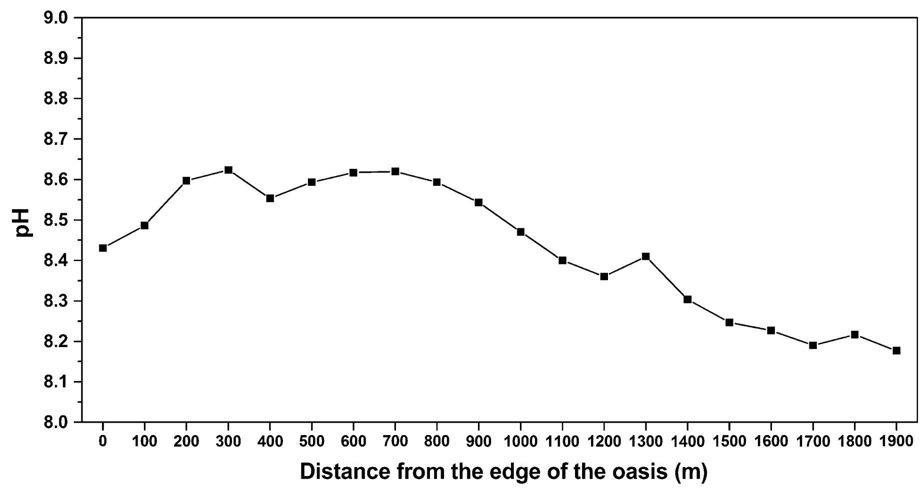


Fig. 6 Changes in soil pH in the critical area of desertification



Soil organic matter, total N, and total P

SOM is both a source of minerals and organic plant nutrients, and an important factor in improving the soil's structure, water-retention capacity, and biological activity (Wang et al. 2012). The SOM content determines a soil's nutrient storage and supply of available nutrients, and therefore controls soil fertility (Tate 1987; Tiessen et al. 1994). SOM content is therefore an important indicator of soil quality (Lal 2002). Figure 7 shows that SOM increased with increasing distance from the edge of the oasis, reaching a maximum at 300 m and then declining steadily. Soil N and P are mainly provided by the decomposition of SOM, so total N and total P followed the same pattern as each other, reaching maximum values at 300 m from the edge of the oasis.

Available nutrients

The levels of available nutrients limit the plant's ability to take up nutrients to support growth; these levels are also affected by soil properties. Figure 7 shows that available N, P, and K followed the same trends as SOM and total N and P, increasing from the edge of the oasis to a maximum at a distance of 300 m, decreasing thereafter.

Analysis of soil quality

Calculation of membership function values for soil quality indicators

Twelve factors (soil water content, bulk density, pH, SOM, total N, total P, Avail. N, Avail. P, Avail. K, and the sand, silt, and clay contents) were selected as soil quality indicators. Because these parameters have different units, it was necessary to standardize their values before calculating a soil quality index (SQI). To perform this calculation, the membership function values were first determined for each parameter to produce a range of values between 0 and 1 (Table 1). Under these conditions, the greater the membership function value of the indicator, the better the soil quality indicator (Andrews et al. 2002). According to the

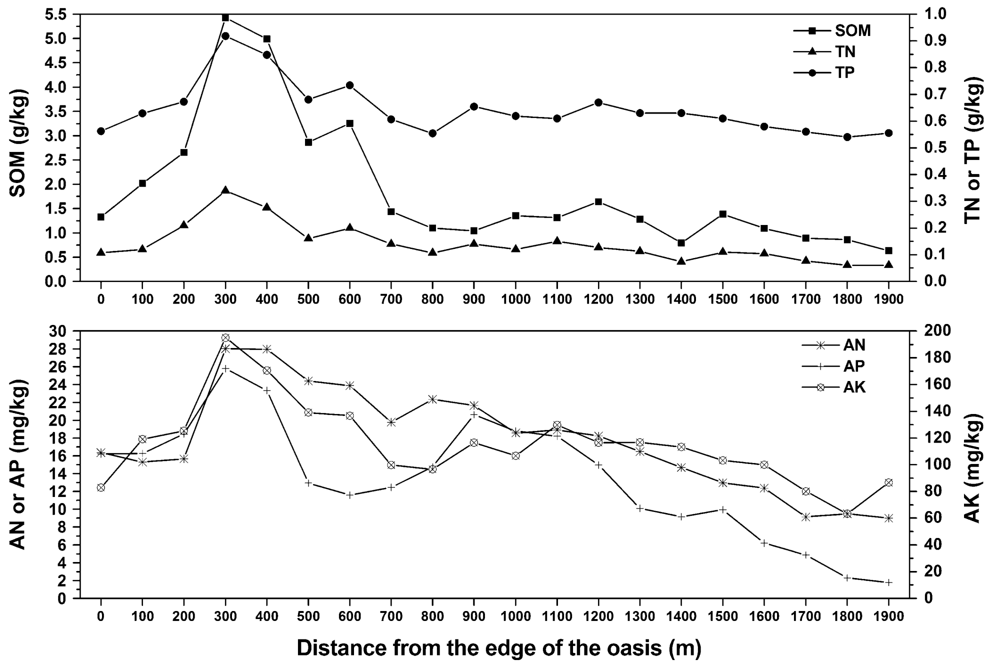


Fig. 7 Changes in soil organic matter (SOM), total nutrients (TN, TP), and available nutrients (AN, AP, and AK) in the critical area of desertification

sign (negative or positive) of indicator's factor loading in PCA, the type of membership function distribution was identified. In this study, soil bulk density and sand content were modeled using a D-type distribution function (Eq. 2), and the other parameters were modeled using an L-type distribution function (Eq. 1):

$$[Q(x_i) = (x_{ij} - x_{i\min}) \div (x_{i\max} - x_{i\min})] \quad (1)$$

$$[Q(x_i) = (x_{i\max} - x_{ij}) \div (x_{i\max} - x_{i\min})] \quad (2)$$

where $Q(x_i)$ is the membership function value for soil quality indicator i, x_{ij} is the measured value of the ith indicator at distance j (j = 0, 100, 200, 300, …, 1,900) m from the edge of the oasis, and $x_{i\max}$ and $x_{i\min}$ are the maximum and minimum measured values of the ith soil quality indicator, respectively (Zheng et al. 2010).

Principal components analysis of soil quality

Because of the large number of indicators and the significant correlations among them, the statistical data overlapped to some extent. Therefore, PCA was used to reduce the total number of variables to a smaller number of uncorrelated composite components that could explain the majority of the variance through linear combinations that minimized the loss of original information (Sharma 1996; Anderson 2003). First, the original data as described in the previous section were standardized, and the eigenvalues were computed for the correlation matrix. Second, the contribution of each principal component (PC) to the total variance (Table 2) was computed to select the combination of PCs that accounted for more than 85 % of the total variance. On this basis, the PCA identified three PCs with a cumulative contribution of 90.22 %: the first, second, and third PCs accounted for 68.90, 12.67, and 8.65 % of the total variation, respectively.

The SOM, Total N, Total P, Avail. K, and silt content had large positive factor loadings (>0.94) and sand content had a large negative factor loading (<−0.94) for PC1 (Table 2), suggesting that this PC represents soil fertility. For PC2, pH had a large positive factor loading (0.594) and clay content had a large negative factor loading (−0.879), suggesting that these parameters represent the soil structure. For PC3, soil water content had a large negative factor loading (−0.665), indicating that PC3 represents water availability.

Because of the differences among the soil quality factors, it is necessary to determine the weighting of each factor. The communality of each evaluation factor was calculated, and the weighting value for each factor equaled the proportion of the sum of the communalities accounted for by the factor's communality (Mao et al. 2010). The communality of each factor, equaling the sum of squares of the factor's loading, was converted to a value between 0 and 1.

Calculation of a soil quality index

To summarize the soil quality based on the parameters identified by the PCA, the value of each parameter was

Table 1 Membership function values for the soil quality indicators in the critical area of desertification

Distance from the edge of the oasis (m)	Soil water content	Bulk density	pH	SOM	Total N	Total P	Avail. N	Avail. P	Avail. K	Sand content	Silt content	Clay content
0	0.846	0.643	0.568	0.144	0.167	0.059	0.386	0.600	0.149	0.000	0.009	0.000
100	0.866	0.143	0.697	0.289	0.214	0.235	0.331	0.603	0.425	0.115	0.042	0.665
200	0.854	0.143	0.947	0.423	0.536	0.348	0.350	0.693	0.472	0.316	0.143	0.617
300	0.895	0.286	1.008	0.999	1.000	0.995	1.000	1.000	1.000	0.990	0.470	0.796
400	1.000	0.643	0.848	0.908	0.774	0.810	0.996	0.897	0.815	0.861	0.399	1.000
500	0.985	0.286	0.939	0.466	0.357	0.370	0.809	0.464	0.576	0.696	0.335	0.522
600	0.997	0.143	0.992	0.547	0.500	0.510	0.782	0.408	0.557	0.486	0.237	0.343
700	0.150	0.143	1.000	0.168	0.286	0.177	0.566	0.444	0.278	0.344	0.177	0.075
800	0.047	0.571	0.939	0.098	0.345	0.037	0.700	0.540	0.253	0.262	0.133	0.152
900	0.153	0.429	0.826	0.086	0.286	0.300	0.664	0.784	0.405	0.253	0.121	0.359
1,000	0.169	0.000	0.659	0.150	0.214	0.207	0.503	0.708	0.329	0.100	0.033	0.694
1,100	0.211	0.214	0.500	0.143	0.321	0.183	0.519	0.684	0.506	0.107	0.026	0.994
1,200	0.161	0.357	0.409	0.211	0.239	0.341	0.485	0.549	0.405	0.171	0.062	0.866
1,300	0.186	0.571	0.523	0.135	0.190	0.238	0.392	0.346	0.405	0.111	0.041	0.636
1,400	0.151	0.714	0.280	0.034	0.048	0.237	0.299	0.307	0.380	0.059	0.011	0.729
1,500	0.067	1.000	0.152	0.157	0.179	0.184	0.208	0.340	0.303	0.075	0.020	0.699
1,600	0.000	0.714	0.106	0.096	0.155	0.105	0.176	0.184	0.278	0.071	0.020	0.675
1,700	0.027	0.571	0.023	0.054	0.060	0.053	0.007	0.129	0.127	0.036	0.001	0.703
1,800	0.341	0.286	0.083	0.048	0.000	0.000	0.025	0.021	0.000	0.031	0.000	0.670
1,900	0.875	0.214	0.000	0.001	0.000	0.041	0.000	0.000	0.177	0.043	0.014	0.442

Table 2 Factor loadings and indicator weightings for the 12 soil quality factors in the PCA

Factor	PC1	PC2	PC3	Communalities	Weight
Soil water content	0.622	−0.004	−0.665	0.829	0.077
Bulk density	−0.684	0.392	0.410	0.791	0.073
pH	0.748	0.594	0.081	0.919	0.085
SOM	0.962	−0.140	−0.097	0.954	0.088
Total N	0.965	−0.039	0.076	0.939	0.087
Total P	0.942	−0.196	0.097	0.935	0.086
Avail. N	0.883	0.312	0.201	0.918	0.085
Avail. P	0.768	0.215	0.425	0.817	0.075
Avail. K	0.942	−0.174	0.167	0.945	0.087
Sand content	−0.954	−0.019	0.079	0.916	0.085
Silt content	0.946	0.083	−0.106	0.913	0.084
Clay content	0.216	−0.879	0.361	0.951	0.088
Eigenvalue	8.268	1.521	1.038	–	–
% of total variance	68.901	12.671	8.652	–	–
Cumulative (%)	68.901	81.572	90.224	–	–

multiplied by its associated weighting, as follows (Wang et al. 2001; Fu et al. 2004):

$$[\mathrm{SQI}_j = \sum_{i=1}^{n} W_i \times Q(x_{ij})] \quad (3)$$

where n was the number of evaluation factors (i.e., the 12 soil indicators), W_i was the weighting of the ith factor in the PCA (Table 2), and $Q(x_{ij})$ was the membership function value of the ith factor at distance j ($j = 0$, 100, 200, 300,…,1,900) m from the edge of the oasis.

The weighting of each evaluation factor reflects the importance of that factor in determining the soil quality (Chaudhury et al. 2005). This result suggests that the order of importance of each factor was as follows: (SOM, clay) > (total N, Avail. K) > Total P > (pH, Avail. N, Sand) > Silt > Soil water > Avail. P > bulk density. This

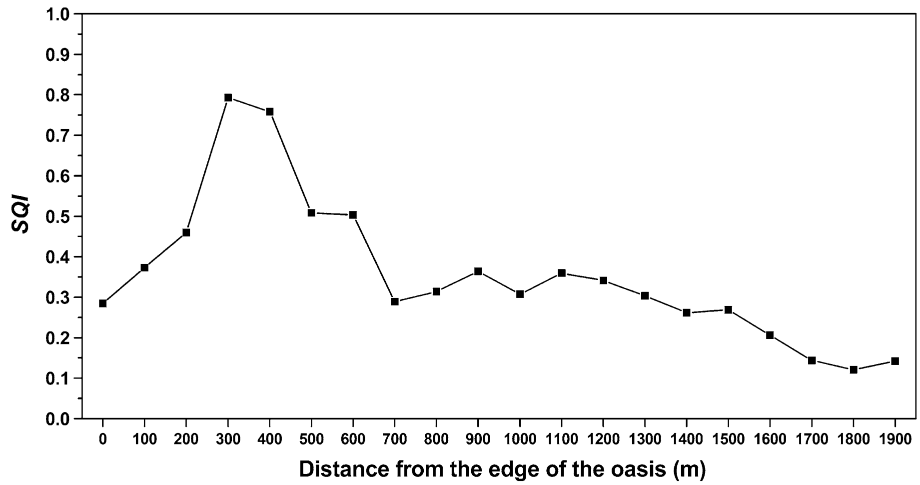


Fig. 8 Changes in the soil quality index (SQI, Eq. 3) in the critical area of desertification

result shows that SOM and the clay content are the key indicators that determined the changes in soil quality from the edge of the oasis to the desert.

Moving from the edge of the oasis to the desert, the change in SQI can be divided into two sections (Fig. 8): SQI increased rapidly to a distance of 300 m from the edge of the oasis, and then decreased, with the most rapid decrease occurring between 300 and 700 m and a gradual decrease between 700 and 1,900 m.

Discussion and conclusions

Previous research in the Minqing Oasis northern China (Jia et al. 2001, 2004), with similar characteristics to the Ejina Oasis indicated that the influence of irrigation water on soil water levels creates an area centered on the oasis with a high groundwater level. Groundwater from the oasis therefore recharges the peripheral areas of desert. The resulting increase in soil moisture improves the environment for vegetation in the desert zone around the oasis. As a result, a greater proportion of the desert soil is stabilized as fixed and semi-fixed soil, with nebkhas being a common geomorphic feature. From an ecological perspective, desertification should be less likely to occur in this zone.

In reality, the contact zone between an oasis and peripheral desert is an ecotonal ecosystem. Different habitats exchange and transfer in the ecotonal ecosystem. Such a contact zone can be considered as a special geographical unit that is formed and maintained by an interface landscape with a hierarchical structure. This landscape has relatively high substitutability, weak anti-interference ability, and low self-recovery capability. It is situated where the rate and dimension of ecological transfers (solar energy, nutrient exchange) have an abrupt change, affecting both soil and biological properties. These characteristics increase the instability and variability of this zone, resulting in lower environmental quality than either the peripheral desert or the oasis; consequently, this critical zone tends to experience the most active desertification processes.

Excessive harvesting or grazing of desert vegetation, the abandonment of cultivation after reclamation of land for agriculture, and unsustainable utilization of water resources contribute to desertification. Without these forms of human damage, the oasis–desert ecotone near the edge of the oasis is typically dominated by fixed sandy land, changing to semi-fixed, or mobile, sandy land with increasing distance from the edge (Jia et al. 2002). However, after human-induced damage to the natural vegetation, this pattern changes to mobile sandy land near the oasis, followed by semi-fixed, fixed, semi-fixed again, and then mobile sandy land away from the oasis. This pattern results from activation of the land surface between the original area of fixed sandy land and the oasis, and further development of desertification. The kind of activation can lead to the intrusion of shifting sands into the oasis, thereby explaining why this contact zone between the oasis and the peripheral desert is referred to as the critical area of desertification. The essence of the desertification process in this critical area is that fixed dunes are subjected to wind erosion where nebkhas have formed to stabilize the sand (Zhu and Chen 1994). The wind erosion decreases the soil quality by changing the soil texture (i.e., by removing fine particles such as silts and clays), and by decreasing the SOM, soil moisture content, and soil nutrient content (Zhao et al. 2006).

The critical area of desertification in the present study area is also a community ecotone. There exists a transition zone from a *Tamarix ramosissima* community (to a distance of 600 m from the oasis edge) to a *Nitraria* *tangutorum* community at a distance of 1,100 m from the oasis edge (Fig. 2). Between these communities lies a community dominated by *Tamarix ramosissima*, *Nitraria tangutorum*, and *Sophora alopecuroides*. From the edge of the oasis to the desert, three different sections of soil water content are recognized: a high water content to a distance of 600 m, a sharp decrease in water content to a consistently low level from 700 to 1,700 m, and an increase in the last 200 m of the transects to 1,900 m. This trend may explain the changes in the vegetation cover and vegetation communities. The dominant vegetation in the study area is a *Tamarix ramosissima* community that extended from the oasis to 600 m from the oasis edge, with vegetation cover of 25–29 % and soil water content exceeding 2.25 %. From 600 to 1,100 m, the vegetation gradually changed to a *Tamarix ramosissima–Nitraria tangutorum* community (30–35 % vegetation cover), followed by a *Nitraria tangutorum* community from 1,100 to 1,700 m (15–25 % vegetation cover). Beyond 1,700 m lies bare land with a vegetation cover of <5 %. Since August is the period with the most vigorous vegetation growth, evapotranspiration also peaks at this time, with the quantity of evapotranspiration in the vegetation zone being higher than that of bare sandy land without vegetation. As vegetation cover decreases, water consumption to support plant growth also decreases. Rainfall in the Ejina Oasis also concentrated in the month of August; consequently, the soil surface moisture content gradually increases from 1,700 to 1,900 m and exceeds the soil surface moisture content from 1,100 to 1,700 m.

Given that soil provides numerous ecosystem services that sustain a range of ecological processes, the soil structure and nutrient contents are key indicators of ecosystem health (Foth 1991). In this study, it was found that the sand content and soil bulk density both decreased from the edge of the oasis to a distance of 300 m. The greater the distance from the oasis, the weaker the human impacts, so soil bulk density gradually decreases and soil structure gradually improves. Over this same distance, the silt and clay contents, soil pH, SOM, total nutrients, and available nutrients all increased greatly. However, from 300 to 1,900 m from the edge of the oasis, the sand content and soil bulk density both showed marked increases, and the silt and clay contents, soil pH, SOM, total nutrients, and available nutrients showed large reductions.

The analysis of the weighting of each soil indicator revealed that SOM and clay content were the key factors that influenced soil quality in the present study area. Soil structure is determined by the soil aggregate structure and stability. The clay mineral content and SOM both affect soil structure and the formation of aggregates, and determine the stability of the soil against erosion. Soil with a weak structure and low SOM tends to be highly erodible, whereas soil with a high water content and a high degree of surface cementation is strongly resistant to erosion. Lal (1998) noted that SOM and clay both had critical levels below which the soil's physical stability was lost. Faraggitaki (1985) reported that soil with poor structure and low SOM was easily eroded by the wind. This suggests that the resistance of soil to wind erosion, in the area between the edge of the oasis and a distance of 300 m, gradually increased. From 300 to 1,900 m, soil physical stability and the resistance to wind erosion decreased with increasing distance from the edge of the oasis.

SQI was used as an indicator of soil quality that integrates the effects of the soil properties, as this indicator had been shown to effectively reflect soil quality (Burger and Kelting 1999; Chaudhury et al. 2005; Amacher et al. 2007). By calculating SQI, the soil quality along a 1,900 m transect can be intuitively and objectively evaluated. SQI gradually increased from 0.284 at the edge of the oasis to a maximum of 0.793 at 300 m from the oasis edge and then gradually decreased to 0.262 at 1,400 m and 0.142 at 1,900 m from the oasis edge. The SQI value at 1,400–1,900 m from the oasis is lower than at other sites in the sampling transect. This change in SQI explains why the soil quality begins to deteriorate from 300 m from the edge of the oasis to the peripheral desert; all of the individual soil parameters showed their best values at this distance, and declined thereafter. As a result of this change, the area ranging from 1,400 to 1,900 m from the oasis was most vulnerable to desertification.

The above results suggest that a distance of 300 m from the edge of the oasis is an important turning point in terms of soil quality, and that the area beyond this point is most vulnerable to desertification. Thus, this area is the key area that must be strengthened to control desertification in the critical area of desertification at the Ejina Oasis. The main control measures for strengthening the critical area are as follows: (1) for the area extending to the oasis periphery, creation of a 1–2 km wide windbreak and sand-stabilizing forest in the key area, and for the area extending to the interior of oasis, the planting of shrub and grass strips with fencing; (2) strengthening the protection of nebkhas, in particular protecting the vegetation on the surface of nebkhas, which plays an important role in stabilizing the ecological environment (nebkhas have been used as a source of firewood and for foraging); (3) controlling excessive human activities (e.g., reclamation of the oasis edge, overgrazing, and deforestation); (4) inhibiting overexploitation of groundwater resources at the oasis; and (5) ensuring the rational allocation of water resources in the Heihe River Basin, protecting the water supply of the downstream Ejina Oasis, and encouraging the construction of efficient water-saving oases.

Acknowledgments This research was supported by the National Natural Science Foundation of China (No. 41201560), the China Postdoctoral Science Foundation (2012M521818), and the National Key Project of Scientific and Technical Supporting Programs (2011BAC07B04). We also thank two anonymous reviewers for valuable comments on an early version of the manuscript.

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