

Changes in soil physical and chemical properties during reversal of desertification in Yanchi County of Ningxia Hui autonomous region, China

Xiaohong Chen · Zhenghu Duan

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Abstract Using field surveys and laboratory analysis, soil physical and chemical properties were studied at a site exhibiting the reversal of desertification in Yanchi County of China's Ningxia Hui autonomous region. The dominant soil particle size changed from coarse-fine sand to a combination of very fine sand and silt + clay, and corresponding levels of each soil nutrient increased. The content of coarse-fine sand (2–0.1 mm) was significantly and negatively correlated with soil nutrient contents, whereas nutrient contents were significantly and positively correlated with the contents of very fine sand (0.1–0.05 mm) and silt + clay (<0.05 mm). The increasingly fine soil texture and the nutrient enrichment both facilitated rehabilitation of desertified land. The silt + clay content contributed the most to the increasing soil nutrient contents, and thus appears to be the key factor in reversal of desertification. Soil nutrient concentrations in the bulk soil increased with increasing content of soil nutrients with different particle fractions, and there were significant positive correlations between them. The nutrients in all particle size classes jointly decided the effect of soil nutrient contents on the reversal process. Principal-components analysis (PCA) revealed that the soil quality tended to increase during the reversal process, and that nutrient factors were more significant than particle size (i.e., were the dominant factor that influenced soil quality). Available nutrients and soil organic matter (SOM) were the most important nutrient factors. Silt + clay were the most important particle factors.

Keywords Desertification reversal · Soil physical and chemical properties · Yanchi County

Introduction

Desertification can be defined as the degradation of land in arid, semi-arid, and subhumid areas as a result of various factors. Among them, the most important are climatic change and human activities (INCD 1994). According to UNCCD (2004), the consequences of desertification include decrease in the land's ability to produce food (possibly endangering food supplies), famines, increased social costs, decline in the quantity and quality of fresh water, increased poverty and political instability, reduction in the land's resilience (ability to withstand natural climate variability), and decreased soil productivity. For these reasons, desertification has been widely recognized as one of the most serious global environmental and socio-economic problems, and a threat to the survival and development of humans in many areas (Wang 2000).

The process of desertification is generally gradual, often occurring after human activities destroy the ecological balance at the Earth's surface (e.g., reducing the vegetation cover), allowing wind erosion to change the Earth's surface features. The occurrence and development of desertification is affected by environmental fragility, but if can mitigate the pressure imposed by human economic activities and adopt measures to control the process, desertification can be stopped, and land that has not been degraded beyond the point of recovery has a considerable self-restoration ability, creating the possibility of reversal of desertification in many environments. Desertification reversal is accompanied by increases in the content of soil organic carbon, improvements in soil physical and chemical properties, stabilization of

X. Chen (✉) · Z. Duan
Cold and Arid Regions Environmental and Engineering
Research Institute, Chinese Academy of Sciences,
320 Donggang West Road, 730000 Lanzhou, China
e-mail: chenxiaohong1125@sina.com.cn

shifting sand to produce more typical zonal soil, increases in land productivity and biodiversity, and restoration of the ecological balance (Cheng et al. 2004). In semi-arid environments, desertification reversal exhibits self-regulating and self-organizing ability, but the effect differs among regions (Cui 2003). The reversal process typically requires 3–5 years to take hold in regions with an annual rainfall of around 500 mm, but in regions with annual rainfall below 200 mm, a much longer time could be required (Cui 1990). Given the importance of desertification reversal, it is currently a significant area of research.

At present, the research mainly focuses on desertification rather than its reversal, and the causes, processes, formation mechanisms, and control measures have been studied systematically (e.g., Ci 1998; Babaev and Kharin 1999; Lal 2001; Zhu and Wang 1993). As a result, some useful conclusions have been obtained. But no systematic studies have examined the reversal of desertification, and particularly the changes in soil properties in areas where this reversal is occurring. In the present study, soil changes were examined during a reversal of desertification that is occurring in Yanchi County of China's Ningxia Hui autonomous region. The physical and chemical properties of the soil were focused, and the changes in the soil particle size distribution and nutrient content as well as the changes in the nutrient contents of the bulk soil and of different particle size fractions were analyzed. In addition, Principal-components analysis (PCA) was used to determine the dominant factors responsible for the improvements in soil quality and in the assessed soil quality during the reversal process. In this paper, discussion on changes in soil physical and chemical characteristics during the reversal process and the contributions of each physical or chemical factor reveals the dominant factors that influenced soil quality. The results of this analysis will provide a scientific basis for soil improvement, for increasing vegetation stability, and for promoting further ecological restoration of desertified areas, and will assist the efforts to develop artificial measures that are capable of controlling or reversing the desertification.

Materials and methods

Study area description

Yanchi County lies in the middle north of China (ranging from 106°30' to 107°41' and from 37°04' to 38°10'), in the eastern part of the Ningxia Hui autonomous region, and covers an estimated area of 6,743 km² (Fig. 1). Terrain in the region is lower in the north and higher in the south, with elevations ranging from 1,295 to 1,951 m. The area is bordered by Shanxi, Gansu provinces, and Ningxia Hui and

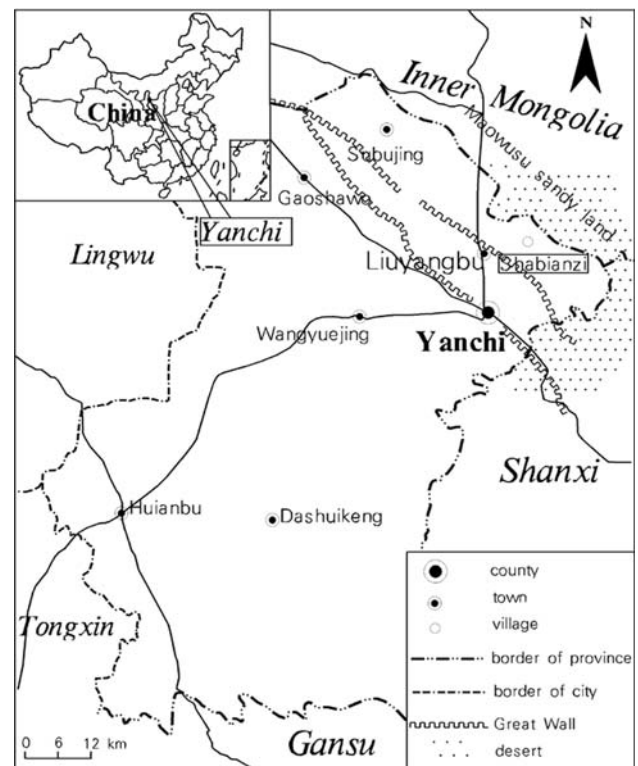


Fig. 1 Location of the study area in China

the Inner Mongolia autonomous region. The northern edge of the County touches the Maowusu sandy land, and the southern edge merges with the Loess plateau. The County is thus a typical transitional zone. From south to north, the terrain changes from the Loess plateau to the Ordos plateau. Soil types in the south are primarily dark loessial soil, but in the north, soil changes to eolian sandy soil and sierozem, with some loess deposits, saline soil, planosol, and other soil types.

The climate ranges from semi-arid to arid, and the vegetation types range from dry steppe vegetation to desert grassland. Land use ranges from farming to herding of animals. The characteristics of the geographical transition create a high diversity of natural resources and a frangible eco-environment. The area is dominated by a semi-arid continental monsoonal climate of the mid-temperate zone, with long winters, short summers, a late spring, and an early autumn. There is abundant sunshine (an annual average of 3,124 h), with a mean annual temperature of around 8.1°C, and the lowest and highest monthly mean temperatures are –24.2°C in January and 34.9°C in July. The frost-free season lasts 165 days. Annual precipitation ranges from 250 to 350 mm, and decreases moving from the south to the north and from the southeast to the northwest. Mean annual pan evaporation is 2,897 mm, which is dramatically higher than annual precipitation. Gales (wind speed >8 m s⁻¹) occur an average of more than 23.4 times per year.

The main vegetation types are shrubs, grasslands, meadows, and sandy or desert steppe or grassland vegetation. The area has no natural forest, with only a few artificial plantations; shrubs are the dominant form of vegetation (e.g., *Salix psammophila* and *Caragana microphylla*). Grasslands are classified into two main types: typical grassland (e.g., *Stipa grandis*, *Stipa bungeana*, *Agropyron cristatum*, *Thymus serpyllum* var. *mongolicus*, and other species) and desert grassland (e.g., *Caragana tibetica*, *Oxytropis aciphylla*, *Nitraria sibirica*, *Kalidium foliatum*, and other species).

During the past 50 years, Yanchi County has experienced both an expansion and a rehabilitation of desertified lands (Zhou and Zhao 2005). Before 1989, the total area of sandy land showed a sharp increase in the extent of desertification (Table 1), with desertified land in all categories increasing from 1006.11 km² in 1961 to 2366.67 km² in 1989, representing an annual increase of 46.92 km² and an average annual increase (linear rather than compound) of 4.66%. However, the total area of sandy land began to diminish after 1989, with an especially rapid change between 2000 and 2003, when it reached its minimum value (455.75 km²) during the study period.

The increase in the areas of different kinds of sandy land (Table 1) from 1961 to 1989 was caused primarily by increases in the areas of mobile and semi-mobile sandy land, whereas the area of fixed sandy land fluctuated but generally decreased. After 1989, the mobile and semi-mobile sandy land began to decrease, whereas the area of fixed sandy land again fluctuated, but with an overall decreasing trend. From 1961 to 1983, irrational grazing activities, felling of shrubs and trees growing in plantations and digging to obtain medicinal herbs, rapidly decreased the area of fixed sandy land. Based on the changes in land use and land cover types from 1986 to 2003 (Zhou and Zhao 2005), the land use structure of Yanchi County changed fundamentally. The area of agricultural land decreased by 46.1 km², the area of forested land

(plantations) increased by 750.1 km², the area of animal husbandry land decreased by 156.7 km², and the area of unutilized land (all land that is not used by humans or that is difficult to use) decreased by 549.8 km². The gradual rationalization of land use (i.e., the abandonment of unsustainable activities) had a positive effect on soil ecological processes and led to an improvement of soil quality, accelerated rehabilitation of the desertified land, and an increase in the diversity and coverage area of vegetation. From 1989 to 2003, the area classified as having a low degree of vegetation coverage (0–10%) decreased remarkably (by 64.62%), while the areas with moderate and high coverage (30–60%) increased by 72.04% (Zhang et al. 2006). As a result of these changes, which resulted from a combination of natural and artificial factors, the desertification in Yanchi County began to reverse in 1989.

In recent years, with increasing human environmental consciousness, many engineering and biological measures have been undertaken to stabilize dunes and restore vegetation. These include the construction of physical sand barriers, such as construction of corn straw fences and wheat straw checkerboards on the ground surface, enclosures to exclude animals, banning of grazing, letting cultivated land revert to grassland, and so on. These measures played an important role in controlling desertification. Simultaneously, the effect of climate cannot be ignored. The years 2002 and 2003 were unusually rainy, with annual precipitation of 399.8 and 302.1 mm, respectively, which were 112.3 and 14.6 mm more than the long-term average precipitation. At the same time, the favorable effects of the macroclimate and vegetation resulted in no serious dust storms in 2003, with only some small transient dust storms. These favorable conditions accelerated the development of grassland vegetation and benefited the natural rehabilitation and recovery of vegetation; in addition, development (e.g., agriculture) was kept within the limits of the land’s carrying capacity, leading to the reversal of desertification and improvement of the ecological environment.

Table 1 Changes in the area of sandy land in Yanchi County from 1961 to 2003 [from the result of Zhou and Zhao (2005)]

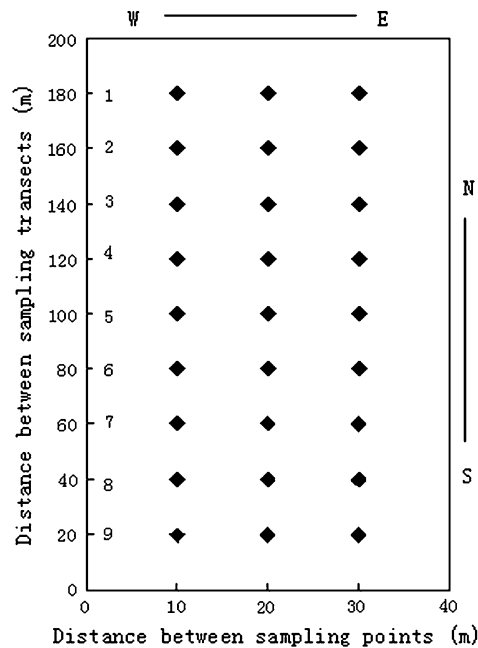
Year	Area of sandy land (km ²)			
	Mobile sandy land	Semi-mobile sandy land	Fixed sandy land	Total
1961	204.13	214.96	587.02	1006.11
1983	394.90	158.99	78.52	1225.80
1986	440.20	422.70	274.40	1090.42
1989	1032.70	997.00	337.90	2366.67
1995	547.20	700.80	268.00	1515.96
2000	424.10	743.30	145.60	1313.02
2003	63.18	166.55	207.96	455.75

Experimental design and sampling

Field research was carried out in mid-September 2006. The field sampling site was located at the southwestern edge of the Maowusu sandy land, in Shabianzi Village of Liuyangbu Town, about 20 km northeast of Yanchi City, the capital of Yanchi County. Shabianzi Village lies near the border of Yanchi County, in an ecological transitional zone, adjacent to the Maowusu sandy land. The region is a typical semi-agricultural and semi-pastoral area, with poor natural environmental conditions. Moving from north of Shabianzi Village to the south, mobile dunes evolve into semi-mobile dunes, fixed dunes, saline-alkaline beaches,

and hill-slopes covered with sand. As early as 1982, the local government built an agriculture, forestry, and animal husbandry experimental base for the purpose of studying the reversal of desertification in the region. This area was the earliest desertification-control area in the region. After more than 20 years of desertification control by installing fences and other barriers to sand movement near the edge of the area of mobile dunes, the shifting sand dunes have been stabilized and vegetation has been restored. The records obtained from the research station showed that this area exhibited a decrease in the proportion of the area covered by mobile sands and an increase in vegetation cover that were comparable to the mean values for the whole region. Owing to the particularity of geographic location and the rehabilitation of desertified lands, the sampling site was selected here. In addition, due to lack of sufficient historical data on the changes in the study parameters described below, the transition on the special scale, not on temporal scale was used, from mobile dunes to stable grasslands as a proxy for these changes.

A typical desertification reversal area near Shabianzi Village was selected as our study area. In this study, the degree of reversal of desertification was defined as the change in total area of land with mobile or semi-mobile sands. From north to south, the terrain changes from mobile sandy land to semi-mobile sandy land, fixed sandy land, and grassland, and the vegetation coverage increases. The vegetation types transit from *Artemisia ordosica* communities with a low vegetation coverage to communities with a moderate to high coverage, mostly *A. ordosica* and *Corispermum patelliforme*. Nine east–west sampling transects moving from north to south (following the prevailing local wind direction) were established, starting at the edge of the mobile dunes and ending at the grassland, with transects spaced at 20-m intervals (Fig. 2). The transects were numbered 1 (in the north) to 9 (in the south). Within each transect, three sampling points (replicates) at 10-m intervals were established for a total of 27 sampling points. At each point, mixed soil samples were obtained from 0 to 20 cm in depth, within a 3-m radius. The following physical and chemical properties of each sample were analyzed in the laboratory: particle size distribution, soil organic matter content, total nitrogen, total phosphorus, available nitrogen, available phosphorus, and available potassium. Each sample was also divided into three particle size fractions (2–0.1, 0.1–0.05, and <0.05 mm) by means of physical separation so that the nutrient content of each soil particle size fraction could be determined separately. The three categories were chosen based on the fact that 0.1 mm was an obvious dividing point, and the coarse-fine sand (2–0.1 mm) was relatively resistant to wind, whereas the very fine sand (0.1–0.05 mm) was easily eroded by the wind, and the silt + clay (<0.05 mm) fraction was easily



(The numbers 1 to 9 represent the sampling transects.)

Fig. 2 Distribution of soil sampling points within the study area

suspended as dust that was carried away by the airflow (Jia et al. 2006).

Laboratory analysis

The three particle size fractions were obtained by means of granulometric wet sieving and sedimentation (Rosell et al. 2000). Soil samples were air dried and hand-sieved through a 2-mm screen prior to laboratory analysis. At the time of sieving, roots and other debris were removed. Our analysis began by taking 50 g of the sieved soil sample and dispersing it in distilled water, followed by repeated shaking in the presence of 3-mm crystal beads, water-based elutriation, and leaching through 0.1-mm and 0.05-mm screens. This process divided the soil sample into three particle size fractions: coarse-fine sand (2–0.1 mm), very fine sand (0.1–0.05 mm), and silt + clay (<0.05 mm). At last the samples of each fraction were dried at 65°C and sieved through a 0.25-mm screen.

The soil physical and chemical properties were determined using routine methods. Soil particle size distribution was determined by means of the pipette method in a sedimentation cylinder, using sodium hexametaphosphate as the dispersing agent (ISSCAS 1978). Soil organic matter (SOM) was measured using the dichromate oxidation method of Walkey and Black (Nelson and Sommers 1982). Total nitrogen (total N) was measured using the Kjeldahl procedure (UDK140 Automatic Steam Distilling Unit, Automatic Titroline 96, Italy) (ISSCAS 1978), and total phosphorus (total P) was measured using a UV-1601

spectrophotometer (Shimadzu, Kyoto, Japan) after H₂SO₄–HClO₄ 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 mol/L NH₄OAc (ISSCAS 1978).

Data analysis

Statistical analysis (ANOVA with least-significant-difference (LSD) tests, correlation analysis, regression analysis, and PCA) was carried out using the SPSS 13.0 software for Windows. For all analysis, statistically significant differences were set at *P* < 0.05.

Results and discussion

Changes in particle size distribution and content of soil nutrients during the desertification reversal process

Table 2 shows the changes in the particle size distribution among the nine sampling transects. The contents of coarse-fine sand, very fine sand, and silt + clay differed significantly among the transects. From the first (1) to the ninth transect (9), the coarse-fine sand content decreased from 92.78 to 34.90%, and the very fine sand and silt + clay contents increased from 3.43 to 15.59% and from 3.79 to 49.51%, respectively. The dominant soil particle class changed from coarse-fine sand to a combination of very fine sand and silt + clay. Because the smaller particles are highly vulnerable to wind erosion, this change showed that the intensity of wind erosion decreased with increasing stabilization of the shifting sand and increasing restoration of the vegetation cover, with the very fine sand and silt + clay fractions gradually being deposited to compensate for their loss during the original desertification that produced mobile sands impoverished in these size classes. In a word, the reversal of desertification was accompanied by an increase in the fineness of the soil texture.

Accompanying this change in soil texture, the content of each soil nutrient also increased (Table 2). A possible explanation for this improvement is that the total surface area per unit volume (thus, the cation exchange surface) increases with increasing fineness of the soil particles, and because weathering of soil minerals to release nutrient cations is also accelerated by the increase in surface area. The increase in SOM resulted from an increase in the vegetation cover (e.g., increased litter fall and increased shading that reduced the decay rate of SOM) rather than from a change in the soil texture. This change shows that

Table 2 Soil particle size distribution and nutrient content along nine transects

Transect	SOM (g kg ⁻¹)	Total N (g kg ⁻¹)	Total P (g kg ⁻¹)	Avail. N (mg kg ⁻¹)	Avail. P (mg kg ⁻¹)	Avail. K (mg kg ⁻¹)	Coarse-fine sand (>0.1 mm, %)	Very fine sand (0.1–0.05 mm, %)	Silt + clay (<0.05 mm, %)
1	2.70 ± 0.4d	0.09 ± 0.01d	0.15 ± 0.04c	27.5 ± 2.19 cd	1.81 ± 0.25d	80 ± 5.64d	92.78 ± 1.7a	3.43 ± 0.48c	3.79 ± 2.26c
2	0.58 ± 0.09e	0.04 ± 0.01d	0.10 ± 0.044c	10.4 ± 0.85e	1.54 ± 0.19d	44 ± 5.35e	93.8 ± 1.21a	2.89 ± 0.22c	3.31 ± 1.43c
3	0.62 ± 0.02e	0.04 ± 0.01d	0.11 ± 0.036c	22.3 ± 1.95d	0.94 ± 0.47e	26 ± 1.65f	93.9 ± 0.28a	2.75 ± 0.4c	3.35 ± 0.68c
4	2.48 ± 0.33d	0.15 ± 0.01d	0.19 ± 0.026bc	11.8 ± 0.56e	3.39 ± 0.41b	90 ± 5.98d	86.1 ± 3.4a	4.66 ± 0.39c	9.24 ± 3.79c
5	8.70 ± 0.75b	0.41 ± 0.07c	0.24 ± 0.096bc	34.4 ± 3.12bc	2.56 ± 0.46c	159 ± 13.78bc	60.7 ± 4.77b	9.95 ± 0.69b	29.35 ± 5.46b
6	8.64 ± 0.8b	0.46 ± 0.11bc	0.34 ± 0.06ab	35.8 ± 4.25bc	2.92 ± 0.33bc	154 ± 3.51c	45.8 ± 5.75c	14.64 ± 1.2a	39.56 ± 6.95b
7	5.58 ± 1.2c	0.38 ± 0.03bc	0.30 ± 0.08ab	30.6 ± 4.02c	2.97 ± 0.05bc	154 ± 5.81c	47.6 ± 8.76c	13.84 ± 2.04a	38.56 ± 10.8b
8	9.36 ± 1.01b	0.53 ± 0.05b	0.26 ± 0.05b	41.1 ± 4.12b	3.04 ± 0.19bc	169 ± 9.57b	32.12 ± 9.31d	15.90 ± 2.5a	51.98 ± 11.81a
9	13.67 ± 1.11a	0.72 ± 0.13a	0.37 ± 0.07a	59.5 ± 8.94a	5.61 ± 0.73a	267 ± 10.87a	34.90 ± 5.15d	15.59 ± 1.8a	49.51 ± 6.53ab

Values are the means of three replicates. Means in a column followed by different letters differ significantly at *P* < 0.05

Table 3 Pearson correlation coefficients for the relationships among the soil properties

	SOM	Total N	Total P	Avail. N	Avail. P	Avail. K	Coarse-fine sand	Very fine sand	Silt + clay
SOM	1.000	0.985***	0.901**	0.929***	0.816**	0.972***	−0.910**	0.894**	0.913**
Total N		1.000	0.932***	0.908**	0.834**	0.976***	−0.959***	0.946***	0.961***
Total P			1.000	0.809**	0.822**	0.926***	−0.912**	0.931***	0.905**
Avail. N				1.000	0.716*	0.899**	−0.827**	0.809**	0.831**
Avail. P					1.000	0.900**	−0.713*	0.700*	0.715*
Avail. K						1.000	−0.897**	0.886**	0.899**
Coarse-fine sand							1.000	−0.996***	−0.999***
Very fine sand								1.000	0.993***
Silt + clay									1.000

Correlation is significant (two-tailed test) at * $P < 0.05$, ** $P < 0.01$, and at *** $P < 0.001$

Table 4 The correlation between soil organic matter (SOM), nutrient contents, and the content of very fine sand (0.1–0.05 mm) and silt + clay (<0.05 mm)

	Dependent variable	Regression equation	Coefficient (R)	Significance level	Number of samples
SOM, silt + clay (<0.05 mm) content; FS, very fine sand (0.1–0.05 mm) content	SOM (g kg^{-1})	$\text{SOM} = 0.202 \text{ SC} + 0.683$	0.913	$P < 0.01$	27
	Total N (TN, g kg^{-1})	$\text{TN} = 0.011 \text{ SC} + 0.025$	0.961	$P < 0.001$	27
	Total P (TP, g kg^{-1})	$\text{TP} = 0.016 \text{ FS} + 0.085$	0.931	$P < 0.001$	27
SC, silt + clay (<0.05 mm) content; FS, very fine sand (0.1–0.05 mm) content	Avail. N (AN, mg kg^{-1})	$\text{AN} = 0.611 \text{ SC} + 14.869$	0.831	$P < 0.01$	27
	Avail. P (AP, mg kg^{-1})	$\text{AP} = 0.047 \text{ SC} + 1.568$	0.715	$P < 0.05$	27
	Avail. K (AK, mg kg^{-1})	$\text{AK} = 3.264 \text{ SC} + 44.159$	0.899	$P < 0.01$	27

the reversal of desertification was accompanied by an enrichment of the soil nutrients. Soil texture is a long-term property of a soil, and is difficult to change under natural conditions. Thus, the reversal of desertification represents a dramatic change.

Correlation analysis indicated a significant negative correlation between the coarse-fine sand content and the soil nutrient contents, versus significant positive correlations for the very fine sand content and the silt + clay content (Table 3). This suggested that the changes in soil nutrients and their availability were controlled by the soil texture, and that the particle size distribution was one of the most important factors in the desertification reversal. This analysis confirmed the results in Table 2, in which the fineness of the soil texture and the enrichment of soil nutrients increased with desertification reversal.

This analysis also supported our conclusion that the increasing fineness of the soil texture and the corresponding increase in soil nutrient contents played an important role in the reversal of desertification. Multiple linear regression (stepwise regression) was performed to quantify the relationships between the two fine particle size classes and soil nutrient contents, with the particle sizes as the independent variables and nutrient contents as the dependent variables (Table 4).

Table 4 shows that the silt + clay content was a significant predictor of nutrient status for all nutrients except

total P and that the very fine sand content was only a significant predictor of total P. This showed that, with the exception of total P, the increasing silt + clay content had the greatest contribution to SOM, total N, available N, available P, and available K. SOM, total N, available N, available P, and available K increased by 0.202, 0.011, 0.611, 0.047, and 3.264 g kg^{-1} , respectively, for each 1% increase in the silt + clay content. Total P content increased by 0.016 g kg^{-1} for each 1% increase in the very fine sand content. Therefore, the increasing silt + clay content had a greater overall contribution to the improvement in soil nutrient content and was the most important factor in the improved soil quality. Thus, this parameter appears to be a key factor in the reversal of desertification.

Differences in soil nutrient contents between the bulk soil and the different soil particle size fractions

The SOM, total N, total P, available N, available P, and available K contents were most strongly associated with the silt + clay fraction, followed by the very fine sand and coarse-fine sand fractions (Table 5). SOM associated with the silt + clay fraction was 1.1–2.5 times the amount associated with the very fine sand fraction and 1.9–10 times the amount associated with the coarse-fine sand fraction. Similarly, total N associated with the silt + clay fraction was 1.1–2.2 and 2.1–7.6 times the values associated with the very

Table 5 Soil nutrient contents in each of the three particle size fraction

Transect	SOM	Total N	Total P	Avail. N	Avail. P	Avail. K
Coarse-fine sand (>0.1 mm)						
1	0.77 ± 0.11e	0.07 ± 0.02c	0.29 ± 0.089d	4.5 ± 1.2j	6.07 ± 1.35e	70 ± 4.98f
2	0.94 ± 0.23e	0.06 ± 0.01c	0.33 ± 0.12c	6.7 ± 1.68f	8.25 ± 1.68d	70 ± 5.06f
3	1.25 ± 0.19e	0.07 ± 0.01c	0.37 ± 0.098c	3.9 ± 0.98j	5.5 ± 1.68e	110 ± 8.67e
4	1.12 ± 0.34e	0.09 ± 0.02c	0.34 ± 0.067c	7.8 ± 2.31e	6.76 ± 2.02e	100 ± 6.84e
5	2.71 ± 0.64d	0.18 ± 0.05b	0.36 ± 0.094c	21.8 ± 3.65c	19.82 ± 3.26b	140 ± 8.63d
6	3.57 ± 0.86c	0.22 ± 0.086b	0.41 ± 0.13b	23.2 ± 5.62c	6.87 ± 1.69e	180 ± 11.9c
7	2.97 ± 0.78d	0.18 ± 0.036b	0.39 ± 0.095c	19 ± 3.67d	5.61 ± 1.38e	160 ± 9.64 cd
8	5.77 ± 1.12b	0.36 ± 0.1a	0.5 ± 0.16a	38.4 ± 7.68a	10.2 ± 2.69c	340 ± 26.5a
9	6.36 ± 2.35a	0.39 ± 0.16a	0.48 ± 0.13ab	33.2 ± 6.57b	21.54 ± 5.39a	240 ± 23.6b
Very fine sand (0.1–0.05 mm)						
1	3.35 ± 0.96e	0.2 ± 0.05e	0.79 ± 0.16b	12.7 ± 2.54d	7.1 ± 1.05e	100 ± 11.26e
2	2.83 ± 0.87e	0.17 ± 0.035e	0.75 ± 0.098b	11.7 ± 1.69d	11.34 ± 3.64c	100 ± 9.68e
3	5.15 ± 1.65d	0.27 ± 0.065d	0.77 ± 0.13b	19.3 ± 5.13c	8.82 ± 2.65e	185 ± 15.78d
4	4.33 ± 1.06d	0.31 ± 0.067d	0.78 ± 0.11b	17.7 ± 4.05c	37.63 ± 6.46a	160 ± 19.58d
5	8.18 ± 2.04c	0.6 ± 0.059b	0.95 ± 0.095a	34.7 ± 6.97b	37.12 ± 3.78a	255 ± 26.37c
6	7.04 ± 2.03c	0.49 ± 0.089c	0.96 ± 0.16a	31.3 ± 7.06b	15.12 ± 4.61c	280 ± 18.96c
7	7 ± 1.95c	0.48 ± 0.078c	0.84 ± 0.18a	30.9 ± 6.19b	19.53 ± 6.59b	275 ± 19.78c
8	9.91 ± 2.35b	0.68 ± 0.11ab	0.95 ± 0.21a	61.8 ± 8.48a	22.91 ± 4.98b	680 ± 29.64a
9	11.29 ± 3.68a	0.78 ± 0.19a	0.98 ± 0.19a	38.3 ± 5.06b	33.8 ± 7.86a	435 ± 18.76b
Silt + clay (<0.05 mm)						
1	7.72 ± 1.38b	0.39 ± 0.15c	1.51 ± 0.65a	26 ± 3.88d	23.71 ± 3.98d	140 ± 10.36e
2	7.21 ± 1.96b	0.37 ± 0.16c	1.45 ± 0.46a	25.2 ± 2.79d	15.01 ± 2.78e	150 ± 11.06e
3	10.74 ± 2.06a	0.53 ± 0.19b	1.54 ± 0.39a	36.8 ± 5.26c	15.12 ± 3.65e	240 ± 15.62d
4	8.26 ± 1.98b	0.51 ± 0.15b	1.55 ± 0.36a	23 ± 4.06d	43.08 ± 5.35b	220 ± 13.98d
5	8.9 ± 1.37b	0.64 ± 0.16b	1.73 ± 0.35a	38.3 ± 5.62c	43.14 ± 3.69b	330 ± 22.08c
6	8.42 ± 2.04b	0.6 ± 0.25b	1.72 ± 0.56a	42.2 ± 6.05c	40.21 ± 7.06c	310 ± 19.57c
7	8.57 ± 0.26b	0.62 ± 0.19b	1.70 ± 0.49a	43 ± 5.98c	48.23 ± 6.98b	340 ± 29.76c
8	10.83 ± 2.35a	0.86 ± 0.26a	1.76 ± 0.37a	79.1 ± 10.65a	37.12 ± 8.56c	880 ± 59.68a
9	11.88 ± 2.67a	0.82 ± 0.15a	1.78 ± 0.29a	53.4 ± 9.68b	57.86 ± 8.99a	640 ± 42.33b

Values are the means of three replicates. Means in a column followed by different letters differed significantly at $P < 0.05$

fine sand and coarse-fine sand fractions, respectively. Total P associated with the silt + clay fraction was 1.8–2.1 and 3.5–5.2 times the values associated with the very fine sand and coarse-fine sand fractions, respectively. Available N associated with the silt + clay fraction was 1.1–2.2 and 1.6–9.4 times the values associated with the very fine sand and coarse-fine sand fractions, respectively. Available P associated with the silt + clay fraction was 1.1–3.3 and 1.8–8.6 times the values associated with the very fine sand and coarse-fine sand fractions, respectively. Available K associated with the silt + clay fraction was 1.1–1.5 and 1.7–2.7 times the values associated with the very fine sand and coarse-fine sand fractions, respectively. These results showed the remarkable soil nutrient enrichment effect of the silt + clay fraction. This difference results from the smaller particle radius of the silt + clay particles and the correspondingly greater specific surface area, which increased the

ability of the particles to adsorb, preserve nutrients and conserve water. Therefore, increasing the silt + clay content of coarse-textured sandy soil had an important impact on soil quality. Based on our correlation analysis, the soil nutrient content in the bulk soil was strongly associated with the different soil particle sizes, there were significant positive correlations between the soil nutrient of the bulk soil and of different particle size fractions, and there were significant differences among the size classes.

Soil quality assessment and analysis of the dominant factors for soil quality

Soil quality can be defined as the “continued capacity of soil to function as a vital living system, within the ecosystem and land use boundaries, to sustain biological productivity, to promote the quality of air and water environments, and to

maintain plant, animal and human health” (Doran and Safley 1997). It is increasingly proposed as an integrative indicator of environmental quality (National Research Council 1993; Monreal et al. 1998), food security (Lal 1999), and economic viability (Hillel 1991). Assessing soil quality requires the measurement of physical, chemical, and biological soil properties and using these measured values to monitor changes in soil quality as a result of changes in land use or management practices (Adolfo et al. 2007). At present, there is no single ideal indicator because of the multitude of soil properties, the inherent variability among soils, and the continuous changes in soil properties along with changing land use and land cover. Therefore, some researchers (e.g., Larson and Pierce 1991; Doran and Parkin 1994) have suggested that identifying a minimum data set could provide some sensitive, reliable, and meaningful information for soil quality assessment. Unfortunately, which basic indicators should be included in this minimum data set and how many measurements are required are still being debated (Schloter et al. 2003). As a result, different researchers continue to select different methods and indicators to assess soil quality.

In the present study, nine factors (SOM, total N, total P, Avail. N, Avail. P, and Avail. K, and the coarse-fine sand, very fine sand, and silt + clay contents) were selected as soil quality indicators. Each of the nine sampling transects was used as an assessment unit. Because of the number of indicators and the significant correlations among them, PCA was used to identify the most significant soil characteristics related to soil quality. This multivariate statistical method results in a data reduction that aims to explain the majority of the variance in the data while reducing the number of variables to a few uncorrelated components (Sharma 1996; Anderson 2003). It also reveals groups of interrelated variables (Luboš et al. 2007). The basic PCA approach was as follows:

1. Because the selected soil physical and chemical indicators have different units, all the original data were standardized. The standardized data equal the original value subtracted by the mean value and

divided by the standard deviation of an indicator for all transects. (Table 6).

2. Based on the standardized data, a correlation matrix was computed (data not shown).
3. Using the Jacobian method (Anderson 2003), the eigenvalues and eigenvectors for the correlation matrix were computed, and these results were used to calculate the principal-component loading matrix for the parameters (Table 7). Each eigenvalue corresponds to the variance of a principal component; the bigger the variance, the greater the contribution of the principal component to total variation. The principal component loading represents the correlation between the original data and the principal component, and its value equals the square root of the eigenvalue multiplied by the eigenvector.
4. The contribution of the proportion of the variance of each principal component was then computed (Table 7) to select principal components whose cumulative contribution to the variance was greater than 85–95%. In this study, our PCA selected two principal components that accounted for more than 85% of the total variation.
5. The component score coefficient matrix (Table 8), which contains values that equal the principal component loading divided by the corresponding eigenvalue was then calculated. Based on this matrix, the score for each transect was computed for each principal component (Table 9), calculation models as follows:

$$f_{1i} = 0.121X_{1i} + 0.123X_{2i} + 0.118X_{3i} + 0.112X_{4i} \\ + 0.104X_{5i} + 0.120X_{6i} - 0.119X_{7i} + 0.118X_{8i} \\ + 0.119X_{9i}$$

$$f_{2i} = 0.146X_{1i} + 0.008X_{2i} + 0.018X_{3i} + 0.145X_{4i} \\ + 1.045X_{5i} + 0.376X_{6i} + 0.526X_{7i} - 0.568X_{8i} \\ - 0.514X_{9i}$$

where f_{1i} represents the score of the i th sampling transect for PC1; f_{2i} represents the score of the i th

Table 6 The standardized data for each indicator used in the PCA

Transect	SOM	Total N	Total P	Avail. N	Avail. P	Avail. K	Coarse-fine sand	Very fine sand	Silt + clay
1	-0.68	-0.92	-0.80	-0.19	-0.70	-0.63	1.04	-1.00	-1.05
2	-1.15	-1.12	-1.31	-1.32	-0.90	-1.11	1.08	-1.40	-1.08
3	-1.14	-1.12	-1.21	-0.53	-1.35	-1.35	1.09	-1.12	-1.07
4	-0.73	-0.67	-0.40	-1.23	0.47	-0.50	0.79	-0.79	-0.79
5	0.63	0.40	0.11	0.27	-0.14	0.43	-0.17	0.11	0.19
6	0.62	0.60	1.13	0.36	0.12	0.36	-0.74	0.92	0.69
7	-0.05	0.27	0.73	0.01	0.16	0.36	-0.67	0.78	0.64
8	0.79	0.89	0.32	0.71	0.21	0.56	-1.26	1.13	1.29
9	1.73	1.67	1.44	1.93	2.13	1.88	-1.15	1.08	1.17

Table 7 Loading matrix for the principle components (PC 1 and PC 2) in the PCA using data from all soil samples ($n = 27$)

Indicators	PC 1	PC 2
SOM	0.978	0.069
Total N	0.996	0.004
Total P	0.953	0.008
Avail. N	0.905	0.068
Avail. P	0.842	0.488
Avail. K	0.975	0.176
Coarse-fine sand	-0.964	0.246
Very fine sand	0.957	-0.265
Silt + clay	0.964	-0.240
Eigenvalue	8.110	0.467
% of variance	90.116	5.193
% cumulative	90.116	95.309

Table 8 The component score coefficient matrix

Indicators	PC 1	PC 2
SOM	0.121	0.146
Total N	0.123	0.008
Total P	0.118	0.018
Avail. N	0.112	0.145
Avail. P	0.104	1.045
Avail. k	0.120	0.376
Coarse-fine sand	-0.119	0.526
Very fine sand	0.118	-0.568
Silt +clay	0.119	-0.514

Table 9 The principal component scores and the resulting integrated value of soil quality

Transect	PC 1 score	PC 2 score	Integrated assessment value
1	-0.827	0.539	-0.752
2	-1.192	-0.011	-1.128
3	-1.170	-0.437	-1.131
4	-0.646	1.281	-0.540
5	0.262	-0.1071	0.241
6	0.656	-0.829	0.575
7	0.423	-0.810	0.356
8	0.846	-1.305	0.729
9	1.648	1.679	1.649

sampling transect for PC2; i represents the number of the sampling transect; X_1 represents SOM; X_2 represents Total N; X_3 represents Total P; X_4 represents Avail. N; X_5 represents Avail. P; X_6 represents Avail. K; X_7 – X_9 represents the content of coarse-fine sand, very fine sand and silt + clay, respectively; and the

X_{1i} – X_{9i} represent the standardized data for the indicators in the i th sampling transect.

- Using the contribution to the variance of each principal component as a weighting coefficient, the score was totaled for each sampling transect for each principal component, then divided the totaled value by the cumulative contribution ratio of variance of the two selected principal components to obtain the integrated score for each transect (Table 9). The following calculation model was used:

$$F_i = (90.116\%f_{1i} + 5.193\%f_{2i})/95.309\% \tag{1}$$

$$F_i = 0.122X_{1i} + 0.117X_{2i} + 0.113X_{3i} + 0.114X_{4i} + 0.155X_{5i} + 0.134X_{6i} - 0.084X_{7i} + 0.081X_{8i} + 0.085X_{9i} \tag{2}$$

where F_i represents the integrated score for the i th sampling transect, and other letters in this model represent the same value in the fifth step.

The integrated score was used as the value of our integrated assessment of soil quality for each transect. The corresponding coefficient of each indicator in the calculation model (2) of the integrated score is the weighting coefficient of each indicator.

The positive weighting coefficient of each indicator was available $P > \text{available K} > \text{SOM} > \text{total N} > \text{available N} > \text{total P} > \text{silt + clay} > \text{very fine sand}$, coarse-fine sand with negative weighting coefficient. This showed that, except coarse-fine sand, all other factors contributed to improving the soil quality value as well as the weight of nutrient factors were larger than particle factors. These results indicated the degree of their contribution to the improvement of soil quality was: nutrient factors $>$ particle factors. As a result of this analysis, the nutrient factors were the dominant factors in determining soil quality. Available nutrients and soil organic matter were the most important nutrient factors. Silt + clay were the most important particle factors. Thus, improvements in these parameters will have important significance for reversing desertification.

Based on the scores for each sampling transect for each principal component, and the contributions to variance of each principal component and the cumulative contribution ratio of variance of the two selected principal components, Eq. (1) was used to compute the integrated assessment of soil quality (Table 9). This value was helpful in revealing the spatial and temporal changes in soil quality. This could be used to evaluate the effect of land management measures on soil degradation and soil maintenance, and monitor the changes in environmental quality. It would also be helpful in distinguishing between the effects of technological progress and soil quality improvement on

productivity (Liu et al. 2006). In areas experiencing soil degradation, this approach can be helpful in identifying the cause and effect mechanisms for artificial activities that lead to soil degradation and for establishing a system of soil quality indicators and an assessment system to reveal the factors responsible for the evolution of soil properties. On this basis, it becomes possible to change land use patterns and land management measures to reverse desertification. In desertification areas, a soil quality database can be set up and used to provide a warning system based on real-time monitoring of the degree of desertification and its development trends, and then determine appropriate control measures that are suitable for local conditions.

Figure 3 shows that the soil quality (i.e., the integrated score for each sampling transect) increased from transect 1 (the most severely desertified soils) to transect 9 (the most restored soils). These results indicated that from the edge of the sandy land to the center of the sampling site, the degree of desertification progressively weakened and soil quality progressively improved as the fixation of the soil increased. This result provides good quantitative evidence that the sand-control measures at the study site (construction of fencing and sand-control barriers nearby the edge of mobile dunes) played a remarkable role in controlling desertification.

Conclusions

During the past 50 years, Yanchi County has experienced both an expansion and a subsequent rehabilitation of its desertified lands. Before 1989, the extent of desertification showed a sharp increase. However, as awareness of the need for environmental protection increased, many engineering and biological measures were taken to protect the land and the land use structure was changed; as a result, the

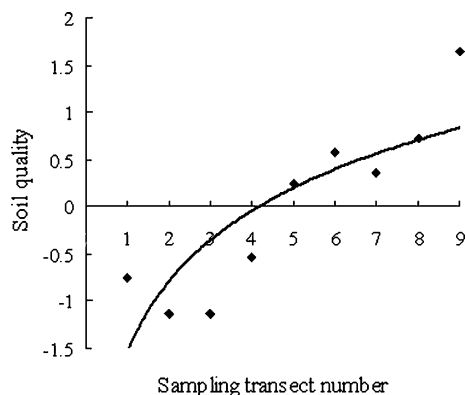


Fig. 3 Changes in the soil quality value along a sequence from transect 1 to transect 9

desertification began to reverse by 1989. The dominant soil particle size changed from coarse-fine sand to a combination of very fine sand and silt + clay fractions, and all soil nutrient contents that were evaluated showed a corresponding increase. The content of coarse-fine sand was significantly and negatively correlated with soil nutrient contents, whereas the contents of very fine sand and silt + clay showed significant and positive correlations with nutrient contents. The changes in soil nutrient contents and their availability were strongly controlled by the changes in the soil particle size distribution, with increased fineness of soil texture accompanied by an enrichment of soil nutrients.

Multiple linear regression of the relationships between the very fine sand content, the silt + clay content, and the soil nutrient contents revealed that the increasing silt + clay content had the largest contribution to the increasing soil nutrient content, was an important factor in determining the improvement of soil quality, and was thus the key to the reversal of desertification. The concentrations of SOM, total N, total P, available N, available P, and available K were most strongly associated with the silt + clay fraction, followed by the very fine sand and coarse-fine sand fractions. Based on our correlation analysis, the soil nutrient content in the bulk soil was strongly associated with the different soil particle sizes, and there were significant differences among the size classes. The nutrients in all particle size classes jointly decided the effect of soil nutrient contents on the reversal process.

In this study, only a limited number of physical and chemical indicators of soil quality were chosen for test. PCA revealed that the nutrient factors were the dominant factors in determining soil quality. Available nutrients and soil organic matter were the most important nutrient factors. Silt + clay were the most important particle factors. Although this approach generally worked well, it had certain disadvantages (i.e., needing a mass of data, the information is lost easily in the process of assess). In future studies, additional indicators should be selected, including other chemical indicators, biological indicators, and changes in the areas of different land uses and of different vegetation coverage classes.

The results of this study provide support for the belief that installing fencing and sand-control barriers near the edge of mobile dunes in areas with severe desertification can improve soil quality. In our study area, soil quality increased from the southern edge of the Maowusu sandy land towards the center of Yanchi County. These results have important implications for the control of desertification in other areas.

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