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Full Length Research Paper

Changes in soil properties during reversal of desertification in agro-pastoral transition zone of Northern China

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Based on the field surveys and laboratory analysis, soil physical, chemical and biological properties were studied at different degrees of the reversal of desertification in the agro-pastoral transition zone of northern China. The resultsobtained show that with the consequence of mobile sand land →semi-mobile sand land →semi-fixed sand land →fixed sand land, the dominant soil particle size changed from coarse sand to a combination of fine sand and silt + clay, and corresponding levels of each soil nutrient increased. The content of coarse sand (>0.25 mm) was significantly and negatively correlated with soil nutrient contents, whereas nutrient contents were significantly and positively correlated with the contents of fine sand (0.25 to 0.02 mm) and silt + clay (<0.02 mm). The increasingly fine soil texture and the nutrient enrichment both facilitated rehabilitation of desertified land. The path analysis showed that soil organic matter was the main factor that affected soil enzymes activities directly while total potassium (P) was less important. Principal-components analysis (PCA) revealed that the soil quality tend to increase during the reversal process and that biological factor were more significant than nutrient factors and particle size. Fine sand was the most important particle factors.

Key words: Soil physical and chemical properties, soil enzymes activities, desertification reversal, agro-pastoral transition zone of northern China.

INTRODUCTION

Desertification is regarded as a form of land degradation in arid, semiarid and dry sub-humid areas resulting from various harmful effects of human activities, as well as natural factors (Sepehr et al., 2007). The direct consequences of desertification include dramatic increase in number of dust storms, decrease in the land's ability to produce food, increased social costs, decline in the quantity and quality of fresh water, increased poverty and political instability, reduction in the land's resilience, and decreased land productivity (Lopez-Bermudez and Garcia-Gomez, 2006; Chen et al., 2003; Su et al., 2004). For all these reasons, desertification has turned to be an important ecological and environmental problem that concerns the whole globe and a threat to the survival and shows the self-regulating and self-organizing ability of development of humans in many areas. The process of desertification is always accompanied by destruction of the ecological balance at the earth's surface and changes of the earth's surface features by wind erosion. But desertification can be stopped by reducing the pressure imposed by human economic activities and adopting measures to control the process. As is well known, the ecosystem has considerable self-restoration ability if it has not been degraded beyond the point of recovery. The possibility of reversal of desertification may occur if the proper restoration measures are adopted. Desertification reversal is actually the change of shifting sand to more typical zonal soil, which increases the content of soil organic carbon, land productivity and biodiversity, improvements in soil physical and chemical properties, and restoration of the ecological balance (Shirato et al., 2005; Su et al., 2005, 2006). Desertification reversal ecosystem, but the effect differs among regions in arid and semi-arid environments. China has been suffering

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from large scale and severe desertification in recent years, especially in the agro-pastoral transition zone of northern China which makes up more than 60% of the desertified land (Liu and Zhao, 2001; Huang et al., 2007). The Chinese government realized the problem of environmental degradation in these areas in 1978. As a result, since 1978, much more attention has been paid to desertification control. Rapid progress has been made in the re-vegetation, soil conservation and rangeland improvement.

At present, most of the researches study the causes, processes, formation mechanisms and measures of controlling the desertification (Pei et al., 2008; Mainali, 2006; Tsunekawa et al., 2005; Jin et al., 2006; Liu et al., 2005; Wang et al., 2003), whilst a small amount of studies focus on the desertification reversal at a specific circumstance (Li et al., 2006, 2007). But no systematic studies have investigated the reversal of desertification, and particularly the changes in soil properties (physi-chemical and biological properties) in areas where this reversal is occurring. In this paper, soil changes were analyzed during the reversal of desertification that is occurring in northern Shaanxi Province of China. The physical, chemical and biological properties of the soils were examined, and the relationships between the physical and chemical properties affecting activities of the three enzymes were analyzed. In addition, the dominant factors responsible for improvement in soil quality were determined by principle-components analysis (PCA) during the reversal process of desertification. The result of this analysis will provide a scientific basis for soil improvement, for increasing vegetation stability, and for promoting further ecological restoration of desertified areas.

MATERIALS AND METHODS

Study area description

The transitional region covers a window encompassing 35 to 50° N and 100 to 125° E. To the south of this region is the semi-humid North China Plain, which is an intensive agriculture region. To the north is the nomadic region of steppes along the Mongolian Plateau (Wang and Gao, 2003). Temporal and spatial variability of climate is one of the most notable features of the transitional region, especially for precipitation and temperature. The study area lies in northern Shaanxi (Figure 1), which has a typical continental semi-arid climate. Annual precipitation ranges from 440 mm in the south-east to 250 mm in the north-west, of which 60 to 80% is concentrated in the period from June to August. The annual mean temperature is about 6.0 to 8.5°C, with monthly mean temperatures of 22°C in July and -11°C in January. The landform in the study area gently undulates and slopes from northwest to southeast, with elevations ranging from 800 to 1400 m. The area is meshed with basically three landforms: hard hills resulting from erosion and aging of bedrock, soft hills consisting of sediments accumulated during the quarternary period, and lower wetlands resulting from cutting on the quarternary sediments by rivers and streams. Most of the sandland is covered by sand with varying thickness. The main vegetation type is sandy grassland, which covers more than 80% of the sandland area. *Artemisia Ordosica* is a dominant species. The other natural vegetation types include steppe, meadow and shrubs. In addition, there are farmlands, distributed along the river or scattered in sandy grassland, and artificial forests and shrubs. The Great Wall passes through this area. Some grassland areas have been reclaimed into farmland, where both animal husbandry and agriculture are the main economic activities.

Soil sampling and analysis

A field survey was conducted in July (growing season) 2006. Composite soil samples of the top 20 cm with different degree of desertification land (mobile sand land, semi mobile-sand land, semi-fixed sand land and fixed sand land) were randomly collected from three different places in each site. Each soil sample represented three subsamples, which were thoroughly mixed to obtain a composite sample. Soil samples were air-dried and hand sieved through a 2 mm sieve to remove roots and other debris. All the samples were analyzed using standard methods as described in the soil analysis book (ISSCAS, 1978; NIS, 1980; Bao, 2000).

Soil particle size was classified into course sand (1 to 0.25 mm), fine sand (0.25 to 0.02 mm) and silt + clay (<0.02 mm). Particle size distribution was determined by the pipette method in a sedimentation cylinder, using sodium hexametaphosphate as the dispersing agent. Soil organic matter (OM) was determined by the $K_2Cr_2O_7$–H_2SO_4 oxidation method. Total soil N (TN) was analyzed using the standard Kjeldahl acid-digestion method. Soil phosphorus and potassium were measured using standard method of Soil and Agricultural Chemistry Analysis (Bao, 2000). Soil available N (Av-N) was determined by the alkaline diffusion method and available P was determined by the Bray method. The cation exchange capacity (CEC) was determined after leaching of 2 mm air-dried soil with 1 M CH_3COONH_4 at pH 7.0; exchangeable cations (K^+ and Na^+) were determined by flame spectrophotometry.

Soil catalase activity (CAT) was measured using the 0.1 N $KMnO_4$ titration methods. Urease activity (UAT) was determined using urea as substrate, measuring the residual urea by a colorimetric method. Alkaline phosphatise activity (APAT) was assessed using p-nitrophenylphosphate as a substrate, and the colored reaction was measured at 405 nm. Invertase activity (SAT) was determined using sucrose as a substrate measuring the produced glucose with a colorimetric method.

Data analysis

Statistical analysis (ANOVA) with least-significant-difference (LSD) tests, correlation analysis, regression analysis, path analysis and PCA was carried out using the DPS 7.55 software for Windows.

Path analyses were carried out on the traits considered as the soil enzymes activities components. Soil enzymes activities were taken as dependent variable in the method. Soil chemical indicators, such as OM, T-N, Av-N, T-P, Av-P, T-K, Av-K, CEC $CaCO_3$, were thought to be effective on soil enzymes activities and were considered as independent variables. Correlation coefficients were found initially in order to determine the simple linear relations between the traits.

RESULTS AND DISCUSSION

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

Table 1 shows the changes in the particle size

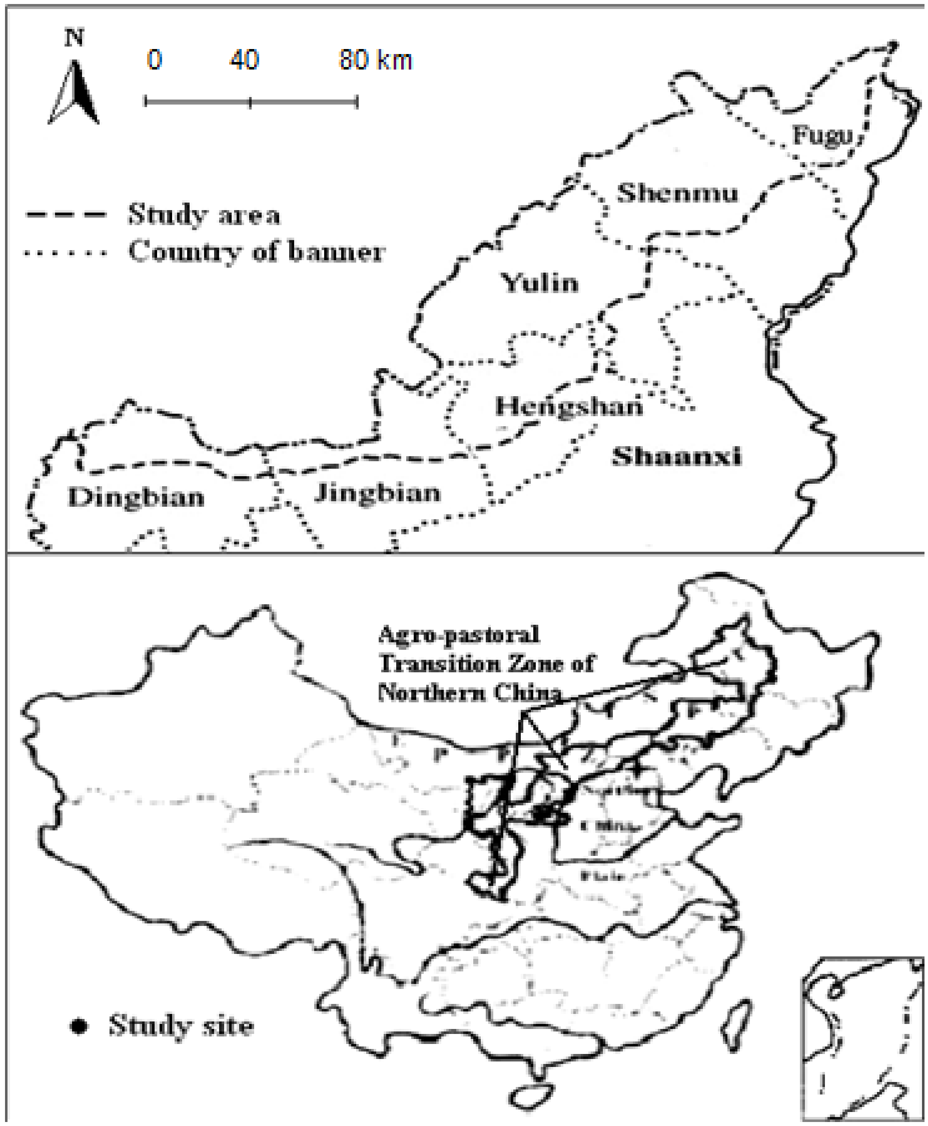

Figure. 1 Map of the location of agro-pastoral transition zone of northern China and study site.

distribution among different degree of desertification land. From mobile sand land to fixed sand land, the content of course sand decreased from 75.63 to 5.43%, and the fine sand and silt + clay contents increased from 17.46 to 57.10% and from 6.90 to 37.47%, respectively. The dominant soil particle class changed from coarse sand to a combination of fine sand and silt + clay. As 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 fine sand and very fine sand fractions gradually being deposited to compensate for their loss during the original desertification that produced mobile sands impoverished in these size classes. In conclusion, the reversal of desertification was accompanied by an increase in the fine particles but decrease in coarse fraction of the soil texture. Accompanying this change in soil texture, the content of each soil nutrient also increased (Table 1). 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 (for example, 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 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

Table 1. Soil particle size distribution and nutrient content in different degree of desertification land.

Variable	Mobile sand land	Semi mobile-sand land	Semi-fixed sand land	Fixed sand land
Coarse sand (>0.25 mm %)	75.63±2.08^{a}	54.23±4.02^{b}	23.90±1.51^{c}	5.43±2.63^{d}
Fine sand (0.25-0.02 mm %)	17.46±2.85^{c}	32.37±5.80^{b}	48.77±2.55^{a}	57.10±3.10^{a}
Silt + clay (<0.02 mm %)	6.90±0.87^{d}	13.40±1.82^{c}	27.33±1.63^{b}	37.47±0.76^{a}
OM (g.kg^{-1})	0.38±0.14^{d}	4.33±1.08^{c}	9.12±0.06^{b}	18.02±0.95^{a}
T-N (g.kg^{-1})	0.11±0.03^{d}	0.56±0.06^{c}	0.81±0.03^{b}	1.09±0.07^{a}
Av-N (mg.kg^{-1})	7.58±0.12^{c}	13.18±3.89^{c}	30.14±5.12^{b}	39.40±0.79^{a}
T-P (g.kg^{-1})	19.62±0.12^{b}	20.93±3.89^{ab}	23.77±5.12^{a}	24.76±0.79^{a}
Av-P (mg.kg^{-1})	27.23±1.75^{c}	91.04±1.23^{b}	96.23±2.34^{b}	139.78±6.01^{a}
T-K (g.kg^{-1})	0.11±0.05^{d}	0.21±0.01^{c}	0.33±0.01^{b}	0.40±0.02^{a}
Av-K (mg.kg^{-1})	3.55±0.11^{d}	6.69±0.43^{c}	8.42±0.33^{b}	10.60±0.49^{a}
C.E.C (cmol.kg^{-1})	1.74±0.39^{c}	4.88±0.02^{b}	5.91±0.07^{ab}	6.67±0.84^{a}
$CaCO_3$ (g.kg^{-1})	1.72±1.35^{d}	23.74±4.10^{c}	58.19±2.30^{b}	97.91±14.78^{a}
CAT (mol.kg^{-1}.h^{-1})	3.77±1.52^{c}	15.37±0.21^{b}	16.03±1.89^{b}	19.13±0.47^{a}
UAT (mg.kg^{-1}.h^{-1})	42.83±11.22^{d}	380.53±13.33^{c}	469.73±19.99^{b}	601.03±3.75^{a}
APAT (mg.kg^{-1}.h^{-1})	275.57±19.25^{d}	540.20±16.29^{c}	752.20±21.39^{b}	972.90±9.41^{a}
SAT (mg.kg^{-1}.h^{-1})	96.87±3.65^{d}	589.23±2.97^{c}	750.03±5.77^{b}	1142.23±18.92^{a}

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

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 2). 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 1, in which the fineness of the soil texture and the enrichment of soil nutrients increased with desertification reversal.

Soil chemical properties affecting activities of the three enzymes

Soil urease activity was closely and positively correlated to soil total N, total P, available K and silt + clay content as shown in Table 2. Path analysis showed that soil organic matter and available K had a positive direct effect on urease activity and the effects were strengthened by all other indirect factors (Table 3). While total N had a positive indirect effect via soil organic matter and was strengthened by other factors, total P showed a closely positive relationship with an accumulated path coefficient though all factors had a rather small effect. Soil total N, available N, and total K had no effect on urease activity. Soil CEC showed an indirect effect via available K and organic matter. Based on these results, we could conclude that soil organic matter has the most significant and positive effect on urease.

Though soil total P, available P, total K and available K did not show any significant direct effect on alkaline phosphatase activity by path analysis (Table 3), simple correlation analysis showed that alkaline phospatase was closely and positively correlated with total P, available P, total K and available K (Table 2). They all showed an indirect positive effect via soil organic matter, total N and available N. Soil $CaCO_3$ had a negative direct effect, but it was counteracted by other soil properties.

Path analysis showed that soil organic matter and available P had a positive direct effect, whereas total N, total P and total K had a negative direct effect on invertase activity (Table 3). Soil total N, total P and total K had a positive indirect effect on invertase via soil available P.

In a word, from the path analysis, the direct effects of natural soil properties on urease, alkaline phosphatase and invertase activities were: Av-K > OM > $CaCO_3$ > Av-P > CEC > T-P > T-K > T-N > Av-N, OM > CEC > T-N > Av-N > T-K > Av-P > T-P > Av-K> $CaCO_3$, and Av-P > OM > Av-K> CEC > Av-N > T-P > T-K > $CaCO_3$ > T-N. This meant available K, organic matter, and available P had the most direct effect on urease, alkaline phosphatase and invertase activities, respectively.

The remaining path coefficient of urease, alkaline phosphatase and invertase activities were 0.1386, 0.1061, and 0.1287, which meant the experimental value has a little error to the theory value. Thus, the factors which affected these three enzymes were explained in this study's discussion.

Soil quality assessment

Soil quality can be described as "the continued capacity

Table 2. Pearson correlation coefficients for the relationships among the soil properties.

Parameter	>0.25 mm	0.25-0.02 mm	Silt + clay	OM	T-N	Av-N	T-P	Av-P	T-K	Av-K	C.E.C	$CaCO_3$	CAT	UAT	APAT	SAT
>0.25 mm	1.000															
0.25-0.02 mm	-0.987***	1.000														
Silt + clay	-0.980***	0.941***	1.000													
OM	-0.948***	0.906***	0.961***	1.000												
T-N	-0.965***	0.939***	0.957***	0.941***	1.000											
Av-N	-0.954***	0.925***	0.967***	0.922***	0.928***	1.000										
T-P	-0.782**	0.740**	0.781**	0.727**	0.717**	0.828***	1.000									
Av-P	-0.882***	0.869***	0.847***	0.883***	0.954***	0.802**	0.595*	1.000								
T-K	-0.936***	0.916***	0.951***	0.929***	0.941***	0.940***	0.698*	0.856***	1.000							
Av-K	-0.976***	0.952***	0.959***	0.929***	0.974***	0.943***	0.780**	0.921***	0.940***	1.000						
C.E.C	-0.924***	0.933***	0.868***	0.811**	0.943***	0.839***	0.676*	0.922***	0.857***	0.947***	1.000					
$CaCO_3$	-0.955***	0.921***	0.965***	0.990***	0.950***	0.946***	0.729**	0.877***	0.947 ***	0.933***	0.827***	1.000				
CAT	-0.833***	0.849***	0.751**	0.763**	0.887***	0.738**	0.597*	0.943***	0.767**	0.879***	0.947***	0.778**	1.000			
UAT	-0.937***	0.932***	0.897***	0.892***	0.975***	0.882***	0.723**	0.971***	0.903***	0.963***	0.966***	0.904***	0.956***	1.000		
APAT	-0.988***	0.966***	0.973***	0.948***	0.978***	0.957***	0.760**	0.912***	0.931***	0.987***	0.933***	0.956***	0.865***	0.954***	1.000	
SAT	-0.961***	0.943***	0.936***	0.939***	0.986***	0.903***	0.712**	0.968***	0.938***	0.983***	0.950***	0.944***	0.921***	0.985***	0.973***	1.000

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

of soil to function as a vital living system, within the ecosystem and land use boundaries, to sustain or enhance productivity while maintaining soil resources for the future, to produce healthy and inexpensive food products, to promote the quality of air and water environments, and to maintain or increase biodiversity, water quality, nutrient cycling and biomass yield" (Shukla et al., 2006; Chen and Duan, 2009). It is increasingly proposed as an integrative indicator of environmental quality, food security, and economic viability (Council, 1994). The capacity of soil to function can be reflected by 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 practice (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 (De La Rosa, 2005; Xua et al., 2006) 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 (Masto et al., 2008).

In the present study, sixteen factors (SOM, total N, total P, total K, Av-N, Av-P, Av- K, CEC, $CaCO_3$, CAT, UAT, APAT, SAT and the coarse sand, fine sand, and silt + clay contents) were selected as soil quality indicators. 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. It also reveals groups of interrelated variables (Boruvka et al., 2007).

After standardizing the original data because they have different units, 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 4). Each eigenvalue corresponds to the variance of a principal

Table 3. Path coefficients between the physical and chemical properties affecting activities of the three enzymes.

Dependent variable	Independent variable	OM(X_1)	T-N(X_2)	Av-N(X_3)	T-P(X_4)	Av-P(X_5)	T-K(X_6)	Av-K(X_7)	C.E.C(X_8)	$CaCO_3$(X_9)	Sum
	X_1	0.981	-0.196	-0.244	0.050	0.403	-0.061	0.925	0.074	0.888	0.859
	X_2	0.923	-0.208	-0.245	0.050	0.436	-0.062	0.970	0.086	0.852	0.955
	X_3	0.904	-0.193	-0.265	0.057	0.366	-0.062	0.939	0.076	0.849	0.864
	X_4	0.713	-0.149	-0.219	0.069	0.272	-0.046	0.777	0.062	0.654	0.706
UAT	X_5	0.866	-0.198	-0.212	0.041	0.457	-0.056	0.917	0.084	0.787	0.953
	X_6	0.911	-0.196	-0.249	0.048	0.391	-0.066	0.936	0.078	0.850	0.881
	X_7	0.911	-0.203	-0.249	0.054	0.420	-0.062	0.996	0.086	0.837	0.968
	X_8	0.795	-0.196	-0.222	0.047	0.421	-0.057	0.943	0.091	0.742	0.974
	X_9	0.971	-0.198	-0.250	0.050	0.400	-0.062	0.929	0.075	0.897	0.871
Remain path coefficient=0.1386											
	X_1	0.451	0.285	0.257	-0.055	0.001	0.084	-0.149	0.256	-0.171	0.958
	X_2	0.424	0.303	0.259	-0.055	0.001	0.085	-0.156	0.298	-0.164	0.995
	X_3	0.416	0.281	0.279	-0.063	0.002	0.085	-0.151	0.265	-0.163	0.949
	X_4	0.328	0.217	0.231	-0.076	0.001	0.063	-0.125	0.214	-0.126	0.726
APAT	X_5	0.398	0.289	0.224	-0.045	0.004	0.078	-0.147	0.291	-0.152	0.935
	X_6	0.419	0.285	0.262	-0.053	0.003	0.091	-0.151	0.271	-0.164	0.960
	X_7	0.419	0.295	0.263	-0.060	0.004	0.085	-0.160	0.299	-0.161	0.981
	X_8	0.366	0.286	0.234	-0.052	0.002	0.078	-0.152	0.316	-0.143	0.933
	X_9	0.446	0.288	0.264	-0.056	0.001	0.086	-0.149	0.261	-0.173	0.967
Remain path coefficient=0.1061											
	X_1	0.286	-0.087	0.050	-0.011	0.408	-0.022	0.190	0.150	-0.033	0.929
	X_2	0.269	-0.093	0.050	-0.011	0.441	-0.023	0.199	0.174	-0.032	0.974
	X_3	0.263	-0.086	0.054	-0.013	0.370	-0.023	0.192	0.155	-0.032	0.882
	X_4	0.208	-0.067	0.045	-0.015	0.275	-0.017	0.159	0.125	-0.024	0.688
SAT	X_5	0.252	-0.089	0.044	-0.009	0.462	-0.021	0.188	0.170	-0.029	0.968
	X_6	0.265	-0.087	0.051	-0.011	0.395	-0.024	0.192	0.158	-0.032	0.908
	X_7	0.265	-0.091	0.051	-0.012	0.425	-0.023	0.204	0.175	-0.031	0.965
	X_8	0.232	-0.088	0.046	-0.010	0.426	-0.021	0.193	0.185	-0.028	0.935
	X_9	0.283	-0.088	0.051	-0.011	0.405	-0.023	0.190	0.153	-0.034	0.927
Remain path coefficient=0.1278											

The data underlined are direct path coefficients, data in sum column are correlation coefficients, and the rest data are indirect path coefficients.

variance of each principal component was then computed (Table 4) to select principal components whose cumulative contribution to the variance was greater than 85%. The principal component loading represents the correlation between the original data and the principal component.

The component score coefficient matrix (Table 5), which contains values that equal the principal

Table 4. Loading matrix for the principle components (PC 1 and PC 2) in the PCA using data from all soil samples.

Variable	PC1	PC2
>0.25 mm	-0.982	0.146
0.25-0.02 mm	0.974	0.007
Silt + clay	0.965	-0.238
OM	0.953	-0.155
T-N	0.990	0.044
Av-N	0.947	-0.247
T-P	0.867	-0.276
Av-P	0.909	0.364
T-K	0.972	-0.097
Av-K	0.995	0.044
C.E.C	0.944	0.205
$CaCO_3$	0.965	-0.149
CAT	0.900	0.413
UAT	0.972	0.196
APAT	0.990	0.003
SAT	0.992	0.049
Eigenvalue	14.770	0.605
% of variance	92.313	3.782
% cumulative	92.313	96.095

Table 5. The component score coefficient matrix.

Variable	PC1	PC2
>0.25 mm	-0.256	0.152
0.25-0.02 mm	0.254	0.014
Silt + clay	0.252	-0.302
OM	0.250	-0.155
T-N	0.259	0.034
Av-N	0.247	-0.311
T-P	0.224	-0.374
Av-P	0.239	0.442
T-K	0.253	-0.130
Av-K	0.258	0.039
C.E.C	0.246	0.250
$CaCO_3$	0.251	-0.179
CAT	0.238	0.488
UAT	0.254	0.249
APAT	0.259	-0.027
SAT	0.257	0.119

component loading divided by the corresponding eigenvalue was then calculated. Based on this matrix, the score for every desertification degree was computed for each principal component (Table 6), calculation models as follows:

$$Z_1= -0.256X_1+0.254X_2+0.252X_3+0.250X_4+0.259X_5+0.247+X_6+0.224X_7+0.239X_8+0.253X_9+0.258+X_{10}+0.246_{11}+0.251+X_{12}+0.238+X_{13}+0.254+X_{14}+0.259+X_{15}+0.257X_{16}$$

Here, X_1 to X_{16} represent the standardized data for the indicators; Z_1 represents the score of the desertification degree for PC1; we got the Z_2 the same way:

$$F_1=0.92313Z_1+0.03782Z_2$$

The positive weighting coefficient of each indicator was

UAT > SAT > T-N > >Av-K > CAT > APAT > Av-P > C.E.C. > Fine sand > T-K> $CaCO_3$ > OM > Silt + Clay > Av-N > T-P, coarse sand with negative weighting coefficient. This showed that, except coarse-fine sand, all other factors contributed to improving the soil quality value. These results indicated that the degree of their contribution to the improvement of soil quality was: biological factors > nutrient factors > particle factors. As a result of this analysis, the biological factors were the dominant factors in determining soil quality. Fine sand was the most important particle factor. Thus, improvements in these parameters will have important significance for reversing desertification.

Based on the aforementioned analysis, Table 6 shows the integrated assessment of soil quality of different desertification degree. 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. 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 2 shows that the soil quality increased from mobile sand land to fixed sand land. These results indicated that in the process of desertification reversal, 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 played a remarkable role in controlling desertification.

Table 6. The principal component scores and the resulting integrated value of soil quality.

Variable	PC1	PC2	Integrated assessment value
Mobile sand land	-4.834	-0.507	-4.481
Semi mobile-sand land	-1.120	1.013	-0.996
Semi-fixed sand land	1.616	-0.216	1.484
Fixed sand land	4.338	-0.289	3.993

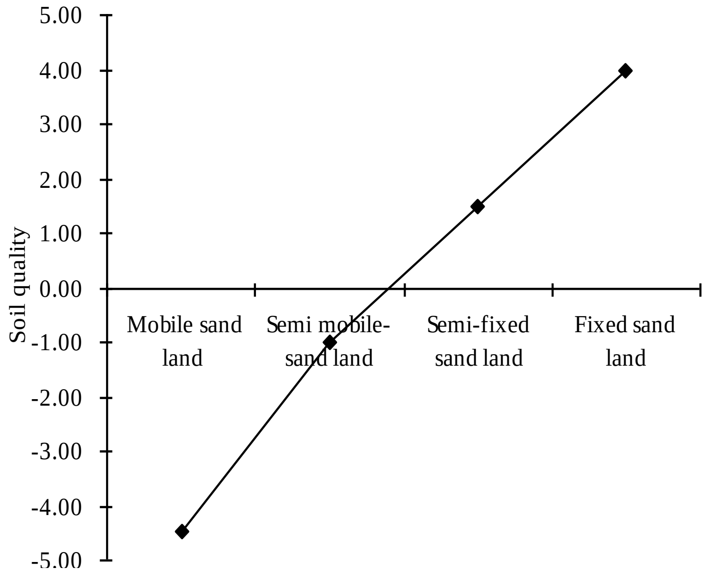

Figure 2. Changes in the soil quality value along a sequence from different degree of desertification land.

Conclusion

The agro-pastoral transition zone of northern Shaanxi has experienced both an expansion and a subsequent rehabilitation of its desertified lands during the past 50 years. Before 1990's, the extent of desertification showed a sharp increase. However, as awareness of the need for environmental protection increased, many engineering and biological measures such as the Three Norths Shelter Forest System Project and Taihang Mountains Afforestation Project were taken to prevent desertification; as a result, the desertification began to reverse by that time. The dominant soil particle size changed from coarse sand to a combination of 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.

Based on the path analysis, soil organic matter was the main factor that affected soil enzymes activities directly while total P was less important. Available K, organic matter, and available P had the most direct effect on urease, alkaline phosphatase and invertase activities, respectively and the relatively minor remaining path coefficients indicated a good reliability of this method. PCA revealed that the biological factors were the dominant factors in determining soil quality. Fine sand was the most important particle factors.

The results of this study provide support for the belief that artificial restoration and reforestation in areas with severe desertification can improve soil quality. These results have important implications for the control of desertification in other areas.

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