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RESTORATION AFFECT SOIL ORGANIC CARBON AND NUTRIENTS IN DIFFERENT PARTICLE-SIZE FRACTIONS

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ABSTRACT

Desertification is reversible and can often be prevented by adopting measures to control the causal processes. Desertification has generally decreased in most of the arid and semiarid areas of China during the last few decades because of the restoration of degraded vegetation and soil nutrients. However, little is known about the responses of soil nutrients in different particle-size fractions to the restoration process and about the importance of this response to the restoration of bulk-soil nutrients. In this study, we separated bulk-soil samples in different sieve fractions: coarse-fine sand (2·0–0·1 mm), very fine sand (0·10–0·05 mm) and silt + clay (<0·05 mm) fractions. Soil organic carbon (SOC), N, P and K contents stored in the silt + clay were greater than the contents of non-protected nutrients in the coarser fractions. During the restoration of desertified land, the content and stability of bulk-soil SOC, total N and P and available N, P and K increased with increasing nutrient contents in all fractions. Topsoil nutrients stored in coarse-fine sand and very fine sand fractions were more sensitive than those stored in the silt + clay fraction to the fixation of mobile sandy lands and vegetation recovery. The changes of bulk-soil nutrients and their stability were decided by the soil nutrients associated with all particle-size fractions. Path analysis revealed that SOC and total nutrients in very fine sand and available nutrients in coarse-fine sand were the key factors driving the soil recovery. These results will help us understand soil recovery mechanisms and evaluate the degree of recovery. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: desertified-land restoration; desertification reversal; distribution of soil nutrients; particle-size fractions; path analysis

INTRODUCTION

Desertification has attracted widespread international attention because of its consequences, including the destruction of resources and environmental systems, increased poverty and social instability and decreased economic development (Reynolds *et al.*, 2011). It can be defined as land degradation in arid, semiarid and dry sub-humid regions as a result of many factors, including climatic variations and human activities (UNEP, 1997). As one of the most important social, economic and environmental problems in the world today (Brevik *et al.*, 2015; Wang *et al.*, 2015), desertification is most damaging in drylands, which cover about 41% of the world's land surface (including hyper-arid areas) and are inhabited by more than 38% of the global population of 6·5 billion people (UNCCD, 2008). Moderately degraded are 10–20% of these drylands (MEA, 2005), which is estimated to directly affect over 250 million people in developing countries (Reynolds *et al.*, 2007).

China is one of the countries that is most significantly affected by desertification. All arid, semiarid and sub-humid areas of northern China are susceptible to desertification on account of the region's frequent droughts, the persistent strong winds and the easily erodible soil surface. This vulnerability may be enhanced by irrational land use and overexploitation of natural resources (Zhang *et al.*, 2007; Chen & Tang, 2005). Desertification has become a challenge facing more than 1·6 million km^2 and 200 million people in northern China (Wang *et al.*, 2015). In this region, the surface area affected by aeolian erosion processes increased at a rate of 1,560 $km^2\,y^{-1}$ from 1955 to 1975, 2,100 $km^2\,y^{-1}$ from 1976 to 1987 and 3,600 $km^2\,y^{-1}$ from 1988 to 2000 (Wang *et al.*, 2004). Reactivation of fixed dunes causes the rapid expansion of sandy desertification in the windy and sandy regions of north-western China. This occurs by the evolution of fixed dunes (usually with vegetation cover above 40%) into semi-fixed dunes (vegetation cover of 15–40%) or mobile dunes (vegetation cover below 15%) under conditions that lead to sand transport, which is aggravated by reduction of the vegetation cover or increased sand transport (Zhu, 1998; Wang & Zhu, 2001). Due to the importance of plants in stabilizing the soil, decreases in vegetation cover are a notable sign of desertification (Wang *et al.*, 2009).

Desertification does not necessarily represent an irreversible and permanent process of land degradation, because dune mobilization can decrease and ecosystem degradation can reverse when vegetation communities are restored (Wang *et al.*, 2009). In addition, desertification can be mitigated or even reversed by decreasing the pressure imposed by excessive human activities and by adopting measures such as revegetation or grazing exclusion to control the process (Briassoulis, 2011). Land that has not been degraded beyond its ecological threshold has considerable self-

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restoration ability (Chen & Duan, 2009), and this means that the restoration of desertified land is possible in a range of environments once the pressure has been removed. The process of restoration can be called "desertification reversal," which is a recovery process that mainly occurs through revegetation in arid, semiarid and parts of the sub-humid regions of China. This process is characterized by restoration of plant communities, stabilization of shifting sands, colonization of soils by organisms that promote the development of soil crusts, improvements in soil physical and chemical properties, increases in vegetation productivity and biodiversity and restoration of the ecological balance (Wienhold, 2001; Cheng *et al.*, 2004; Su *et al.*, 2010; Su *et al.*, 2013).

Currently, the area under potential, light and moderate desertification risk is estimated as ~60% of desertified land in northern China (Wang, 2004). Research suggests that restoration of vegetation communities and other desertification-control measures might help these areas recover within a relatively short time (Zhang *et al.*, 2004). For example, during the past 20 years, some reversal of desertification has occurred in the central and eastern regions of northern China as a result of the adoption and implementation of sustainable and effective management measures such as planting of new vegetation and grazing exclusion, especially in the Nenjiang and Horqin sandy lands, the Mu Us Sandy Land on the edge of the East Asian monsoonal area and the Hexi Corridor in north-western China (Wang *et al.*, 2015). As a result of such measures, combined with the effects of a less harsh climate, desertification processes were controlled in most of the arid and semiarid areas of China by the 2000s, except for parts of western China such as the Tarim Basin (Wang *et al.*, 2008). During recent decades, efforts to rehabilitate desertified land have been concentrated in northern China. However, desertification caused by frequent and fierce floods, over-cultivation of sloping land and deforestation of hillslopes is more serious in central and south-western China. In particular, the watersheds of the middle and lower Yangtze River in the southwest, the Pearl River in the south and the Yellow River in central China have become somewhat neglected (Zhang *et al.*, 2007). We conclude that China still faces a serious desertification problem.

The development or reversal of desertification is strongly conditioned by changes in the vegetation cover. Because the soil is a key factor that controls vegetation growth, changes in vegetation cover and composition depend strongly on soil characteristics within the rooting zone (Robertson *et al.*, 1993; Jafari *et al.*, 2004). Thus, changes in soil properties are reliable indicators of desertification processes in arid and semiarid regions (Mabbutt, 1986; Jin *et al.*, 2013). Many studies have focused on the effects of desertification control and vegetation restoration on soil physical properties (e.g. water-holding capacity, particle-size distribution and structure), soil C sequestration and bulk-soil nutrients availability (N, P and K) and have aimed to elucidate the responses of these soil properties to the reversal of desertification (Verrecchia *et al.*, 1995; Lal, 2002; Li *et al.*, 2007; Chen *et al.*, 2009; Raiesi & Asadi, 2006; Chen & Duan, 2009). These researchers found that the reversal of desertification was accompanied by an increased content of fine particles in soil and in soil nutrient contents. Soil structure is continuously improved during the process of desertification reversal, as it does during the soil formation process (Duan *et al.*, 2004; Brevik, 2013).

However, research has ignored an essential characteristic of soil: it is a mixture of particles in a range of size classes. These different particle-size fractions have different contributions to soil's nutrient supply capacity (Wang *et al.*, 2000). For example, the amounts of soil C, N, P and K differ greatly among the particle-size fractions (Hinds & Lowe, 1980). The soil organic C (SOC) stored in fine particles is considered to be stable SOC, with a high degree of humification, because it is "protected" against degradation and leaching by the small pores in these materials (Rosell *et al.*, 2000). The proportion of SOC associated with the sand fractions is called particulate organic C, which is non-protected and is therefore the most active component of SOC (Gregorich & Ellert, 1993). Thus, the clay and silt fractions generally contain more SOC than the sand fraction (Galantini *et al.*, 2004; von Lützow *et al.*, 2007; Balabane & Plante, 2004). In recent years, more researchers have studied the effects of long-term tillage, crop rotation, revegetation, desertification and land-use change on the distribution of SOC among the different particle-size fractions (Lobe *et al.*, 2001; Wu *et al.*, 2006; Qin *et al.*, 2010; Gelaw *et al.*, 2013; Kocyigit & Demirci, 2012). However, only a few studies have focused on the distribution of soil total N (TN). For example, Su & Zhao (2003) studied the dynamic variation of TN in different particle-size fractions (2–0·1, 0·1–0·05 and <0·05 mm) of sandy soil (0–15-cm depth) during the process of desertification in the Horqin Sandy Land of Inner Mongolia in northern China, and Jia *et al.* (2006) analysed the influence of revegetation on the distribution of TN in different fractions (2–0·1, 0·1–0·05 and <0·05 mm) of the surface soil (0–5-cm depth).

These studies showed different responses and sensitivity of SOC and TN in different particle-size fractions to changes in the soil environment. However, no studies focused on the responses of other soil nutrients. Thus, the effects of restoration of desertified land on the distribution of soil nutrients among the particle-size fractions remain poorly understood. In particular, there has been no detailed report on the contributions of nutrients in the different particle-size fractions to the bulk-soil nutrient contents or on the contributions of particles in different size classes to the soil's overall nutrient supply capacity.

The aim of the present study was to clarify the effects of restoration of desertified land on soil nutrients in the various particle-size fractions. To accomplish this, we examined the restoration that is occurring in Yanchi County of China's Ningxia Hui Autonomous Region. In addition, we used path analysis to investigate the contributions of nutrients in different particle-size fractions to the overall soil nutrient pool.

Our study hypotheses were that restoration would have significant impacts on the soil nutrients in individual particle-size fractions, that the soil nutrients associated with different-sized soil particles would respond differently during ecosystem recovery and that the contributions of nutrients associated with different particle sizes to the restoration of bulk-soil nutrients would differ. To test these hypotheses, our specific research objectives were as follows: (1) to analyse changes in SOC and other nutrients in the bulk soil and in the different particle-size fractions (2–0·1, 0·1–0·05 and <0·05 mm) during the restoration process; (2) to evaluate the impact of desertification reversal on the distribution of SOC and other nutrients among the particle-size fractions; and (3) to assess the contributions of nutrients in the different particle-size fractions to the restoration of overall bulk-soil nutrients. The results are expected to improve our understanding of soil recovery mechanisms during the restoration of desertified land and provide a way to evaluate the degree of recovery from desertification.

MATERIALS AND METHODS

Study Sites

Yanchi County lies in the eastern part of China's Ningxia Hui Autonomous Region (106°30′E to 107°41′E, 37°04′N to 38°10′N; elevation ranges from 1,295 to 1,951 m asl), where it covers a total area of 6,743 km^2 (Figure 1). The county is bordered by Shanxi and Gansu provinces and by the Inner Mongolia Autonomous Region. Its north-eastern edge touches the Maowusu sandy land, and the south-western edge merges with the Loess Plateau. It is a typical transitional zone: from south to north, the terrain changes from the Loess Plateau to the Ordos Plateau, the climate changes from semiarid to arid (across the isoline for 200-mm mean annual rainfall) and the vegetation types change from dry steppe vegetation to desert steppe.

The region has a typical temperate continental climate. Long-term climate data recorded at the Yanchi County Weather Station between 1980 and 2010 indicate a mean annual temperature of 8·5 °C, with the highest and lowest monthly mean temperatures in July and January, at 34·9 and −24·2 °C, respectively. The mean annual precipitation is 279·5 mm, of which 62% falls between July and September. The mean annual pan evaporation is 2,897 mm, which is much higher than the annual precipitation. Gales (with a wind speed >8 m s^{-1}) occur at an average of 23·4 times per year.

According to World Reference Base for Soil Resources (FAO/ISRIC/ISSS, 1998), the soil types are Calcic Kastanozems in the south and Calcaric Arenosols and Haplic Calcisols in the north. The main vegetation types are shrubs (e.g. *Salix psammophila* and *Caragana microphylla*), steppe vegetation (e.g. *Stipa grandis*, *Stipa bungeana*, *Agropyron cristatum* and *Thymus serpyllum* var. *mongolicus*) and sandy or desert steppe vegetation (e.g. *Artemesia ordosica*, *Caragana tibetica*, *Oxytropis aciphylla*, *Nitraria sibirica*, *Kalidium foliatum* and *Corispermum patelliforme*).

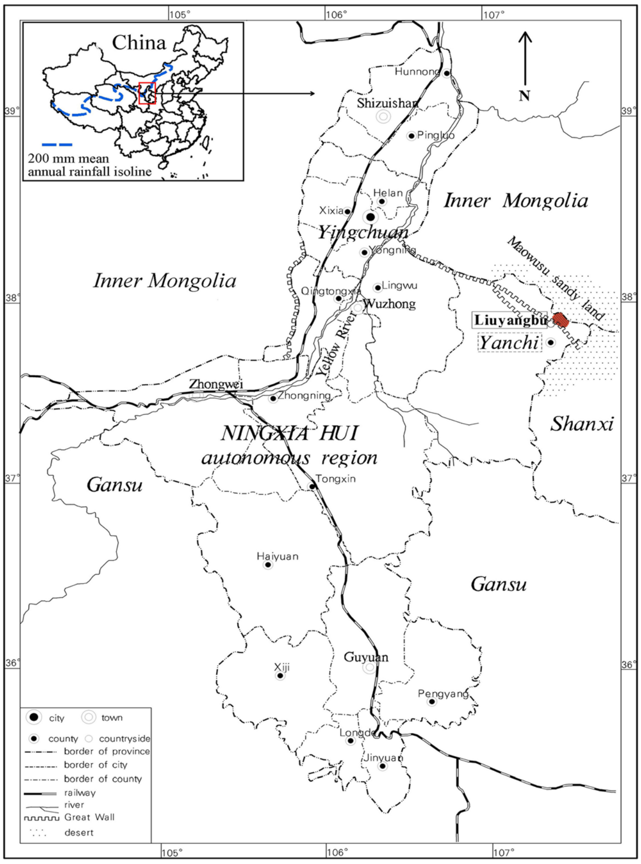

Figure 1. Location of the study area in China. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

During the last 50 years, Yanchi County has experienced both an expansion and a rehabilitation of desertified lands. During 1961–1989, the area of desertified land expanded from 1,006·11 to 2,366·67 km^2 (Zhou & Zhao, 2005). After 1989, however, the area of desertified land began to diminish, probably because of the combined impact of change in climate and land management. According to the precipitation data from the Yanchi County weather station, mean annual precipitation from 1980 to 1989, from 1990 to 1999 and from 2000 to 2010 was 254·4, 309·9 and 274·7 mm, respectively; thus, the mean annual precipitation from 1990 to 2010 was higher than that from 1980 to 1989. The years 2001 and 2002 were unusually wet, with an annual precipitation of 377·9 and 399·1 mm, respectively, which was 98·4 and 119·6 mm higher than the long-term average.

As early as 1982, the local government implemented various measures to control desertification in this region, such as installing fences and other barriers near the edges of the areas of mobile dunes. Subsequently, land management changed; restoration of farmland to forest and grassland began in 2001, as did the construction of exclosures to prevent grazing, the prohibition of overexploitation and deforestation and tree planting (Chen & Duan, 2009). The area of mobile sandy land decreased by 64·6% between 1989 and 2003, with the areas of fixed sandy land and non-desertified land increasing greatly, whereas the area of semi-fixed sands did not change significantly (Zhou & Zhao, 2005).

Desertification reversal is a long-term dynamic process. The most accurate method of studying the changes in soil properties during this recovery process would be long-term monitoring at each study site, but this method requires long-term monitoring data that are usually not available, and the results may be limited in applicability to the specific study sites. Because of a lack of sufficient historical data in the study area, it was necessary to instead combine data from sites with different durations of restoration plans. We therefore studied the variation of SOC and other nutrients along a transect from mobile dunes to stable steppe vegetation, with the transect serving as a proxy for the temporal changes that would occur with the increasing duration of restoration. From north to south, the terrain of the study area changes from mobile sandy land to semi-mobile sandy land, fixed sandy land and steppe, and the vegetation cover increases. Along this transect, the total area of land with mobile or semi-mobile sands shows a continuous decrease. The natural vegetation transitions from communities dominated by *A. ordosica* to *A. ordosica* and *C. patelliforme* communities.

Soil Sampling

Our field sampling site was a fenced area that excluded grazing for more than 25 years, and was located in Shabianzi Village of Liuyangbu Town (107°19′E, 37°50′N), about 20 km north-east of the capital of Yanchi County. Shabianzi Village is adjacent to the south-western edge of the Maowusu sandy land. Moving from Shabianzi Village in the north towards the south, mobile dunes evolve into semi-mobile dunes, fixed dunes, flat saline–alkaline areas and hillslopes covered with stabilized sand. After more than 30 years of desertification control practices, the shifting sand dunes have mostly been stabilized, and the vegetation has began to recover.

We established three parallel 800-m sampling transects running from north to south (following the prevailing local wind direction), with the lines separated by 50 m and points within each line separated by 100 m (Figure 2). This amounted to sampling at nine distances from the sandy land, with three replicates at each distance. Each transect started 100 m from the edge of the Maowusu sandy land and ended 900 m from the edge. At 900 m from the sandy land, the vegetation community had changed into steppe with a mean vegetation cover of 50%. At each sampling point, all surface vegetation and litter were removed by hand, and a mixed sample of about 2 kg of soil was collected to a depth of 20 cm at a single randomly chosen location within a 3-m radius of the plot centre using a soil drill (diameter 5·1 cm). The collected soils were sealed in clean plastic bags and transported to the laboratory. The samples were air-dried for about 3 days in a dry, cool, well-ventilated room until they reached constant weight and then dry-sieved through a 2-mm screen to remove stones, roots and other debris. The sieved soil samples were divided into two sub-samples. One sub-sample was separated into three different particle-size fractions using physical fractionation, and the other was prepared for analysis of bulk-soil properties.

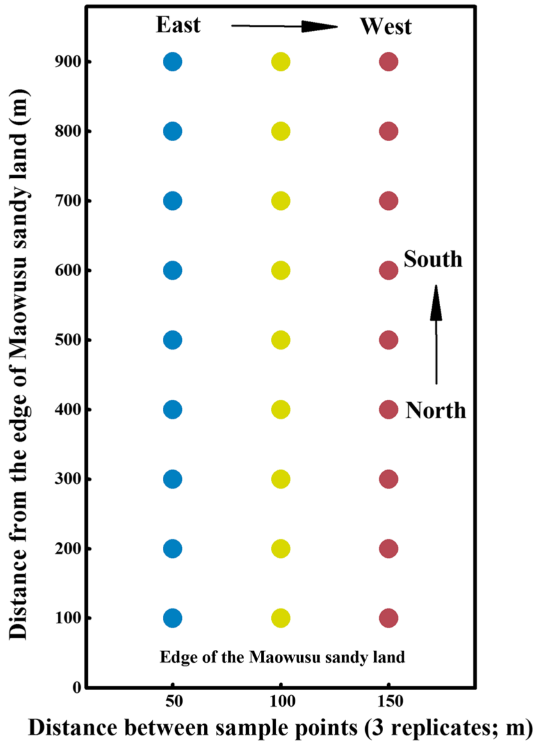

Figure 2. Distribution of the soil sampling points along the 800-m transect from north to south within the study area. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Physical Fractionation of the Soil

Individual particles larger than 0·10 mm in diameter are relatively resistant to the wind, whereas particles between 0·10 and 0·05 mm in diameter are easily eroded by the wind and particles below 0·05 mm in diameter are easily suspended as dust and carried away by the airflow (Bagnold, 1941; Jia *et al.*, 2006). Thus, we partitioned the soil samples into three size fractions by means of physical fractionation: coarse-fine sand (2·0–0·1 mm), very fine sand (0·10–·05 mm) and silt + clay (<0·05 mm). These definitions are based on the soil texture classification system formulated by the United States Department of Agriculture in 1951 (USDA, 1951).

The fractionation procedure (Rosell *et al.*, 2000) involved dispersing 50 g of the sieved soil sample in 100-mL distilled water, with repeated shaking for 1 h in the presence of ten glass beads (3 mm in diameter), followed by water-based elutriation, and leaching through 0·10-mm and 0·05-mm screens. In the final step, the samples of each fraction were dried at 65 °C for 24 h before further analysis. This method relies on physical fractionation of the soil based on its particle sizes, which has a smaller effect on subsequent analyses of soil nutrients than alternatives such as dry-sieving, ultrasonic or chemical dispersion (Saviozzi *et al.*, 1997; Stemmer *et al.*, 1998). Disadvantages of methods such as dry sieving are the difficulty of separating very fine particles and the potential loss of the silt + clay fraction (<0·05 mm). The fractionation procedure has therefore proven to be a useful tool for studying soil organic matter (Christensen, 1992) and other soil properties such as the soil N and P contents (Rosell *et al.*, 2000; Jia *et al.*, 2006).

Soil Properties Analysis

We analysed the particle-size distribution of the bulk soil; the contents of SOC, TN, total P (TP), available N (AN), available P (AP) and available K (AK) stored in bulk soil; and each separated sieve fraction.

The particle-size distribution was determined using the pipette method in a sedimentation cylinder, using sodium hexametaphosphate as the dispersing agent (Gee & Bauder, 1986). SOC was determined using the potassium dichromate volumetric method with external heating (Nelson & Sommers, 1982). TN was determined using the semi-micro Kjeldahl procedure (UDK 140 Automatic Steam Distilling Unit, Automatic Titroline 96, Italy) (ISSCAS, 1978), and TP was determined using a UV-2,450 spectrophotometer (Shimadzu, Kyoto, Japan) after H_2SO_4–$HClO_4$ digestion (ISSCAS, 1978). AN was determined using the alkaline diffusion method (ISSCAS, 1978), AP was determined using the Bray method (ISSCAS, 1978) and AK was determined by means of flame spectrometry, after extraction with 1-M NH_4OAc (ISSCAS, 1978).

Data Analysis

All statistical analyses (analysis of variance followed by LSD, correlation analysis, regression analysis and path analysis) were carried out using version 17·0 of SPSS for Windows (IBM, Armonk, NY, USA), with significance at $p < 0·05$. Before the statistical analyses, all data were analysed for normality and were found to have a normal distribution.

The relationship between any two variables in a multiple-variable system is likely to be affected by the values of other variables. To account for these confounding effects, path analysis is necessary. We therefore carried out path analysis to partition the relationships among the soil nutrient contents associated with different particle-size fractions and the bulk-soil nutrient contents into direct and indirect effects. This technique generates standardized partial regression coefficients for each nutrient by means of multiple linear regression (Wright, 1934). The standardized partial regression coefficients are called direct path coefficients (DPCs). Indirect path coefficients equal the correlation coefficients multiplied by the corresponding DPCs. In this study, we used the bulk-soil soil nutrient contents as the dependent variables and the contents in the different particle-size fractions as the independent variables in our path analysis. DPCs therefore measure the direct effect of the soil nutrients associated with a given particle-size fraction in the bulk-soil nutrients, whereas indirect path coefficients specify the effect of a soil nutrient in a given particle-size fraction that acts through the corresponding nutrient in another fraction.

RESULTS

Changes of Soil Organic Carbon and Nutrient Contents in the Bulk Soil and Particle-size Fractions

The contents of SOC, total N and P and available N, P and K associated with the different particle-size fractions were in the following order: silt + clay > very fine sand > coarse-fine sand (Figure 3). Figure 3 shows that the contents of all nutrient parameters in the three fractions followed the same trends as the trends for the bulk-soil nutrients: they increased significantly with increasing distance from the edge of the mobile sands. The coefficients of variation for all nutrient parameters in all of the particle-size fractions were in the following order: coarse-fine sand > very fine sand > silt + clay.

Changes in the Distribution of Soil Organic Carbon and Nutrients Among the Different Particle-size Fractions

Theoretically, the proportion of SOC or TN in a given particle-size fraction equals the nutrient content in this fraction multiplied by the proportion of the bulk soil composed

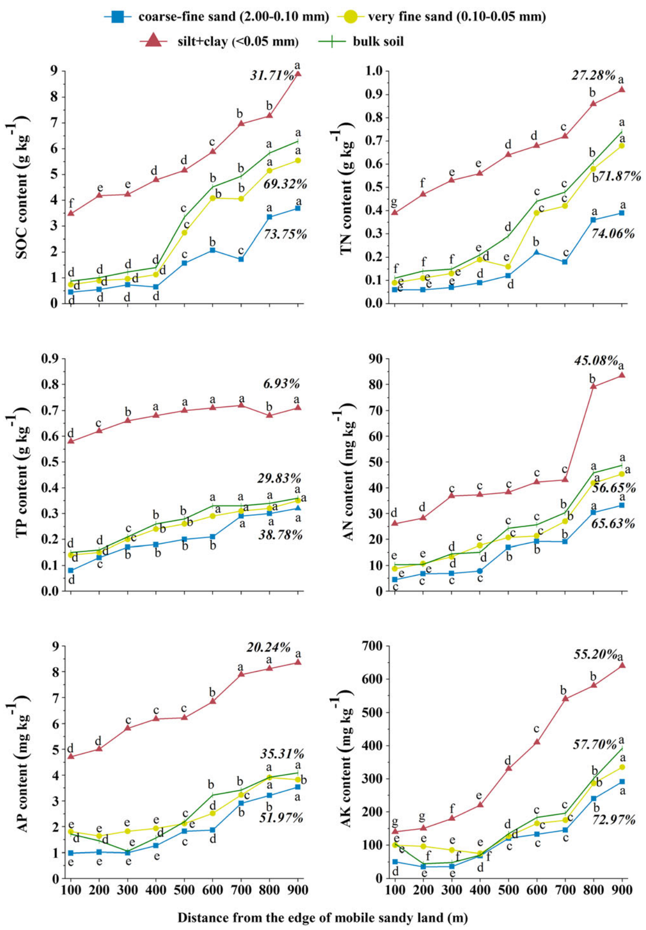

Figure 3. Mean soil nutrient contents in the bulk soil and in the three particle-size fractions (2–0·1, 0·1–0·05 and 0 < 0·05 mm) along the studied transects (the percentages represent the coefficients of variation of the soil nutrients in each particle-size fraction. Values labeled with different lowercase letters differ significantly between particle-size fractions at a given distance ($p < 0·05$)). SOC, soil organic carbon; TP, total P; AN, available P; TN, total N; AN, available N; AK, available K. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

of that fraction and then divided by the nutrient content in the bulk soil (Garten *et al.*, 1999). Figure 4 shows the particle-size distribution as a function of the distance from the edge of the mobile sands. Coarse-fine sand made up the majority of the particles at all distances between 100 and 500 m but decreased with increasing distance, reaching about 35% at 900 m. Very fine sand and silt + clay contents increased with distance from the mobile sands, with the silt + clay content statistically surpassing the fine sand content at 400 m and the coarse-fine sand content at 800 m.

Figure 5 shows the proportions of SOC and nutrients stored in each particle-size fraction. To a distance of 500 m from the edge of the mobile sands, the proportions were in the following order: coarse-fine sand > silt + clay > very fine sand. Between 600 and 900 m, the order changed to silt + clay > coarse-fine sand > very fine sand. This behaviour fits the trends in the relative proportions of these particle-size fractions (Figure 4). Figure 5 also shows that the proportion of the soil nutrients in the silt + clay fraction increased rapidly with increasing distance from the mobile sands versus a slow increase in the very fine sands; the proportion in the coarse-fine sand fraction increased to a distance of about 300 m from the edge of the mobile sands and decreased thereafter.

Changes in the Enrichment Factor for Soil Organic Carbon and Nutrients in the Different Particle-size Fractions

The enrichment factor (E) for a given soil nutrient in a given particle-size fraction equals the ratio of its amount in that fraction to its amount in the bulk soil (Christensen, 1992). Values greater than 1 therefore indicate that the fraction is enriched in a particular element.

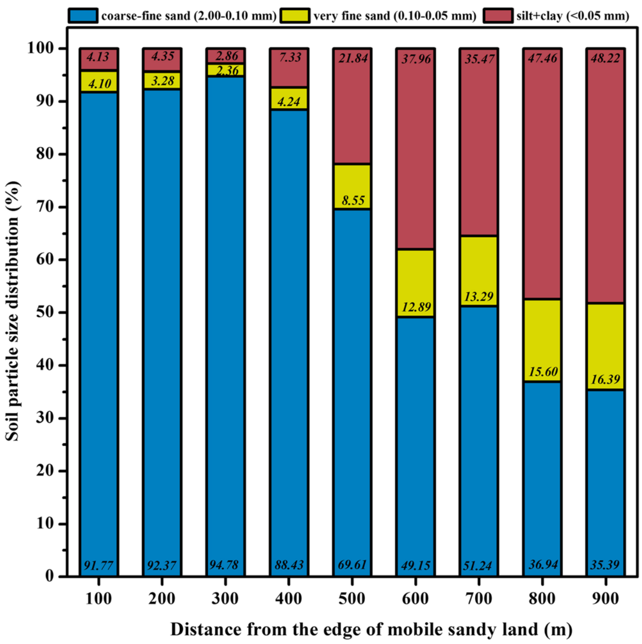

Figure 4. Changes in the soil particle-size distribution along the transect in the study area. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table I shows that the enrichment factors for all nutrient parameters were in the order silt + clay > very fine sand > coarse-fine sand at all distances from the edge of the mobile sands. Mean E values for the coarse-fine sand fraction were less than 1, with averages ranging from 0·48 (E_{TN}) to 0·77 (E_{AP} and E_{AK}), and there were no significant differences with increasing distance from the edge of the mobile sands. For the very fine sand, all values of E_{SOC}, E_{TN} and E_{TP} were less than 1, but E_{AN}, E_{AP} and E_{AK} were occasionally greater than 1, as well as mean E_{AP} and E_{AK}. None of the enrichment values changed significantly with increasing distance from the edge of the mobile sands. However, all E values for the silt + clay fraction were greater than 1, with averages ranging from 2·04 (E_{AN}) to 3·01 (E_{AP}). Values between 100 and 400 m were often significantly larger than those between 500 and 900 m.

Relationship Between the Soil Organic Carbon and Nutrients in the Particle-size Fractions and the Bulk-soil Nutrients

As expected, the amounts of all nutrient parameters in the bulk-soil were strongly and significantly correlated with the corresponding parameter values in the three particle-size fractions (Table II). Thus, it was necessary to use path analysis to determine the direct and indirect effects of all nutrient parameters in the three particle-size fractions on the corresponding parameter values in the bulk soil.

Table III shows that the impact and significance of the six nutrient parameters associated with the three particle-size fractions in the bulk-soil nutrients differed among the fractions. For SOC, the DPC was the highest for the impact of SOC in the very fine sand in bulk-soil SOC (1·047), and the sum of the direct and indirect coefficients for all three fractions (0·999) was also the highest for this fraction. This suggests that the direct and indirect impacts of SOC were the strongest in the very fine sand, followed by the DPCs for coarse-fine sand (0·077) and silt + clay (−0·126). The sum of the direct and indirect coefficients (0·953) was equal for the two latter fractions.

For TN and TP, the DPCs for the impacts of TN and TP in bulk-soil TN and TP were the highest in the very fine sand (0·619 and 1·188, respectively), and the sums of the direct and indirect coefficients (0·988 and 0·994, respectively) were also the highest. The DPCs for TN were lower for the coarse-fine sand (0·006) than those for the silt + clay (0·380), and the sum of their direct and indirect coefficients was also lower (0·972 and 0·977, respectively). The DPC for the impacts of TP in bulk-soil TP was lowest for the silt + clay (0·061), and the sum of its direct and indirect coefficients (0·906) was lower than that for coarse-fine sand (0·932). Thus, TN and TP had opposite patterns for the silt + clay fraction and the coarse-fine sand fraction.

For all three available nutrients (AN, AP and AK), the DPCs and the sum of the direct and indirect coefficients were both strongest for the coarse-fine sand fraction, followed by the very fine sand fraction.

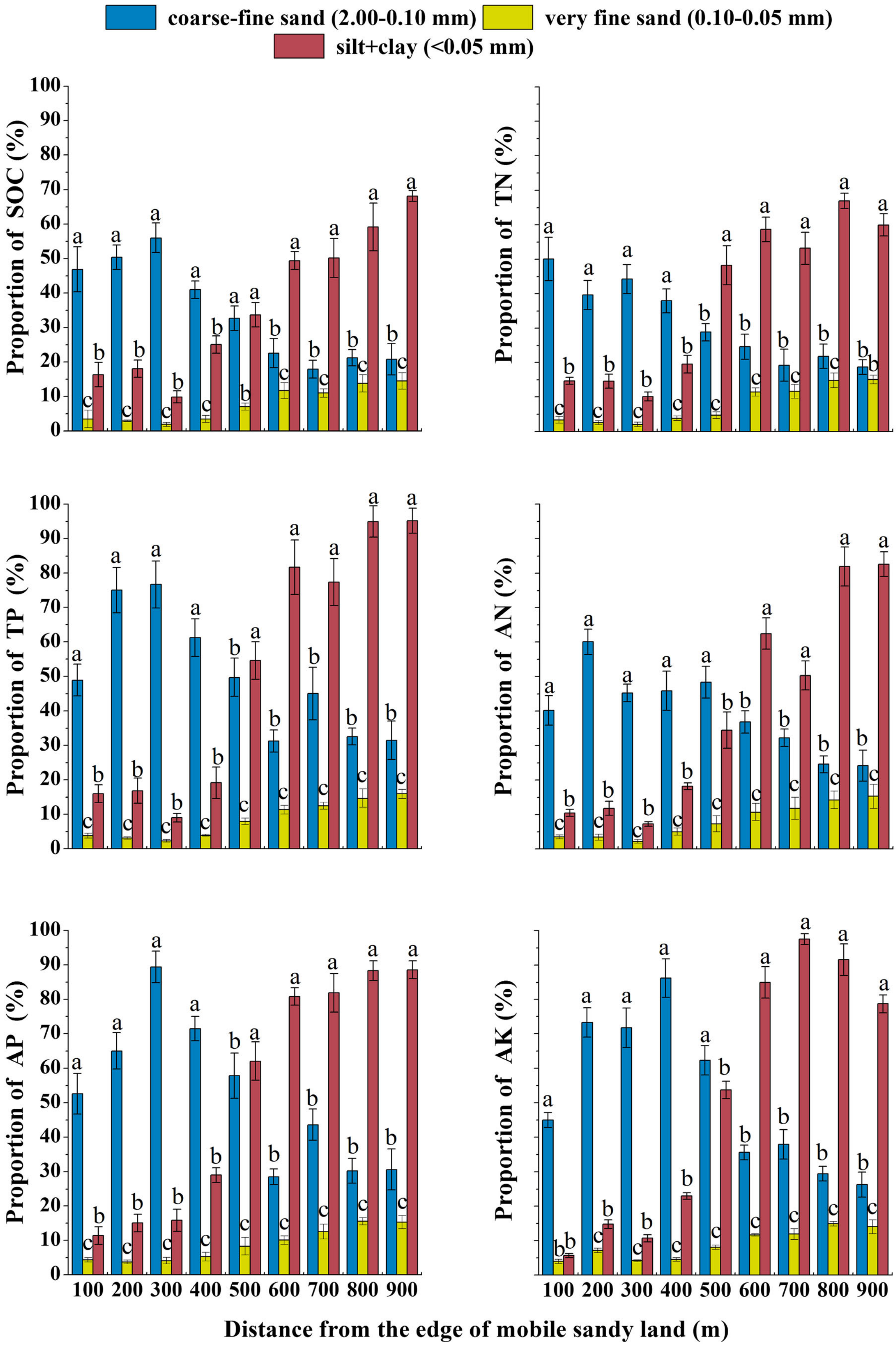

Figure 5. Proportions of soil nutrients in each of the three particle-size fractions (values labelled with different lowercase letters differ significantly between particle-size fractions at a given distance ($p < 0{\cdot}05$)). SOC, soil organic carbon; TP, total P; AN, available P; TN, total N; AN, available N; AK, available K. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

Table I. The enrichment factors (E, which represents the ratio of the value in the fraction to the value in the bulk soil) for the soil nutrient parameters in the three particle-size fractions

Sample	E_{SOC}	E_{TN}	E_{TP}	E_{AN}	E_{AP}	E_{AK}
Coarse-fine sand (2·0–0·1 mm)						
100	0·51a	0·55a	0·53c	0·44b	0·57b	0·49b
200	0·54a	0·43b	0·81a	0·65a	0·70a	0·79a
300	0·59a	0·47a	0·81a	0·48b	0·94a	0·76a
400	0·46a	0·43b	0·69b	0·52b	0·81a	0·97a
500	0·47a	0·41b	0·71b	0·69a	0·83a	0·90a
600	0·46a	0·50a	0·64b	0·75a	0·58b	0·72a
700	0·35b	0·38b	0·88a	0·63a	0·85a	0·74a
800	0·57a	0·59a	0·88a	0·66a	0·82a	0·80a
900	0·59a	0·53a	0·89a	0·68a	0·87a	0·74a
Average	0·50	0·48	0·76	0·61	0·77	0·77
Very fine sand (0·10–0·05 mm)						
100	0·84a	0·82a	0·93a	0·85a	1·06bc	0·97b
200	0·88a	0·79a	0·94a	1·03a	1·13b	2·17a
300	0·78a	0·87a	0·95a	0·92a	1·73a	1·76a
400	0·81a	0·90a	0·92a	1·18a	1·24b	1·07b
500	0·82a	0·55b	0·93a	0·85a	0·97c	0·94b
600	0·90a	0·89a	0·88a	0·83a	0·78c	0·90b
700	0·82a	0·88a	0·94a	0·89a	0·94c	0·89b
800	0·88a	0·95a	0·94a	0·91a	1·00bc	0·95b
900	0·88a	0·92a	0·97a	0·93a	0·93c	0·86b
Average	0·85	0·84	0·93	0·93	1·09	1·17
Silt + clay (<0·05 mm)						
100	3·95a	3·55a	3·87a	2·54a	2·75bc	1·36c
200	4·14a	3·36a	3·88a	2·72a	3·46b	3·39a
300	3·42a	3·53a	3·14ab	2·54a	5·54a	3·73a
400	3·41a	2·67b	2·62b	2·48a	3·96b	3·14a
500	1·54b	2·21b	2·50b	1·58b	2·84b	2·46b
600	1·30b	1·55c	2·15b	1·64b	2·13c	2·24b
700	1·41b	1·50c	2·18b	1·42b	2·31c	2·75b
800	1·25b	1·41c	2·00b	1·73b	2·07c	1·93c
900	1·41b	1·24c	1·97b	1·71b	2·04c	1·63c
Average	2·43	2·34	2·70	2·04	3·01	2·51

SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; AN, available nitrogen; AP, available phosphorus; AK, available potassium. Values in a column followed by the same letter are not significantly different ($p \leq 0·05$).

Table II. Correlation coefficient (R^2) between soil nutrients in the bulk soil and soil nutrients in the three particle-size fractions

	CFOC	VFOC	SCOC
SOC in bulk soil	0·971**	0·987***	0·981***
	CFTN	VFTN	SCTN
TN in bulk soil	0·988***	0·994***	0·947***
	CFTP	VFTP	SCTP
TP in bulk soil	0·872***	0·682**	0·653**
	CFAN	VFAN	SCAN
AN in bulk soil	0·928***	0·984***	0·943***
	CFAP	VFAP	SCAP
AP in bulk soil	0·931***	0·924***	0·919***
	CFAK	VFAK	SCAK
AK in bulk soil	0·889***	0·769**	0·877***

CFOC, soil organic carbon (SOC) in the coarse-fine sand; VFOC, SOC in the very fine sand; SCOC, SOC in the silt + clay; CFTN, total nitrogen (TN) in the coarse-fine sand; VFTN, TN in the very fine sand; SCTN, TN in the silt + clay; CFTP, total phosphorus (TP) in the coarse-fine sand; VFTP, TP in the very fine sand; SCTP, TP in the silt + clay; CFAN, available nitrogen (AN) in the coarse-fine sand; VFAN, AN in the very fine sand; SCAN, AN in the silt + clay; CFAP, available phosphorus (AP) in coarse-fine sand; VFAP, AP in the very fine sand; SCAP, AP in the silt + clay; CFAK, available potassium (AK) in coarse-fine sand; VFAK, AK in the very fine sand; SCAK, AK in the silt + clay.
**Significant at $p \leq 0·05$;
***Significant at $p \leq 0·001$.

DISCUSSION

Effects of Restoration of Desertified Land on the Proportions of the Three Particle-size Fractions and Corresponding Changes in Soil Organic Carbon and Nutrients Contents

The gradual decrease in desertification along the sampling transects from mobile sandy land, semi-mobile sandy land, semi-fixed sandy land and fixed sandy land to steppe is seen as a process of restoration. Our study showed that this process resulted in the accumulation of very fine sand and silt + clay particles in the top 20 cm of the soil and a decrease in the proportion of coarse-fine sand fractions. This agrees with the result of previous work by Duan *et al*. (2003), who reported that a 43-year recovery from desertification caused by a combination of windbreaks, straw checkerboard barriers and planted xerophytic shrubs was generally accompanied by increased fineness in the surface soil texture. This change probably resulted from the increased vegetation cover, because this improvement increases the soil surface roughness, thereby decreasing the entrainment of fine particles by the wind and increasing the capture of fine particles blown from other sites (Yu *et al.*, 2000). Furthermore, this observation is consistent with the fact that increasing vegetation cover efficiently improves soil quality by intercepting and retaining more precipitation and aeolian dust, thereby mitigating or reversing the effects of desertification on the soil (Yao *et al.*, 2009; Hooke & Sandercock, 2012).

In the present study, we found that the soil nutrient contents associated with the three particle-size fractions decreased in the order silt + clay > very fine sand > coarse-fine sand for all nutrients. This was because the smaller particles have a higher surface area and the large content of Fe and Al oxides and alkaline elements (Ca) in these fine particles increases their ability to adsorb nutrients (Parton *et al.*, 1987; Percival *et al.*, 2000; Kahle *et al.*, 2002). Studies have also reported that the amount of soil nutrients adsorbed on particles decreases with increasing particle size in both natural and cultivated soils (e.g. Groffman *et al.*, 1996).

Moving away from the edge of the mobile sands towards the steppe, the changes in soil nutrient contents indicate that the increasing vegetation cover and decreasing degree of desertification result in significant nutrient accumulation in the bulk soil and in each particle-size fraction. This was likely to be caused by the increasing content of the silt + clay fraction, which is usually associated with increasing nutrient levels (Caravaca *et al.*, 1999; Qin *et al.*, 2010). Increasing soil fineness also increases a soil's water-holding capacity and retention capacity for nutrients (Wezel *et al.*, 2000). At the same

Table III. Path analysis for the direct effects (italics, underline) and indirect effects of the six soil nutrient parameters in the three particle-size fractions on the corresponding bulk-soil values. Summation represents the sum of the direct and indirect effects

	CFOC → SOC	VFOC → SOC	SCOC → SOC
CFOC	*−0·126*	−0·121	−0·118
VFOC	1·007	*1·047*	0·994
SCOC	0·072	0·073	*0·077*
Summation	0·953	0·999	0·953
	CFTN → TN	VFTN → TN	SCTN → TN
CFTN	*0·006*	0·006	0·006
VFTN	0·605	*0·619*	0·591
SCTN	0·361	0·363	*0·380*
Summation	0·972	0·988	0·977
	CFTP → TP	VFTP → TP	SCTP → TP
CFTP	*−0·258*	−0·248	−0·212
VFTP	1·140	*1·188*	1·057
SCTP	0·050	0·054	*0·061*
Summation	0·932	0·994	0·906
	CFAN → AN	VFAN → AN	SCAN → AN
CFAN	*0·504*	0·491	0·471
VFAN	0·486	*0·498*	0·487
SCAN	0·001	0·001	*0·001*
Summation	0·991	0·990	0·959
	CFAP → AP	VFAP → AP	SCAP → AP
CFAP	*0·630*	0·618	0·602
VFAP	0·434	*0·442*	0·418
SCAP	−0·112	−0·111	*−0·117*
Summation	0·952	0·949	0·903
	CFAK → AK	VFAK → AK	SCAK → AK
CFAK	*0·556*	0·544	0·528
VFAK	0·418	*0·427*	0·391
SCAK	0·014	0·014	*0·015*
Summation	0·988	0·985	0·934

CFOC, soil organic carbon (SOC) in the coarse-fine sand; VFOC, SOC in the very fine sand; SCOC, SOC in the silt + clay; CFTN, total nitrogen (TN) in the coarse-fine sand; VFTN, TN in the very fine sand; SCTN, TN in the silt + clay; CFTP, total phosphorus (TP) in the coarse-fine sand; VFTP, TP in the very fine sand; SCTP, TP in the silt + clay; CFAN, available nitrogen (AN) in the coarse-fine sand; VFAN, AN in the very fine sand; SCAN, AN in the silt + clay; CFAP, available phosphorus (AP) in coarse-fine sand; VFAP, AP in the very fine sand; SCAP, AP in the silt + clay; CFAK, available potassium (AK) in coarse-fine sand; VFAK, AK in the very fine sand; SCAK, AK in the silt + clay.

time, the change in soil texture accelerates the transformation from the inorganic soil surface crusts that are frequently observed during the early stages of desertification reversal to the biological surface crusts that appear in later stages, accompanied by gradual soil nutrient accumulation (Li *et al.*, 2004a). In addition, the improvement of the soil structure will affect the activity of aerobic bacteria, strengthen the adsorption of nutrients by clay minerals and speed up mineralization and transformation of soil nutrients (Franzluebbers *et al.*, 2000; Lal, 2000).

According to Yu *et al.* (2000), the significant accumulation of bulk-soil nutrients with increasing vegetation cover makes soil nutrients available for plants. In addition, the increased growth of aboveground and belowground biomass leads to increased contributions of litter and plant secretions such as root exudates to the soil, thereby increasing SOC (Li *et al.*, 2004b; Brevik, 2013). These changes would increase the contents of both protected nutrients (those in the silt + clay fraction) and non-protected nutrients (those in the sand fractions) during the process of desertification reversal.

Soil nutrients in different fractions respond differently to improvements of the soil environment. However, relatively little is known about the specific sensitivity of SOC, N, P and K to changes in the soil-forming environment. In the present study, we found that SOC, N, P and K in the two sand fractions responded more promptly to the reversal of desertification than those in the silt and clay fraction. In particular, soil nutrients associated with the coarse-fine sand appear to be the most sensitive. This can be attributed to soil nutrients associated with coarse sand particles (>0·05 mm), which represent the non-protected portion of the nutrients that can be more easily decomposed and transformed by microorganisms than the protected component (Cambardella & Elliott, 1993). Moreover, soil nutrients interact with the finer particles (<0·05 mm) associated with the protected fractions in the soil to form complexes and micro-aggregates, which make SOC and N less accessible to decomposers and protect P and K from transformation (Diekow *et al.*, 2005; Bosatta & Agren, 1997).

Based on the distribution of SOC, total and available nutrients among the particle-size fractions, our results suggest that the relative contents of SOC, N, P and K in the coarse-fine sand were greater than those in the silt + clay and very fine sand fractions during the initial stages of recovery but that the pattern reverses during later periods. This change occurs because the silt + clay and very fine sand fractions together become the main components of the soil (accounting for 50% or more of the total) at distances of 600–900 m from the mobile sands (Figure 4). We found that the non-protected SOC, N, P and K associated with the coarse-fine sand are the dominant components of the nutrients during the initial period of recovery (i.e. at the sites closest to the mobile sands), whereas the protected nutrients associated with the silt + clay fraction become dominant during the later stages as the content of this fraction increases. This result suggests that the stability of the soil nutrients increased during the reversal of desertification.

By calculating the enrichment factors for soil nutrients in each particle-size fraction, it was possible to quantify the ability of each fraction to retain soil nutrients during the desertification reversal process. The enrichment factors (E_{TN}, E_{TP}, E_{AN}, E_{AP}, E_{AK}) were much larger for the silt + clay fraction than those for the coarse-fine sand and very fine sand fractions (Table I). This confirms that the increase in the silt + clay fraction plays an important role in the sequestration of SOC and N and in the accumulation of P and K. The enrichment factors for all nutrients in the silt + clay fraction were significantly greater at distances of about 100–400 m from the edge of the mobile sands than they were at distances of 500–900 m, which indicates that the enrichment effect is greater during the initial stages of recovery of desertified lands. This is mainly because the SOC, N, P and K contents and the silt + clay content are low during the early stages of recovery but the silt + clay particles that are present have a stronger bonding capacity than the coarser particles (Chepil, 1951).

Effects of Soil Organic Carbon and Nutrients Associated with the Three Particle-size Fractions in the Bulk-soil Nutrients

The bulk-soil SOC, total nutrients and available nutrients are composed of the protected nutrients in the silt + clay fraction and the non-protected nutrients in the two sand fractions. During the reversal of desertification, the bulk-soil SOC, TN, TP, AN, AP and AK contents increased with the accumulation of soil nutrients in all three fractions. In our research, the significantly positive correlations between the bulk-soil nutrient levels and the nutrient levels in each of the three particle-size fractions showed that the changes in soil nutrient contents and in their stability in the bulk soil depended on the contents and their stability in all three particle-size fractions. The path analysis showed that the effects of SOC, TN, TP, AN, AP and AK associated with different particle fractions had different effects in the bulk-soil nutrient contents. Based on the direct and indirect path coefficients: (1) the order of direct plus indirect effects for SOC and TP in each particle-size fraction was very fine sand > coarse-fine sand ≥ silt + clay; (2) the order of direct plus indirect effects for TN was very fine sand > silt + clay > coarse-fine sand; and (3) the order of direct plus indirect effects for all three available nutrients (AN, AP and AK) was coarse-fine sand > very fine sand > silt + clay. This indicated that SOC and total nutrients associated with the very fine sand and available nutrients associated with the coarse-fine sand were the key factors to driving the evolution of soil quality during the reversal of desertification. This conclusion can be explained by considering that the soil nutrients associated with the two sand fractions belong to the unstable non-protected pool of nutrients and respond more sensitively to the fixation of mobile sands and the restoration of plants. This can explain the rapid changes of soil quality during desertification reversal.

CONCLUSIONS

The restoration of desertified land significantly affects soil nutrient contents differently in the different particle-size fractions. The feedback between vegetation and soils during the restoration of desertified land accelerates the accumulation of SOC and of total and available nutrients both in the bulk soil and in the different particle-size fractions. The responses and sensitivity of SOC and of total and available nutrients differed among the three particle-size fractions. The near-surface nutrients in the coarse-fine sand and in the very fine sand, which represent the unprotected components, responded more sensitively than those in the silt + clay to the changes that occurred during vegetation recovery and the associated fixation of mobile sands. This study also indicated that the contents of protected SOC, N, P and K in the silt + clay fraction were always greater than those of non-protected nutrients in the coarse-fine sand and very fine sand fractions. However, because of the changes in the particle-size distribution during vegetation restoration, the proportions of SOC, N, P and K in the coarse-fine sand were greater during the early period, whereas the proportions of these nutrients associated with finer particles increased during the later stages. Thus, the stability of bulk-soil SOC, total N and P and available N, P and K increased with increasing nutrient contents in all fractions. In addition, the contents and stability of the bulk-soil nutrients were decided by the soil nutrients associated with all particle-size fractions. By performing path analysis, we found that SOC and total nutrients in the very fine sand and available nutrients in the coarse-fine sand were the most important factors during restoration of the soil. In conclusion, the natural succession of vegetation observed in our study area in response to grazing exclusion and artificial regeneration of plants through planting has helped control desertification and appears to have played an important role in the accumulation of soil nutrients.

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