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Changes of soil particle size fraction along a chronosequence in sandy desertified land: a fundamental process for ecosystem succession and ecological restoration

Ji-Yi Zhang[1] **· P. F. Gu**[1] **· L. Y. Li**[1] **· L. Y. Zong**[1] **· Wen-Ju Zhao**[2]

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Abstract
Purpose Soil is composed of particles of different sizes. A fraction of soil particles with different sizes has many vital effects on soil properties such as soil texture, soil porosity, and soil nutrient content. We intended to explore what change took place in soil particle distribution along the chronosequence of restoration and to address what implication this change has for ecosystem restoration.
Materials and methods Six restoration ecosystem sites were selected to form a chronosequence in a sandy desertified region, northern China. We examined the relative content of soil particles with different sizes and established an index of enrichment ratio to reflect the change trend of soil particle size fraction.
Results and discussion It was showed that soil substrate in this region is mainly composed of coarse sand (>0.25 mm) and fine sand (0.25–0.10 mm), the fraction of which are averagely 23.62 and 57.07 %, respectively. These characteristics make soil coarse, loose and erodible, and to be one of the reasons why sandy desertification was quickly developed in this region. In sandy desertification process, the grades of soil particles were air-classified. Fine sand was strongly enriched 1.36 times than average level, while very fine sand (0.10–0.05 mm) and silt and clay (<0.05 mm) were strongly diluted 0.14 and 0.22 times than average level, respectively. Along with the chronosequence of restoration, very fine sand and silt and clay were deposited and markedly enriched. This change in soil particle size fraction along the chronosequence has many fundamental roles for the subsequent restoration succession of sandy land ecosystem, such as promoting plant growth, strengthening soil anti-erodibility, leading to species replacement and community succession.
Conclusions From this research, it could be concluded that the response of soil particle size fraction to ecological restoration in sandy desertified lands is ecologically valuable, demonstrating that a positive cycle between plant and soil was formed to strengthen the stability of soil-plant system, and the ecosystem has the ability of self-recovering or self-organizing.

Keywords Desertification · Ecological restoration · Fraction · Plant-soil · Sandy land ecosystem · Soil particle size

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✉ Ji-Yi Zhang
zhangjy2015@126.com

[1] School of Petrochemical Engineering, Lanzhou University of Technology, 287 Langongping Road, Qilihe District, Lanzhou 730050, People's Republic of China

[2] School of Fluid Dynamics and Control Engineering, Lanzhou University of Technology, 287 Langongping Road, Qilihe District, Lanzhou 730050, People's Republic of China

1 Introduction

Sandy desertification is a serious environmental problem all over the world and a major threat for the sustainability of agriculture and economic development, especially in arid and semi-arid regions (Lal 2000; Wang 2000). In China, the total area subjected to desertification has reached 861, 600 km^2, accounting for 9 % of the total land area, of which, 66,400 km^2 exists in arid, semi-arid, and dry sub-humid areas (Research groups of "Study on Combating Desertification/ Land Degradation in China" 2008). Desertification exacerbates the problem of poverty and poor environmental quality in part of north China.

While wind erosion is the direct agent which induces desertification, soil capability of resistance to wind erosion is an important factor concerning the development rate of desertification. Because soil is the complex of particles that have different sizes, particle size fractions have many vital effects on soil properties such as soil texture, soil porosity, and soil nutrient content. Soil capability of resistance to wind erosion is influenced by its particle size fractions. Previous researches have shown that the soil with higher clay content has the higher capability of preventing soil from wind erosion than the one with less clay content under the same condition (Bagnold 1941; Hu and Liu YZ 1991; Wu 1987).

Soil particle size distribution reflected the extent of soil erosion by the wind (Lobe et al. 2001). In desertification, soil particles are air-classified because of undergoing continuous wind erosion. In the end, desertification makes the soil coarse, loose, and barren. Formerly done researches mainly focused on the changes of soil particle size fraction in desertification, while few studies worked to examine what change will take place in soil particle size fraction in the ecological restoration of sandy desertified lands. Such researches about the changes of soil particle size fraction are useful for understanding the ecology of sandy land restoration. In this paper, we examined the soil particle size fraction along with a restoration chronosequence of sandy lands in northern China and intended to address the interactions between changes in soil particle size fractions and processes of ecological restoration of sandy desertified lands.

2 Materials and methods

2.1 Study area and site description

This study was conducted at the Naiman Desertification Research Station, Chinese Academy of Sciences. The area lies at 42° 54′ N and 120° 41′ E, with an elevation of 300 m, belonging to Naiman Banner, Autonomous Region of Inner Mongolica, China. Also, the study area was located at the central-southern part of a region called Horqin Sandy Land, which is characterized by extensively distributed sand soil substrate in northern China.

This is the typical semi-arid and agro-pastoral interlocked zone, with mean annual precipitation of approximately 366 mm, falling predominantly between June and August. Average temperature in July is 23.7 °C and −12.7 °C in January. Average annual wind speed is 3.5 m s^{-1} with most of the strong wind and wind storm distributing between March and May. There are 200 annual days when wind speed is more than 5 m s^{-1} causing soil erosion. Because of farming tillage and overgrazing, as well as windy climate and loose sandy soil substrate, land desertification in this region has spread rapidly. Topography is characterized by inter-distribution of mobile sand dune, semi-fixed sand dune, stabilized sand dune, and lowland meadow (Zhao et al. 2000). The natural predominant plants are mainly some forbs such as *Agriophyllum squarrosum* (L.) Moq., *Salsola collina* Pall., *Corispermumelongatum* (Bge.ex Maxim.), *Bassia dasyphylla* (Fisch. et Mey.), *Artemisia halodendron* (Turcz. ex Bess), and *Chenopodium glaucum* L. and some grasses such as *Cleistogenes squarrosa* (Trin.) Keng and *Setaria viridis*(L.) Beauv.

Six sites selected for investigation had been abandoned from livestock grazing and afterwards enclosed about 3, 6, 10, 18, 30, and 45 years for natural revegetation, respectively. Because of the favorable water-holding capacity of sand soil substrate, seriously desertified land can accomplish better restoration with the not abundant rainfall of about 366 mm in this semi-arid region if anthropogenic disturbances are eliminated. So these sites all become more vegetated since abandoned, and the succession time of these sites was correspondingly considered as 3, 6, 10, 18, 30, and 45 years. The initial condition of these sites was all mobile sand dune with a gentle slope, and the topography and soil type were similar. Therefore, these sites were only different in ages and were comparable to each other. They also could be divided into three succession stages: 3- and 6-year sites were mobile sand dune, 10- and 18-year sites were semi-fixed sand dune, and 30 and 45-year sites were mobilized sand dune. Because these sites were the results of ecological restoration practices called as “nurture and prohibit grazing” launched by local government, rather than results of an intended research program, the restoration activity was conducted at different positions from 1 year to another. Thus, the position of these sites could not be determined intentionally but could only be selected from already existed situations, and these sites were not regularly arranged or neighbored each other in one same position but spatially partitioned from each other with a different distance from 0.5 to 7.2 km. Due to the same reasons, it was difficult to select more than one site for each age, and there was only one replicate in this study. However, we still could draw some meaningful implications for promoting ecological restoration in this region (Zhang and Wu 2014).

2.2 Field investigation and soil sample

In each of the six sites, the aboveground plant community was investigated in 60 quadrats, with the abundance, height, and cover of every species measured and recorded (Zhang et al. 2005a). Soil cores were collected in two depths of 0–10 and 10–20 cm using a soil auger at every quadrat, and soil cores from every four quadrats were loaded in one soil bag and mixed together to form one soil sample. Thus, a total of 15 soil samples were taken for each of the six sites.

2.3 Laboratory analysis of soil sample

Soil samples were carried to laboratory, air-dried, and passed through a 2-mm sieve. Then, soil particle size analysis was done by pipette method (Institute of Soil Sciences, Chinese Academy of Sciences ISSCAS 1978).

2.4 Data analysis

Because each of the six sites is at one location and not replicated, we have followed the approach of Frank et al. (1995) and considered each of the six sites as a replication of summary statistics. Values from the 15 soil samples within each site were averaged. Then, one-way analysis of variance (ANOVA) procedures were used to detect the differences in soil particle size fraction between sites. The least significant difference (LSD) was performed to determine the significance of treatment means at $P < 0.05$.

Furthermore, in order to clearly identify differences in soil particle size fraction between the six sites, we defined an enrichment ratio $(E) = B/A$. It was calculated as the ratio for each group of the particle size, where A is the average of the six sites for one particle size, and B is the value of this group of particle size in this site. When $E > 1$, it shows that this specific size of soil particle is enriched in this site. The more the value of E, the stronger the enrichment. When $E < 1$, it shows that this specific size of soil particle is diluted in this site. The lesser the value of E, the stronger the dilution. When $E = 1$, it shows that this specific size of soil particle is just at an average level. The value of E should reflect the effect of ecological restoration of different ages on soil particle size distribution.

3 Results

3.1 Changes in fraction of soil particle size along the chronosequence of ecological restoration

In the top layer (0–10 cm), Table 1 shows that content of fine sand (0.25–0.10 mm) was the highest among the four grades of soil particle size in all the six sites, and it declined in the process of ecological restoration from 77.62 % in the 3-year site to 33.85 % in the 45-year site. Content of coarse sand (>0.25 mm) was the medium, and it fluctuated slightly between 16.85 and 31.64 % among the six sites. There was not a consistent trend for coarse sand in the process of ecological restoration. Both of the content of very fine sand (0.10–0.05 mm) and silt and clay (<0.05 mm) were very small with nearly equal fraction of 1.65 and 1.67 % in the 3-year site, but they increased gradually to remarkable point with fraction of 27.38 and 16.27 % in 45-year site, respectively. The increasing trend was consistently positive.

In the neighboring subtop layer (10–20 cm), fraction and the change trend of the four grades of soil particle size along the chronosequence of ecological restoration was similar as that in the top layer. Differences between subtop layer and top layer were that fraction of fine sand in subtop layer was even bigger than other grades of soil particle size and in top layer, but the fraction of very fine sand and silt and clay in subtop layer was even smaller than other grades of soil particle size and in top layer. Fraction of coarse sand still fluctuated between 17.40 and 28.27 % which is similar to that of 16.85–31.64 % in top layer along the chronosequence of ecological restoration. Fraction of fine sand declined from 78.04 % in the 3-year site, which is nearly equal to that of 77.62 % in the top layer, to 48.73 % in the 45-year site, which is bigger than that of 33.85 % in the top layer. A fraction of very fine sand increased from a very small content of 1.87 % in the 3-year site, which is nearly equal to that of 1.65 % in top layer, to 19.23 % in the 45-year site, which is smaller than that of 27.38 % in top layer. A fraction of silt and clay also increased from an even smaller content of 0.29 % in the 3-year site than that of 1.67 % in top layer to 9.76 % in 45-year site, which is smaller than that of 16.27 % in top layer.

3.2 Enrichment ratio of soil particle size in the process of ecological restoration

Table 2 showed that, in the top layer, enrichment ratio of coarse sand was fluctuated near 1 between the 6 sites. It shows that the changes of coarse sand along the process of ecological restoration have no regular pattern. Enrichment ratio of fine sand was at the highest top of 1.36 in 3-year site, then it declined in sequence to the lowest of 0.59 in 45-year site. Inversely, both of the enrichment ratios of very fine sand and silt and clay were very small with the value of 0.14 and 0.22, respectively, in 3-year site, and they increased steadily to 2.32 and 2.16, respectively, in 45-year site.

As for subtop layer, the changes of enrichment ratio of the four grades of soil particle size along the process of ecological restoration were similar as that in the top layer.

4 Discussion

4.1 Effect of sandy desertification on soil particle size fraction

In all the six sites, the fraction of fine sand was the highest whatever in top layer or in the neighboring subtop layer, and the fraction of very fine sand and silt and clay was small. This suggests that fine sand and coarse sand are the grades of majority particles which consist of the regional soil substrate. This characteristic of soil particle size distribution makes the soil coarse, loose, and erodible. Therefore, because of

Table 1 Soil particle size distribution

Depth (cm)	Site	Particle size fraction (%)			
		Coarse sand (>0.25 mm)	Fine sand (0.25–0.10 mm)	Very fine sand (0.10–0.05 mm)	Silt and clay (<0.05 mm)
0–10	3 years	19.06 ± 7.33a	77.62 ± 7.32d	1.65 ± 1.14a	1.67 ± 0.9a
	6 years	30.14 ± 12.41b	65.72 ± 11.79c	2.27 ± 1.39a	1.87 ± 0.87a
	10 years	31.64 ± 4.72b	59.5 ± 9.48c	11.67 ± 3.5b	6.37 ± 1.65b
	18 years	21.52 ± 7.43a	55.42 ± 8.98bc	14.58 ± 5.97b	8.48 ± 1.92b
	30 years	16.85 ± 5.88a	50.32 ± 5.81b	13.11 ± 7.23b	10.54 ± 1.56c
	45 years	22.50 ± 5.54a	33.85 ± 4.59a	27.38 ± 6.63c	16.27 ± 1.37d
	Mean	23.62	57.07	11.78	7.53
10–20	3 years	19.80 ± 0.79a	78.04 ± 1.81c	1.87 ± 0.86a	0.29 ± 0.16a
	6 years	28.27 ± 0.68c	69.11 ± 1.21b	1.84 ± 0.2a	0.78 ± 0.33b
	10 years	24.38 ± 13.65abc	65.82 ± 14.9b	7.64 ± 1.68b	2.17 ± 0.43c
	18 years	19.85 ± 5.29a	70.09 ± 0.53b	7.78 ± 2.89b	2.28 ± 1.88cd
	30 years	17.40 ± 4.99a	68.68 ± 2.5b	10.56 ± 2.11c	3.36 ± 0.3d
	45 years	22.27 ± 2.26b	48.73 ± 3.6a	19.23 ± 5.4d	9.76 ± 0.45e
	Mean	22.00	66.75	8.15	3.11

Within columns, means ± SD with different letters indicate significant differences at $P < 0.05$

vegetation destruction caused by irrational anthropogenic activities such as overgrazing and land tillage, sandy desertification developed rapidly in the past 30–50 years under the windy climate in this region (Zhu and Wang 1992).

Enrichment ratio could clearly reflect the degree of change that occurred in soil particle size fraction. In 3-year site, enrichment ratio showed that fine sand was the most strongly enriched particle whose fraction was the 1.36 times of average level, while very fine sand and silt and clay were strongly diluted. The dilution of very fine sand and silt and clay could be explained as that these two grades of soil particle were more easily blown away by wind erosion because of their light quality and transported to other position with a longer distance. While coarse sand and fine sand could be seen as weight component and they were transported to nearby place with a shorter distance. Therefore, the weight component and light component of soil were separated spatially, and this consequence made the soil more coarse, loose, and easily erodible. Three-year site, the seriously desertified sandy land, is called mobile sandy land. Its soil particle size fraction could reflect the effect of sandy desertification on soil particle composition and soil texture. From the above results, it could be found out that the four grades of soil particle size were separated by wind in sandy desertification process. So, we can conclude that soil texture and quality were further degraded in

Table 2 Enrichment ratio of soil particle size

Depth (cm)	Site (years)	Particle size fraction (%)			
		Coarse sand (>0.25 mm)	Fine sand (0.25–0.10 mm)	Very fine sand (0.10–0.05 mm)	Silt and clay (<0.05 mm)
0–10 cm	3	0.81	1.36	0.14	0.22
	6	1.28	1.15	0.19	0.25
	10	1.34	1.04	0.99	0.85
	18	0.91	0.97	1.24	1.13
	30	0.71	0.88	1.11	1.40
	45	0.95	0.59	2.32	2.16
10–20 cm	3	0.90	1.17	0.23	0.09
	6	1.29	1.04	0.23	0.25
	10	1.11	0.99	0.94	0.70
	18	0.90	1.05	0.95	0.73
	30	0.79	1.03	1.30	1.08
	45	1.01	0.73	2.36	3.14

sandy desertification, and this formed a malignant cycle between soil texture and wind erosion/desertification.

4.2 Response of soil particle size fraction to ecological restoration

Another earlier research of us showed the community status of the six sites (see Table 3) (Zhang et al. 2005b). From Table 3, it could be found that 3-year site was the most seriously desertified sandy land, for its coverage was only 13.1 %, both of species richness and diversity were small, and the importance value of the single dominant species was extremely high, suggesting that plant community was simple and seriously destroyed by desertification. Time of the six sites formed a chronosequence of vegetation restoration. However, along chronosequence of the six sites, community coverage was gradually rising up to a rather ideal state of 69.1 % in 45-year site, and both of species richness and diversity gradually increased, suggesting that results of ecological restoration were promising.

When we investigated what changes happened for soil particle size distribution in the process of ecological restoration along with this chronosequence, the most worthy to be remarked thing is that a fraction of fine sand declined and it was diluted, while both of very fine sand and silt and clay were enriched. This kind of changes in soil particle size distribution could be attributed to the fine particles including very fine sand and silt and clay increased. When the content of fine particles including very fine sand and silt and clay increased, the relative content of coarse particles (mainly composed of fine sand) correspondingly declined. This suggested that fine particles including very fine sand and silt and clay were deposited in process of vegetation restoration. The longer the restoration time, the more the deposited particles.

Distribution of fine particles such as dust fall or crust in sandy desertification region indicated the intensity of aeolian activity and the stability of the aeolian environment (Zhang et al. 2014). Deposition of fine particles is an indicator for the important contribution of vegetation, implying that the improved vegetation by ecological restoration not only immobilized soil particle but also sequestrated airborne fine particles making soil texture fine.

4.3 Implication of changes in soil particle size fraction for ecological restoration

Complex interrelationships existed during recovery of ecosystem function (Kenji et al. 2014). It is important to work out what interrelationships exist in plant-soil system among every biotic and abiotic factor to understand the mechanisms of sandy desertification land recovery. From the above discussion, we can point out that desertification made the soil coarse, while ecological restoration made the soil fine. This change in soil particle size fraction is ecologically valuable. Soil with higher fine particle content has stronger water-holding capability. When more fine particles deposit in the upper layer of soil along ecological restoration, more rain or water will be sequestrated in the top and upper layer of soil. For arid and semi-arid regions, because of the inadequate rainfall, water distributed to the eeper layer of soil will decrease. Then soil in the deeper layer will be dried. Because of water importance for ecological process, this kind microcosmic change in soil water has profound influence on ecosystems. This change is more helpful for herbaceous plants with shallow root system than others, and in the end, plant species composition will be altered, leading to species replacement and community succession (Zhang et al. 2005a). Bunch grass will be the dominant species because of its strong competitiveness for water by their dense root system.

A power relationship equation established to predict soil erodibility showed that the soil with higher clay content has the higher capability preventing soil from wind erosion than the soil with less clay content (Hu et al. 2011). From these results, we can infer that deposition of fine particles including very fine sand and silt and clay can improve soil anti-erodibility and enhance soil stability. So in ecological restoration process, a positive feedback cycle between soil and vegetation as this existed: vegetation prevents wind erosion and sequestrates fine particles, then the fine particles make top layer of soil fine and higher water content, improving soil anti-erodibility and promoting plants growth.

Table 3 Plant community status in the six sites

Site (year)	Coverage (%)	Species richness	Diversity Shannon-Wiener index	Dominant species and its importance value (%)	
3	13.1	7	1.0112	*Agriophyllum squarrosum* (L.) Moq.	68.1
6	17.2	11	1.8092	*Setaria viridis* (L.) Beauv.	30.8
10	27.6	14	2.1572	*Bassia dasyphylla* (Fisch. et Mey.) D.	32.9
18	39.8	17	2.2972	*Artemisia halodendron* Turcz. Ex Bess.	29.6
30	48.3	28	2.5955	*Salsola collina* Pall.	21.0
45	69.1	30	2.5274	*Cleistogenes squarrosa* (Trin.) Keng	24.0

5 Conclusions

1 We quantified particle size fraction of soil substrate in Horqin Sandy Land, a seriously desertified region in northern China. Our results showed that sandy soil of this region is mainly composed by coarse sand and fine sand, fraction of which are averagely 23.62 and 57.07 %, respectively. These characteristics make soil erodible and to be one of the reasons why sandy desertification was quickly developed in this region.
2 Grades of soil particle were separated in sandy desertification process. Enrichment ratio could clearly reflect the change of different group of soil particles. Fine sand was strongly enriched, while very fine sand and silt and clay were strongly diluted. This change makes soil texture more coarse and erodible, forming a vicious cycle between wind erosion and soil quality.
3 Along with the chronosequence of restoration, very fine sand and silt and clay were deposited and markedly enriched. This change is ecologically valuable such as promoting plant growth, strengthening soil anti-erodibility, and leading to species replacement and community succession. Changes of soil particle fraction in sandy desertified land are either the result of ecological restoration or the driver of the subsequent succession of sandy land ecosystems. Because of the sediment of fine particles, a positive cycle was formed between plant and soil to strengthen stability of soil-plant system.

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