Soil aggregation, aggregate stability, organic carbon and nitrogen in different soil aggregate fractions under forest and shrub vegetation on the Loess Plateau, China

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A B S T R A C T
Revegetation has been reported as one of the most effective counter measures to reduce soil and water erosion on the Loess plateau in China. Soil aggregate stability and the distribution of organic carbon and nitrogen in different aggregate fractions would be affected by different plant communities. The objectives of this study were to elucidate the effects of different plant communities on soil aggregate stability and the distribution of organic carbon and nitrogen in different aggregate fractions in order to prove that the different plant covers enhance soil aggregate stability.

Six kinds of soil samples under forest (Quercus liaotungensis, Populus davidiana, Pinus tabuliformis, Bothriochloa, a 14 year abandoned land, and a 19 year bare fallow soil. Four kinds of soil samples under shrub land (the 24 year old Caragana korshinskii Kom.; the 14 year old C. korshinskii Kom., 3 year old abandoned grazing land and traditional slope cropland which is claimed by the farmers for production with very low fertilizers) were collected from the hilly–gully area on the Loess Plateau, which was divided into 0–10 cm and 10–20 cm. We investigated soil aggregate stability and soil aggregate fractions by ultrasonic fractionation (USAS), and the distribution of organic carbon and nitrogen in different fractions under forest and afforested land, as key indicators for soil remediation through revegetation.

The results showed that soil organic carbon (Corg) and total nitrogen (Nt) were strongly increased under forest and artificial shrub land compared to cropland and bare fallow land and were higher in the surface layers (0–10 cm) than in the subsurface (10–20 cm). Soil aggregate stability (SAS) was quite low under bare fallow land and cropping land soils, in comparison with the 4 forest communities. The three main fractions of soil aggregates, obtained by ultrasonic fractionation, were <63 μm, 63–100 μm and 100–250 μm, which represented approximately 60%, 10% and 10%, respectively. In all land uses, macro-aggregates, 1000–630 μm had a higher Corg content than micro-aggregates, 250–100 μm and 100–63 μm, which was about 1064 to 1400 times higher than that in the macro-aggregates. We concluded that revegetation of eroded soils accelerates soil remediation and rehabilitation.

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1. Introduction

The Loess Plateau has become one of the most severely eroded areas in the world due to frequent heavy summer rain storms, steep landscapes, long-term human activities (since the 15th century), and highly erodible soils on loess. The impacts of human activities on the Loess Plateau have been mainly caused by over-grazing and large scale monocultures of wheat and maize (Fu et al., 2000; Lal, 2002).

Recently, a few studies have concentrated on the effects of deforestation on accelerated soil erosion in the Ziwuling area of the Loess Plateau. For example, Zheng et al. (2005) reported that soil losses from ephemeral gully catchment on deforested land reached from 159.7 to 210.0 Mg/ha yr−1 according to a 10-year field observation, which was about 1064 to 1400 times higher than those in the undisturbed forest land. Consequently accelerated soil erosion caused soil nutrient losses as well. Zheng et al. (2005) found that 22% to 37% of soil organic matter (SOM) was lost from the upper
20 cm of the soil profiles in the first year following deforestation. Recently, Zhang et al. (2006) reported that after 15 years of deforestation, soil loss from deforested land reached up to 22.7 Mg/ha yr\(^{-1}\), and up to 204.0 Mg/ha yr\(^{-1}\) near the watershed boundaries, e.g., in ephemeral gully channel areas. In contrast, soil loss from forestland was only 0.10 to 0.15 Mg/ha yr\(^{-1}\) at different locations along hill slopes. After 15 years of deforestation, soil organic carbon, total nutrient content, and available phosphorus in the 0–20 cm horizons were reduced by 42%–86%, 38%–83%, and 24%–80%, respectively.

Soil aggregate stability is a fundamental property that determines its productivity and resistance to erosion and degradation (Raine and So, 1997; Six et al., 2000). Aggregate stability is a highly complex parameter influencing a wide range of soil properties, including carbon stabilization, soil porosity, water infiltration, aeration, compactibility, water retention, hydraulic conductivity, resistance to erosion by water and overland flow. Maintaining high soil stability of soil aggregate is essential for preserving soil productivity, minimizing soil erosion and degradation and thus minimizing environmental pollution as well. Arshad and Cohen (1992) described aggregate stability as one of the soil physical properties that can serve as an indicator of soil quality. Hortensius and Welling (1996) included this parameter in the international standardization of soil quality measurements.

A variety of techniques have been developed for measuring soil aggregate stability (Amekzeta, 1999). Among these, ultrasonic processing of soil–water suspensions has been investigated by North (1976, 1979), Field and Minasny (1999) and Field et al. (2006). In contrast to most conventional methods, ultrasonic stability tests can regulate and quantify the level of mechanical energy applied to soil (North, 1976; Raine and So, 1993) and compare them in a continuous treatment with different intensities. In addition, ultrasonic processing allows for considerable control and flexibility over both the individually applied power and the total energy of application (Fristensky and Grismer, 2008; Zhu et al., 2009).

Organic matter influences soil structure and stability by binding soil mineral particles, reducing aggregate wettability, and influencing the mechanical strength of soil aggregates, which is the measure for the coherence of inter-particle bonds (Onweremadu et al., 2007). The determination of the soil organic carbon (Corg) and the soil nitrogen content (Nt) of different aggregate sizes is important for determining the quantity of soil that is easily lost by erosion processes (since smaller aggregates are more easily lost than larger ones).

In 1999, the Chinese government launched the national project “Grain for Green” in Northwest China. The timeline and the direction which should be considered for this project are still under discussion by scientists. This has a major influence on political decisions and on the improvement of the environmental quality of the Loess Plateau. Relatively little information is available on the carbon content and its improvement of the environmental quality of the Loess Plateau.

2. Materials and methods

2.1. Study site description

Twenty soil samples were collected from two sites on the Loess Plateau representing typical landscapes and vegetation types in forests and in agriculturally used areas. Twelve forest soil samples were collected from Ziwuling which is the only forest region still existing on the Loess Plateau. The study area lies within N (36°03′35″–36°05′26″) and E (109°08′57″–109°10′53″) in the hilly–gully region between the Dongzhi and Luochuan Plateaus. The soil samples were taken nearby the Fuxian Observatory for Soil Erosion and Eco-Environment that was established in 1989 (Tang et al., 1993) on the eastern slopes of the Ziwuling Forest region. The land forms are characterized by low mountains and hills covered by loess with elevations ranging from 920 to 1683 masl, with a relative individual height of 100 to 150 m and a gully density of 4.5 km km\(^{-2}\). The mean annual temperature ranges from 6 to 10 °C and mean annual precipitation is between 600 mm and 700 mm with a summer maximum. The soil type of the arable land is Typic-Loessi Orthic Primosols according to Keys to Chinese Soil Taxonomy (3rd edition, 2001).

2.2. Soil sampling and preparation

Soil samples were taken from 0 to 10 cm and 10 to 20 cm depths in March 2008. Soil samples were collected from 6 different plant communities: forest were Quercus liaotungensis (Q.), Populus davidiana (Po), Pinus tabulaeformis (Pt), Bothriochloa (Bo.), a 14 year abandoned land (Ab.), and a 19 year bare fallow soil (Ba.). Four additional soil samples were collected from the neighboring areas, the 24 year old Caragana Khorshinskii Kom., the 14 year old C. Khorshinskii Kom., 3 year old abandoned grazing land and traditional slope cropland which are claimed by the farmers for production with very low fertilizers input.

An area of 60 m × 60 m was selected for each plot and within this area three 60 m × 20 m plots were selected for sampling. Seven core samples (3 cm) were taken from each plot and mixed to form a bulk sample of about 1 kg for the measurement of total organic carbon (Corg) and total nitrogen (Nt). Undisturbed soil samples were taken for aggregate stability analysis from each plot with three replicates in the subplots, sealed in plastic bags and transported to the laboratory, where they were air dried at room temperature. Each soil was sieved (2 mm) to remove large roots, stones and the macrofauna.

2.3. Analysis of soil physical and chemical properties

Chemical analyses were performed on soil samples sieved at 2 mm, using standard methods. Soil pH was determined in a mixture of 2 parts 0.01 M CaCl\(_2\) and 1 part sieved soil. Total Soil C (Ct) was determined by combustion, and soil inorganic carbon was measured gas-volumetrically by the Scheibler Method which was already soaked by HCl to remove inorganic carbon. The determination of Corg and Nt in different soil aggregate sizes was carried out according to Austrian Standard ON L 1080-99 (1999) and ON L 1082-99 (1999) with a Carlo Erba (NA 1500) elementary analyzer, using the dry combustion technique and gas chromatographic analyses.

2.4. Soil aggregate stability (SAS) by wet sieving

Soil aggregate stability was determined by wet sieving according to ON L 1072, 2004. With this method, soil aggregates with a diameter of 2000–1000 µm are dipped on a sieve of 250 µm. The mass of soil (EW) used in the experiment is 4 g. The mass of stable aggregates after dipping (mK) and the mass of sand after chemical dispersion of the remaining aggregates (mA) is determined. These
parameters are used to calculate the percentage of stable aggregates (%SAS).

\[
\%SAS = \frac{m_K - m_A}{EW - m_A} \cdot 100
\]

2.5. Ultrasonic soil aggregate stability (USAS)

The most important parameter to describe the degree of aggregate breakdown and particle dispersion during sonification is the specific ultrasonic energy absorbed by a soil–water mixture. Soil aggregate distribution (USAS) was carried out by a new, probe-type dispersion equipment. A titanium alloy probe is inserted into the soil–water mixture and vibrates at approximately 20 kHz. The ultrasonic probe has a cylindrical shape and a circular cross section (diameter 30 mm). The same ultrasonic probe is used in all experiments, and the insertion depth is kept constant at 2 mm.

Dispersion experiments were performed with 2 g soil in 50 ml pure degassed water. The solution was stirred with a magnetic stirring device (2 Hz, cylindrical shape with length 25 mm and thickness 8 mm). Stirring starts 10 s prior to the ultrasonic vibration and was continued during the ultrasonic experiments to obtain a homogeneous distribution of soil in the solution. All soils were tested at a constant vibration amplitude of the ultrasonic probe of 0.5 \( \mu \)m (1 J/ml). The vibration amplitude was determined using electromagnetic induction coil and strain gauges as described previously (Mayer et al., 2002; Mentler et al., 2004). Mass fractions in ultrasonic experiments were determined by wet sieving immediately after the ultrasonic treatments. The aggregates were analysed with standard sieves and classified in different aggregate fractions: macro-aggregates (>1000 \( \mu \)m), medium aggregates (630–250 \( \mu \)m), and small aggregates (250–100 \( \mu \)m, 100–63 \( \mu \)m, <63 \( \mu \)m). Determination of mass fractions (accuracy 0.001 g) was performed by weighing after drying at 105 °C for 24 h.

2.6. Statistical analysis

One-way ANOVA followed by the Duncan test \((P < 0.05)\) was used to compare the sites representing different land use and plant communities. An exponential regression model was fitted to describe the relationships between the variables. The means and standard errors were determined by triplicate soil extracts from three separate samples for each plot. All statistical analyses were carried out with Excel 5.0 and SPSS 16.0 (Bühl, 2008).

3. Results

3.1. Total organic carbon (Corg) in the top soils (0–20 cm) under different plant communities

Compared to the bare fallow soil, the Corg content was quite different between different forest plant communities (Fig. 1A). The highest content of Corg is about 25 g kg\(^{-1}\) which corresponds to typical grass communities in forest areas. There are clear differences between different communities. The Corg content in the abandoned cropland decreased approximately to 13 g kg\(^{-1}\). Because of the abandonment for 14 years, the Corg content is not extremely low after only 5 years of cropping. Compared to the soil under forest and

\[\text{Fig. 1. Corg under different types of forest (A) and afforested land (B) at 2 different depths; Q: Quercus liaotungensis; Po.: Populus davidiana; Pi.: Pinus tabulaeformis; Bo.: Bothriochloa; Ab.: 14 years abandoned land; Ba.: 19 years bare fallow soil. 24 C.K.: Caragana Korsinskii Kom.; 14 C.K: C. Korsinskii Kom., A.G.: abandoned grazing land and Cr.: traditional cropland.}\]

\[\text{Fig. 2. Soil aggregate stability (SAS) under different forests (A) and afforested land (B); for explanations, see Fig. 1.}\]
the abandoned cropped soil, the content of bare fallow soil was very low, with about 8 g kg$^{-1}$ in the surface layer. This was possibly caused by heavy soil erosion during the rainy seasons. This explains that the vegetation cover conserves the Corg effectively. The data of Fig. 1B indicate that afforestation can accelerate the accumulation of Corg under the shrubland soil. After 24 years of afforestation, the Corg content in the shrub soil is about 18 g kg$^{-1}$, which was dramatically increased in comparison to that in the farmland. These results indicated that the afforestation can conserve Corg effectively.

3.2. Soil aggregate stability (SAS) by wet sieving

Compared to the bare fallow land, there is little difference of SAS between the 4 forest plant communities. In addition, the SAS was not largely different between the surface layer and subsurface layer. As shown in Fig. 2A, the SAS under the 4 forest vegetation types is about 80%–85% in the surface layer (0–10 cm) and the subsurface layer (10–20 cm). SAS increased after 15 years of soil abandonment, and is about 70% both in the surface layer (0–10 cm) and in the subsurface layer (10–20 cm). However, SAS is only about 20% under bare fallow land.

Compared to the forest soil, SAS was enhanced in the afforested shrub (Fig. 2B). The enhancement in the surface layer was more effective than that in the subsurface layer. In the 24 and 14 year old shrub land, the SAS in the surface layer is almost 20% higher than that in the subsurface layer.

3.3. Soil aggregate fractions under different plant communities by ultrasonic method (USAS)

The results of the soil aggregate fractionation under different forest types are shown in Fig. 3A–B. The size of the main three fractions was <63 µm, 63–100 µm and 100–250 µm, which accounted for approximately 60%, 10% and 10%, respectively. The other 3 fractions accounted for approximately 20%. There were obvious differences between bare fallow soils and forest soils. The data indicated that large soil aggregate fractions including >1000 µm, 630–1000 µm, and 250–630 µm are quite rare under bare fallow soil.

The distribution of soil aggregate fractions under different afforestation types was shown in Fig. 3C and Fig. 3D, for 0–10 cm and 10–20 cm soil depths, respectively. In comparison, the soil under revegetated shrubland showed higher aggregate stability, with about 80% in the surface layer and over 75% in the subsurface layer. The soil aggregate stability was decreased by 50% under cropland and 20–30% under overgrazed pasture. The size of the main two fractions in these areas were <63 µm, 63–100 µm and 100–250 µm, accounting for approximately 60%, 10% and 10%, respectively. This indicates clear differences between cropland soils and forest soils.

3.4. Distribution of Corg and Nt in different aggregate fractions by USAS

Fig. 4A–B showed the distribution of Corg in the soil fractions 63–100 µm, 100–250 µm, 250–630 µm and 630–1000 µm under different plant communities and cropland. Under all forest land uses, higher
values of Corg were obtained in the top soil horizons, with the exception of fraction with 630–1000 µm. The data showed 0.66%–14.98% in 0–10 cm, 0.37–15.67% in 10–20 cm for forest soils, and 0.84%–13.63% in 0–10 cm, 0.55–10.60% in 10–20 cm for the afforested soils. The values in the subsurface layers decreased with depth under all land uses.

Fig. 4. Distribution of organic carbon (Corg) in different aggregate fractions under different forests (A) and afforested soils (B); compare Fig. 1.

Fig. 5. Distribution of total nitrogen (Nt) in different aggregate fractions under different forest (A) and afforested soils (B); for explanations see Fig. 1.
There is a clear trend that macro-aggregates have a higher Corg content than micro-aggregates in the order of 1000–63 µm > 630–250 µm > 250–100 µm > 100–63 µm, which is valid for forest soils, abandoned land soils and bare fallow soils. Generally, Corg in the 0–10 cm top soil was higher than that in 10–20 cm, especially in 630–250 µm-, 250–100 µm-, and 100–63 µm-fractions. In contrast, Corg in 10–20 cm top soil was higher than that in 0–10 cm in the fractions 630–1000 µm.

The distribution of total nitrogen (Nt) in different aggregate fractions showed the same trend as organic carbon (Corg) under forest and afforestation land (Fig 5A–B). Nt was normally higher in 0–10 cm than in 10–20 cm. There was also an obvious trend that macro-aggregates have higher Nt contents than the micro-aggregates with the order of 1000–63 µm > 630–250 µm > 250–100 µm > 100–63 µm. There is a positive correlation ($R = 0.8837, n = 128$) between Nt and Corg.

4. Discussion

4.1. The effect of land use on soil aggregation and aggregate stability

In our previous studies (An et al., 2008, 2009), we showed that soil quality parameters were extremely affected by deforestation. The decrease of soil quality in differently cultivated areas also showed the importance of maintaining the natural vegetation on the eroded land. Mitigation of soil erosion can be obtained by appropriate land use, e.g., afforestation and a natural succession on eroded land, which is reflected in the recent policy of ecosystem reconstruction in Northwest China.

In our present study, SAS was extremely high under forest soils compared to bare fallow land and cropland soils. On the Loess Plateau, cropland is characterized by continuous plowing and low organic and inorganic fertilizers. The heavy soil erosion which is continuing on the Loess Plateau was mostly induced by land misuse. The natural soil structure is destroyed by the plow and the stabilizing effects of root fibers become insignificant because the roots are shreded by the tillage and subsequent microbial decomposition following cropping. As pore space increased due to the mechanical cultivation, the air exchange increased the oxygen availability for the microbial decay of organic matters. This factor, coupled with the accelerated erosion, rapidly depleted the SOM in the plow layer and weakened the SAS (Zhang and Horn, 2001).

SAS measurements are always conducted in relation to soil erosion on the Loess Plateau (Zha et al., 1992; Wang et al., 1994; An et al., 2009), indicating that the content of soil–water stable aggregates (WSA) is the best factor reflecting the ability of a soil to resist erosion. The conversion of forestland to cropland, grazing land, and settlements has often resulted in soil degradation and nutrient losses (Dinesh et al., 2003). The stability in these water stable aggregates could be due to hydrophobic bonding of SOC contained in these soil aggregate classes, which had been previously reported by Piccolo et al. (1996).

4.2. The effect of vegetation on soil aggregate fractions

We speculate that the higher organic matter and carbohydrate content of the surface layer (0–10 cm) contributes to aggregate stabilization through bridging between clay particles.

The increase in aggregate stability in mull A-horizons under forest has been reported by Mehta et al. (1960). Clapp and Emerson (1965) found that aggregates collected from a forest soil exhibited greater stability and resistance to periodate in combination with borate or pyrophosphate than the aggregates from a grass soil. The presence of fungal hyphae may also contribute to the enhanced stability of a forest mull horizon (Tisdall and Oades, 1982).

Among the different factors that affect aggregate stability and the improvement of the structure of semiarid soils, the level of soil organic matter is most important (Diaz et al., 1994). The parameters

![Fig. 6. C/N ratio in different aggregate classes under different forests (A) and afforested soils (B); for explanations see Fig. 1.](image-url)
responsible for aggregate stability are mainly organic matter and its biological origin and are usually developed in the rhizosphere. Any increase in aggregate stability produced by microorganisms may be of a physical nature (Tisdall and Oades, 1982) or arise from the formation and excretion of microbial polysaccharides, which act as binding agents.

4.3. Effect of vegetation on the Corg and Nt distribution and on the Carbon–nitrogen (C:N) ratio in different aggregate fractions

The wider C:N ratio in the water stable aggregate fractions of the top soil (0–10 cm) indicates the occurrence of raw organic material that is less decomposed when compared with organic matter contained in the water stable aggregates at a depth of 10–20 cm. Wider C:N ratios of the total top soils (10–49) for forest sites and even bare fallow land were observed in comparison with the water stable aggregate fractions, with C:N ratios of 7–21 under afforested land. The C:N ratio was narrower in smaller water stable aggregates: 100–60 µm and 250–100 µm (Fig. 6 A–B), indicating the relatively complex nature of organic matter in such aggregate fractions. Narrow range of C:N ratio implies less rapid turnover of soil organic carbon (Buyanovsky et al., 1994). These results implied that soil organic carbon is more stable in micro-aggregates than in macro-aggregates. The C:N ratio indicates the degradation of fresh plant residues which is important in the C sequestration and soil aggregation (Potter et al., 1998). It is possible that micro-aggregates contain carbon that has undergone more degradation than the macro-aggregates and therefore have comparatively a less diverse carbon occluded in micro-aggregates resulting in the C:N ratio.

These trends suggest that Corg is important in the aggregation of larger water stable aggregate fractions and that there are other aggregating forces than Corg, influencing these aggregation processes in the study sites. Nwadialo and Mbagwu (1991) reported that organic carbon does not influence micro-aggregate stability greatly when the values of Corg are low and do not reach critical limits.

5. Conclusions

The Corg and Nt contents were extremely increased under forest and artificial shrubland compared to bare fallow land and cropland soil. It was also found that the vegetation type influences Corg and Nt. SAS was quite low under bare fallow land and cropland, whereas there is no significant difference among the 4 forest plant communities. Artificial shrub can also enhance the SAS and is even more effective in the surface layer than in the subsurface layer.

The three main fractions of soil aggregates were <63 µm, 63–100 µm and 100–250 µm, which accounted for approximately 60%, 10% and 10%, respectively. The other 3 fractions accounted for approximately 20% under different plant communities and cropland. In all land uses, higher Corg values were found in the top horizons. Macro-aggregates have higher Corg content than micro-aggregates in different fractions: 1000–63 µm >630–250 µm >250–100 µm >100–63 µm. The same trend was also observed in forest soils, abandoned land soils and bare fallow soils. There is a positive correlation between Nt and Corg and a positive relationship between SAS and soil organic carbon.

Higher C:N ratios of macro-aggregate fractions were observed in the top soils, indicating the relative complex nature of organic matter in forest sites and even of bare fallow land. The narrow C:N ratio, e.g., in micro-aggregates, implies that soil organic carbon is more stable in the micro-aggregates than in the macro-aggregates.

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