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Aggregate Characteristics During Natural Revegetation on the Loess Plateau[*1]

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ABSTRACT

Field investigations and laboratory analysis were conducted to study the characteristics of soil water-stable aggregates during vegetation rehabilitation in typical grassland soils of the hilly-gullied loess area. The relationship between water-stable aggregates and other soil properties was analyzed using canonical correlation analysis and principal component analysis. The results show that during the natural revegetation, the aggregates > 5 mm dominated and constituted between 50% and 80% of the total soil water-stable aggregates in most of the soil layers. The 2–5 mm aggregate class was the second main component. The mean value of water-stable aggregates > 5 mm within the 0–2 m soil profile under different plant communities decreased in the following order: *Stipa grandis* > *Stipa bungeana* Trin. > *Artemisia sacrorum* Ledeb. > *Thymus mongolicus* Ronn. > *Hierochloe odorata* (L.) Beauv. Clay, organic matter, and total N were the key factors that influenced the water stability of the aggregates. Total N and organic matter were the main factors that affected the water stability of the aggregates > 5 mm and 0.5–1 mm in size. The contents of Fe_2O_3, Al_2O_3, and physical clay (< 0.01 mm) were the main factors which affected the water stability of the 1–2 and 0.25–0.5 mm aggregates.

Key Words: canonical correlation analysis, loess area, natural revegetation, principal component analysis, soil water-stable aggregates

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INTRODUCTION

Soil structure is a key soil property that impacts plant and animal life, moderates environmental quality changes through soil carbon (C) sequestration, and affects water quality. Aggregate stability is used as an indicator of soil structure (Six *et al.*, 2000). Aggregation results from the rearrangement of particles through flocculation and cementation (Sun *et al.*, 1999). Aggregation is mediated by soil organic carbon (SOC), biota, ionic bridging, clay, and carbonates. SOC acts as a binding agent and is the key constituent in the formation of aggregates. Biota and their organic products contribute to the development of soil structure which in turn affects SOC dynamics. SOC residence time and decomposition rate are also factors that influence aggregation. Crystalline and amorphous metal oxides and hydroxides are important binding agents in soils. Metal ions form bridges between mineral and organo-mineral particles. Clay also acts as an aggregant, binding particles together and affecting SOC decomposition and turnover. Long term stability of aggregates is often related to the presence of recalcitrant carbon

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compounds and metal ions. Formation of secondary carbonates in arid and semi-arid regions is also linked to aggregate dynamics.

Soil structure can be defined in terms of form and stability (Bronick and Lal, 2005). Good soil structure is a most desirable soil characteristic for sustaining agricultural productivity and for preserving environmental quality (Peng *et al.,* 2004). Soil structure depends on the presence of stable aggregates. The stability of the aggregates and the pores between them affect the movement and storage of water, aeration, erosion, biological activity, and the growth of crops (Zhang and Miller, 1996). Thus aggregate stability affects a wide range of physical and biogeochemical processes in the natural and agricultural environment. Maintaining high soil aggregate stability is essential for preserving soil productivity and minimizing soil erosion and environmental pollution resulting from soil degradation. Arshad and Cohen (1992) proposed aggregate stability as one of the physical soil properties that can serve as an indicator of soil quality. Hortensius and Welling (1996) included this property in the international standardization of soil quality measurement.

The Loess Plateau ecosystems have for millennia been impacted by various forms of human activities (Lal, 1991). During the last century, fragmentation and degradation of ecological environments have been accelerated due to increasing population pressure. In order to withstand further deterioration of the natural ecosystems, the Chinese government has launched a series of nation-wide conservation projects focusing on the rehabilitation and recovery of these damaged ecosystems (Wang, 2002). One of the most urgent tasks to achieve sustainable agricultural development for the Loess Plateau may be the recovery of the natural vegetation that was destroyed (Li *et al.*, 2005). The impacts of human activity on the Loess Plateau can basically be attributed to continuous and widespread stress, *e.g.*, over-grazing and large-scale monocultures (wheat and maize) (Fu *et al.*, 2000).

Soil water-stable aggregation research is always conducted in relation to soil erosion on the Loess Plateau (Zha *et al.,* 1992; Wang *et al.,* 1994). Researchers have reported that the content of soil water-stable aggregates (WSA) is the best factor reflecting the ability of a soil to resist erosion on the Loess Plateau. But only few papers are available on the evolvement of soil WSA during natural revegetation. This study investigated the characteristics of soil WSA during the process of vegetation rehabilitation in the loess region and their relationship to other chemical and physical soil properties based on canonical correlation analysis and principal component analysis.

MATERIALS AND METHODS

The study area is located in the Yunwu Mountain in the Loess Plateau of China (36° 14′–36° 20′ N, 106° 25′–106° 29′ E). The 4 000 ha study area was enclosed in 1983 and the vegetation originated from natural regrowth. The region mainly consists of hills (90%), 4% are villages, rivers and lakes, and only 6% is considered suitable for intensive agriculture. The study area has a sub-arid climate characterized by heavy seasonal rainfall with periodic local flooding and drought. The average annual rainfall at the experimental site is 400 mm (1941–2000). There are distinct wet and dry seasons. The rainy season starts in July and ends in October. The growing season is from June to October. July rainfall accounts for 24% of the annual rainfall. The average annual potential evapotranspiration is approximately 1 000 mm, resulting in an average rainfall deficit of 600 mm year^{-1}. The average annual temperature is about 7 °C. Most of the area has an elevation ranging from 1 800–2 040 m and is intensely dissected with sharp-edged and steep or very steep slopes. The soil is slightly alkaline (pH 7.8–8.2), classified as a Cambosol according to the Chinese Soil Taxonomy (CST) classification system (3rd edition).

Soil profiles were described and sampled for physical, chemical, and mineralogical characterizations at three locations along transects on the hill slopes (upper, middle and lower part). Little morphological differentiation was observed within the horizons, texture, and color in the regolith materials. Based on the natural occurrence of plant communities in this area (Zou and Guan, 1997), soil profiles from under five different plant communities were collected. These communities are *Stipa grandis*, *Stipa bungeana* Trin., *Artemisia sacrorum* Ledeb., *Thymus mongolicus* Ronn. and *Hierochloe odorata* (L.) Beauv. Different soil layer samples were collected according the soil genetic layers. Undisturbed soil samples in different layers were collected using plastic boxes for soil aggregate analysis, and mixed samples for physical and chemical analyses. Soil samples were air-dried and crushed. Soil aggregate stability was determined by the revised Yoder method (Zhu, 1982), using a set of sieves with openings of 5, 2, 1, 0.5, and 0.25 mm. The sieve set was rapidly immersed in distilled water and oscillated with a displacement of 5, 2, 1, 0.5, and 0.25 mm at 37 r $\min^{-1}$ for 3 minutes. All fractions were dried at 70 °C and weighted.

For all other analyses, soil samples were air-dried and passed through a 2-mm sieve. Part of the air-dried and sieved samples was ground and passed through a 0.25-mm sieve for C and N determinations. Texture was measured with the pipette method (Gee and Bauder, 1986) after dispersion with sodium pyrophosphate ($Na_4P_2O_7$).

Analytical methods described in ISSCAS (1981) were chosen for the determination of chemical soil properties. Soil pH was determined on the day of sampling with a 0.01 mol L^{-1} $CaCl_2$ solution at a fresh weight/volume ratio of 1:2. The suspensions were swirled and a pH electrode was placed in the suspended supernatant. Organic matter was determined by wet digestion with a mixture of potassium dichromate and concentrated sulfuric acid. Total N was measured by the semi-macro Kjeldahl method. The concentrations of Fe and Al oxides were determined by atomic absorption spectrophotometry. $CaCO_3$ was determined by dissolving soil samples in HCl and measuring the amount of CO_2 released. Cation exchange capacity was measured by the NaOAc exchange, flame luminosity method.

The mean weighted diameter (MWD) was calculated according to $\Sigma w_i x_i$, where w_i is the mean diameter of size fraction i and x_i is the proportion of the total sample weight of size fraction i. The summation was performed over all size fractions, including the one passing through the finest sieve.

Canonical correlation and principal component analyses were used to relate the index of the aggregates to other soil properties. The averages of three duplicates were taken and a canonical correlation analysis was carried out using a data processing system (DPS) (Tang and Feng, 2002). In canonical correlation analysis, soil properties, Al_2O_3, Fe_2O_3, $CaCO_3$, total N, organic matter, total P, pH, cation exchange capacity, free Fe, clay (< 0.002 mm), and physical clay (< 0.01 mm), were taken as Group A. The contents of the five different textural classes of soil aggregates were taken as Group B. The data obtained were subject to principal component analysis (PCA) with varimax rotation. Based on PCA, the variables that explain most of the variance in aggregate stability were extracted.

RESULTS

Characteristics of selected soil properties under different plant communities

The relationships between characteristics of soil properties and natural revegetation in the experimental area were studied in detail in An *et al.* (2006). We selected some of these characteristics that affect WSA (Table I). Appreciable differences were noted in the soil nutrient composition among the soil horizons. The highest organic matter content of 40.5 g kg^{-1} was observed in the surface horizon under the *Stipa grandis* community and the lowest, 2.5 g kg^{-1}, in the 110–200 cm soil layer under the *Artemisia Sacrorum* Ledeb. community. The $CaCO_3$ contents of the surface horizons were generally less than those of the deeper layers. Al_2O_3 and Fe_2O_3 levels were very similar among the different soil layers in the profile.

Characteristics of soil water-stable aggregates under different plant communities

Mean values for the WSA content and the MWD under different plant communities and in different soil horizons are presented in Table II. The aggregates > 5 mm made up the highest proportion (an average of 50%–80%) of the total WSA in all the profiles. About 10%–15% of the aggregates were 2–5 mm in size. The amounts in other size ranges were small. This observation is similar to the aggregation model proposed by Tisdall and Oades (1982) for soils where organic matter is a major binding agent.

TABLE I

Selected soil properties affecting water-stable aggregation in different profiles under different plant communities

Plant community	Layer	Al_2O_3	Fe_2O_3	$CaCO_3$	Total N	Organic matter	Total P	pH	Cation exchange capacity	Free Fe	Clay (< 0.002 mm)	Physical clay (< 0.01 mm)
	cm	g kg^{-1}					mg kg^{-1}		cmol kg^{-1}	g kg^{-1}		
Stipa bungeana Trin.	0–20	124.01	46.51	88.5	2.251	31.5	0.344	8.02	19.50	6.42	275	462
	20–60	127.02	47.40	82.5	2.207	28.7	0.327	8.10	17.25	5.75	287	468
	60–150	125.80	45.35	143.9	1.300	18.7	0.306	7.97	16.00	5.55	312	507
	150–200	120.00	42.92	163.7	0.756	9.6	0.265	8.00	14.50	5.01	297	472
Stipa grandis	0–40	128.75	46.95	46.9	2.774	40.5	0.392	8.13	34.75	5.38	260	454
	40–80	126.58	49.26	72.6	2.126	28.1	0.395	8.19	31.25	5.77	323	486
	80–130	125.96	46.64	91.4	1.703	27.0	0.390	8.14	34.50	5.69	303	511
	130–200	121.68	45.42	103.5	1.463	20.8	0.343	8.17	30.75	5.75	329	527
Artemisia sacrorum Ledeb.	0–20	119.21	42.85	138.9	1.054	15.4	0.245	7.96	21.75	5.21	250	422
	20–110	117.91	41.76	136.0	0.290	3.6	0.241	8.21	21.25	5.03	228	368
	110–200	116.66	41.55	128.1	0.219	2.5	0.255	8.20	21.75	4.86	230	347
Thymus mongolicus Ronn.	0–30	120.17	44.18	67.7	2.386	34.7	0.326	7.99	29.00	5.71	291	468
	30–60	118.69	45.42	112.2	1.640	22.9	0.287	8.03	26.00	5.35	323	493
	60–140	112.38	42.21	155.8	0.507	7.1	0.243	7.95	20.00	5.41	313	491
	140–200	114.31	42.92	136.0	0.292	4.1	0.239	8.20	19.50	4.89	311	462
Hierochloe odorata (L.) Beauv.	0–10	125.06	44.35	116.7	1.618	27.0	0.287	7.89	25.75	5.61	224	414
	10–40	119.54	44.07	172.6	0.937	14.4	0.270	7.96	23.00	5.81	281	465
	40–120	118.01	42.36	159.1	0.471	7.2	0.238	8.02	17.00	5.73	253	423
	120–200	116.52	42.14	130.1	0.235	4.2	0.211	8.03	15.44	5.33	228	401

TABLE II

Soil water-stable aggregate (WSA) characteristics in different profiles under different plant communities

Plant community	Layer	WSA					Mean weighted diameter
		> 5 mm	2–5 mm	1–2 mm	0.5–1 mm	0.25–0.5 mm	
	cm	g kg^{-1}					mm
Stipa bungeana Trin.	0–40	520	103	59	72	35	3.10
	40–80	634	70	35	29	20	3.84
	80–130	716	64	31	32	13	3.48
	130–200	661	45	32	28	14	3.52
	Mean	670	60	34	33	16	3.49
Stipa grandis	0–20	498	114	81	78	49	3.10
	20–60	574	115	47	76	23	3.35
	60–150	518	103	59	47	23	3.03
	150–200	465	90	62	63	33	2.78
	Mean	514	106	62	66	32	3.06
Artemisia sacrorum Ledeb.	0–30	628	89	44	43	25	3.53
	30–60	533	95	50	59	31	3.11
	60–140	383	212	109	82	34	2.74
	140–200	116	159	129	173	79	1.53
	Mean	415	139	83	89	42	2.73
Thymus mongolicus Ronn.	0–10	586	73	28	22	12	3.20
	10–40	415	69	33	32	11	2.35
	40–120	138	57	78	80	53	1.17
	120–200	56	44	66	95	95	0.88
	Mean	299	61	51	57	43	1.90
Hierochloe odorata (L.) Beauv.	0–20	566	91	44	43	22	3.22
	20–110	135	73	138	106	69	1.33
	110–200	52	40	65	104	93	0.85
	Mean	251	68	82	84	61	1.80

There were appreciable differences in soil aggregate characteristics among the horizons of the soil profiles under different plant communities. The highest content of macroaggregates > 5 mm was observed in two soil layers of 80–130 and 130–200 cm depths under the *Stipa bungeana* Trin. community. This suggested that in these two layers factors such as the content of clay or $CaCO_3$ were important. The contents of soil aggregates decreased with soil depth under three communities: *Artemisia sacrorum* Ledeb., *Thymus mongolicus* Ronn. and *Hierochloe odorata* (L.) Beauv.

WSA index, as measured by the MWD, varied from 0.85 to 3.84 mm (Table II). The mean value of MWD within the 0–2 m profile decreased in the order *Stipa grandis* community > *Stipa bungeana* Trin. community > *Artemisia sacrorum* Ledeb. community > *Thymus mongolicus* Ronn. community > *Hierochloe odorata* (L.) Beauv. community. For all soil profiles the MWD values of the top soil horizons were higher than those of the subsoil horizons.

Relationships between soil aggregation and other soil properties

The results of the canonical correlation analysis are summarized in Tables III–IV. The correlation coefficient of the first pair of canonical variables was 0.999, significant at the $P < 0.01$ level (Table III). The most important soil property variables in determining the first pair of canonical variables were total N and organic matter. The most important aggregate variables in determining the first pair of canonical variables were the aggregate classes > 5 and 0.5–1 mm (Table IV). This result indicated that

TABLE III

Canonical correlation coefficients and eigenvalues

Canonical vector	Canonical correlation coefficient	Eigenvalue	Degree of freedom	P value
1	0.999	0.998	55	0.0005
2	0.970	0.958	40	0.0492
3	0.955	0.911	27	0.8318
4	0.914	0.836	16	0.9707
5	0.551	0.303	7	0.9990

TABLE IV

Correlations between soil aggregates and other soil properties

Eigenvector[a)]	Soil property			Soil aggregates		
	1st pair	2nd pair	3rd pair	1st pair	2nd pair	3rd pair
a_1	0.094	−0.409	−0.051	–	–	–
a_2	−0.019	0.321	0.204	–	–	–
a_3	−0.113	−0.209	0.218	–	–	–
a_4	0.541	−0.514	−0.036	–	–	–
a_5	−0.793	0.392	0.437	–	–	–
a_6	0.009	0.244	−0.447	–	–	–
a_7	−0.186	−0.111	0.307	–	–	–
a_8	0.120	−0.221	−0.020	–	–	–
a_9	0.027	0.164	−0.063	–	–	–
a_{10}	−0.036	−0.273	−0.379	–	–	–
a_{11}	0.070	0.215	0.525	–	–	–
b_1	–	–	–	−0.454	0.453	−0.101
b_2	–	–	–	0.389	0.542	−0.185
b_3	–	–	–	−0.162	−0.245	0.028
b_4	–	–	–	−0.763	−0.067	0.631
b_5	–	–	–	−0.183	0.661	−0.746

[a)] $a_1 - a_{11}$ are the soil Al_2O_3, Fe_2O_3, $CaCO_3$, total N, organic matter, total P, pH, cation exchange capacity, free Fe, clay (< 0.002 mm), and physical clay (< 0.01 mm), and $b_1 - b_5$ are the soil aggregates > 5, 2–5, 1–2, 0.5–1, and 0.25–0.5 mm, respectively.

organic matter and total N had an obvious impact on these two aggregate classes. The correlation coefficient of the second pair of canonical variables was 0.970, significant at $P < 0.05$ (Table III). The most important soil property variables in determining the second pair of canonical variables were Fe_2O_3, Al_2O_3, and physical clay (< 0.01 mm). The aggregate classes of 1–2 and 0.25–0.5 mm were the most important in determining the second pair of canonical variables (Table IV). This indicated that Fe_2O_3, Al_2O_3, and physical clay (< 0.01 mm) obviously impacted these two aggregate levels. The correlation coefficient of the third pair of canonical variables was 0.955, not significant at $P > 0.05$ (Table III).

In principal component analysis (PCA), the main component can be used to describe most of the variance when the percentage of the cumulative eigenvalue is greater than 85%. According to this principle, the following equations were obtained:

$$\begin{aligned} Y_1 = {} & 0.3311X_1' + 0.3760X_2' + 0.3384X_3' + 0.3763X_4' + 0.3732X_5' + 0.3828X_6' + 0.0379X_7' \\ & + 0.2648X_8' + 0.2561X_9' + 0.1474X_{10}' - 0.2245X_{11}' \end{aligned} \tag{1}$$

$$\begin{aligned} Y_2 = {} & -0.1417X_1' + 0.0596X_2' + 0.2954X_3' - 0.04867X_4' - 0.0598X_5' - 0.0723X_6' - 0.3552X_7' \\ & - 0.2386X_8' + 0.2283X_9' + 0.562X_{10}' + 0.5717X_{11}' \end{aligned} \tag{2}$$

$$\begin{aligned} Y_3 = {} & -0.1904X_1' + 0.0538X_2' - 0.0984X_3' - 0.1784X_4' - 0.2133X_5' + 0.1182X_6' + 0.6554X_7' \\ & + 0.2585X_8' - 0.3620X_9' + 0.4353X_{10}' + 0.2073X_{11}' \end{aligned} \tag{3}$$

where $Y_1 - Y_3$ are the soil aggregate class, and $X_1 - X_{11}'$ are the soil Al_2O_3, Fe_2O_3, $CaCO_3$, total N, organic matter, total P, pH, cation exchange capacity, free Fe, clay (< 0.002 mm), and physical clay (< 0.01 mm), respectively. The results of the PCA are summarized in Table V. The first three principal components explained 86.9% of the variance. The 1st principal component represented the variation in the effects of soil Al_2O_3, Fe_2O_3, $CaCO_3$, total N, soil organic matter, and total P. The 2nd principal component reflected the effects of soil clay (< 0.002 mm) and physical clay (< 0.01 mm). The 3rd principal component included the information about the variation in soil pH.

TABLE V

The eigenvalues and percentages of variance explained of the principal component (PC) analysis

Item	PC1	PC2	PC3
Eigenvalue	6.308	1.791	1.464
Variance explained (%)	57.3	16.3	13.3
Cumulative variance explained (%)	57.3	73.6	86.9

DISCUSSION

Many studies have shown that the amount and stability of soil aggregates are major factors affecting soil erosion. In southern China, much research of soil aggregates has been conducted (Sun *et al.*, 1999; Zhang and Horn, 2001). In contrast, only few studies for the Loess Plateau are reported, especially about the relationship between natural vegetation succession and soil quality changes. The results presented in Tables III–IV showed that soil organic matter and total N, as expected, had a significant impact on the > 5 and 0.5–1 mm aggregate size classes. The fact that the other values were not significant suggested that their relationships with other aggregate levels would not be significant either. Soil organic matter is composed of a series of pools from very active ones to passive ones; therefore, understanding the effect of these organic matter pools on WSA is important for evaluating carbon and nutrient dynamics in agricultural ecosystems. Much attention has been paid to the role of OM in the formation and stabilization of both macroaggregates and microaggregates but the physical and chemical characteristics of these aggregates are not well understood (Amezketa, 1999). Dormaar (1983) reported that SOC, polysaccharides, polyuronides, and phenols were associated with the > 0.25 mm WSA.

The results presented in Tables III–IV also showed that soil Al_2O_3, Fe_2O_3, and physical clay (<

0.01 mm) clearly impacted the 1–2 and 0.25–0.5 mm aggregates. Clay concentration physically affects aggregation through swelling and dispersion. The potential of swelling induced disaggregation is reduced at low clay levels (Attou *et al.*, 1998). Increasing clay concentration is associated with increasing SOC stabilization (Sollins *et al.*, 1996). Clay minerals affect properties that affect aggregation: surface area, cation exchange capacity, charge density, dispersivity, and expandability and these in turn affect SOC decomposition rates. The interaction of clay, SOC, and aggregates is affected by soil pH, cation exchange capacity, and ions (Na^+, Ca^{2+}, and Mg^{2+}), all of which are related to the amount and type of clay present in the soil (Amezketa, 1999). Clay mineralogical composition is modified with soil development.

CONCLUSIONS

The aggregates > 5 mm were the dominant soil WSA under different plant communities. Contrary to expectation, the highest amount of aggregates was not observed in the surface layer but in deeper layers. This meant that factors other than soil organic matter, such as soil clay and Fe and Al oxides, affect the WSA in the Loess Plateau. Soil organic matter and total N were the main factors which affected the > 5 and 0.5–1 mm aggregates. Soil Fe_2O_3, Al_2O_3, and physical clay (< 0.01 mm) clearly had an impact on the 1–2 and 0.25–0.5 mm aggregates. The results of PCA also showed that organic matter, total N, Fe_2O_3, and Al_2O_3 were the main factors which affected the WSA; clay (< 0.002 mm) and physical clay (< 0.01 mm) were secondary.

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