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Soil aggregate stability under different land-use types in North China Plain

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ABSTRACT: Soil aggregate stability is a vital indicator for evaluating soil quality. Land-use types may affect size distribution and stability of soil aggregates via changing soil organic carbon content. This study was conducted to evaluate effects of long-term different land-use types on soil aggregates. Three land-use types (forestland, grassland, and cropland) were selected in Zhoukou City (Central China). Soil aggregates were assessed by both wet and dry sieving methods. Significant difference of mean weight diameter (MWD) was observed under different land-use types and sieving methods. In 0–20 cm layer, MWD ranged from 0.32 to 1.45 mm under wet sieving method, while it ranged from 3.43 to 6.32 mm under dry sieving method; in 20–40 cm layer, the MWD ranged from 0.66 to 1.15 mm and from 2.74 to 6.48 mm under wet and dry sieving methods, respectively. The MWD for the wet sieving method was lower than that under dry sieving method, which might indicate that the soil tended to suffer from erodibility. MWD under both sieving methods was the highest in forestland, suggesting that the forestland soil was more resistant to soil erosion. The positive correlation between MWD and soil organic carbon was significant under wet sieving method. These results showed that land-use types had significant effects on soil aggregates, and soil organic carbon was related to stability of soil aggregates. These results would help to provide guidance for alleviating soil erosion and promoting soil quality under different land-use types.

KEYWORDS: land-use types, soil aggregate stability, wet sieving method, dry sieving method

INTRODUCTION

A good soil structure is essential for enhancing soil biota, ensuring sustainable agriculture, and moderating environmental quality. Stable aggregates are regarded as an indicator of the soil structure. Soil aggregate stability, an ability to resist breakdown by external forces, influences several soil physical or chemical processes, such as soil nutrient storage, water infiltration, and the ability to resist soil erosion [1]. Aggregate stability is a key factor in questions of soil fertility and environmental problems. Enhancing soil aggregate stability is an effective way to increase soil quality and prevent soil erosion and other environmental problems caused by soil degradation [2, 3].

Human activities have had large impacts on the ecosystems of the world. Over the past 50 years, humankind has accelerated the change in ecosystem services more rapidly than at any other periods. One important effect of human activities on ecosystems is land use change, which was more obvious in China. With the national introduction of household responsibility system, the North China Plain has experienced rapid land use changes, i.e. conversions from virgin land to arable land [4]. This has resulted in lots of environmental problems, such as soil erosion and degradation, and the disturbance of ecosystems. In North China Plain, soil loss due to crop harvesting is a soil erosion process that significantly contributes to soil degradation in arable land. Recently, it has been shown that vegetation restoration could improve soil fertility and decrease soil disintegration rate, which was helpful for the sustainability of ecosystem [5]. Generally, mechanical stable aggregate obtained by dry sieving method was used to measure wind erosion in both arid and semiarid areas [6], while the water stable aggregate could reflect the sensitivity to resist erosion when soil suffered from land use changes [7, 8]. Land-use type is an important factor influencing soil aggregates via affecting soil organic matter and iron and aluminum oxides [9, 10]. In the North China Plain, results related to soil aggregate stability were mainly obtained from wet sieving method [11–13]. A study in Florida suggested that dry sieving method was more suitable for sandy soil [14]. However, few studies are available regarding the soil aggregate stability in different land-use types determined by both wet and dry sieving methods in North China Plain. Therefore, it is well worth getting more specific information to understand the effects of land-use types on soil aggregates.

The North China Plain, as the second largest plain in China, covers 31 000 km^2 and is one of the major food-producing areas of China. The region has a typical warm temperate monsoon climate. It is also an ideal research area. As the precipitation is unevenly distributed throughout the year, of which above 70% occurs from May to October. Thus, this research was conducted in this area with three selected land-use types: forestland, grassland, and cropland. The objective of this project was to evaluate the impact of land use on soil aggregate stability in North China Plain. The findings will promote the understanding of effects of land-use types on soil structure and will help to guide the use of cropland for enhancing soil aggregate stability.

MATERIALS AND METHODS

Study sites and soil sampling

The study sites were located in three small regions in Zhoukou City (33°17′ N, 114°38′ E) in Southern Henan Province, which is located in the North China Plain, to compare how land use (forestland, grassland, and cropland) affecting the stability of soil aggregates. The area has a typical temperature and monsoonal climate with dry winters and wet summers. The prevailing wind direction is from the southeast in summer and northwest in winter. The annual mean temperature is 15 °C and annual mean precipitation 700 mm. The forest sites are secondary forests, with predominance of *Populus trichocarpa* and *Ligustrum compactum*. The grass sites consist of various kinds of grass, and the main species of grass at the sampling sites are *Artemisia sacrorum* and *Poa sphondylodes*. The croplands are used for grain crops, such as wheat (*Triticum aestivum*), maize (*Zea mays*). Winter wheat (early October–early June) and summer maize (Middle June–later September) double cropping is the prevalent agricultural system. The cropland sites received traditional tillage and have been cultivated for more than 50 years. The details of land-use types are shown in Table 1.

At each site, soil samples were collected from 0–20 and 20–40 cm layers in March 2019. In each land use, 8 sample sites having similar terrain and similar plant communities were selected, and three 25 m × 25 m subplots were marked for sampling. The fresh soil samples from each plot were mixed to form a composite sample. Visible plant residues were removed from the soil samples. The samples were air dried and sieved through a 2 mm mesh to determine soil organic carbon (SOC), total nitrogen (TN), and soil pH. The undisturbed soil samples were collected for analysis of soil aggregates with three replicates from each subplot. The soil samples were sieved through an 8 mm mesh and then stored at 4 °C until fractionation.

Analysis of soil chemical properties

The soil bulk density (BD) was calculated from the oven-dried mass and volume of the undisturbed soil sample. Soil water content (SWC) was measured after drying the soil in an oven at 105 °C for 24 h. Soil pH was determined with a pH electrode using a soil:water ratio of 1:2.5. SOC was determined by the wet digestion with $K_2Cr_2O_7$ and H_2SO_4 [15], and the TN was measured using the Kjeldahl method.

Aggregate stability measurements

To obtain different size fractions of water stable aggregates, one hundred grams of fresh soils were placed on the top of a nest of sieves (5, 2, 1, 0.5, 0.25 mm) and fractionated into six aggregate sizes. The sieve set was placed on the shock rack of a Yoder aggregates analyzer (Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China), submerged in water and shaken with amplitude of 4 cm and a frequency of 30 cycles per minute for 10 min. The sieved materials remained in the sieves and the part through all the sieves were washed into a container, dried and weighed.

The dry sieving method was performed as described by Mendes et al [16]. The fresh soil placed on the top of five sieves was agitated for 90 s with a sieve shaker at 600 oscillation/min (Octagon 2000, Endecotts Ltd., London). Soil recovered from each sieve was dried and weighed.

The mean weight diameter (MWD) was calculated using the following equation according to

Table 1 The descriptions of different vegetation systems.

Land use	Slope (°)	Aspect	Coordinates	Site description	Soil type
Forestland	8	Southeast	N 33°38′, E 114°40′	> 50 yrs mixed forest	Fluvo-aquic
Grassland	8	Southeast	N 33°38′, E 114°41′	> 50 yrs mixed grass	Fluvo-aquic
Cropland	3	Southeast	N 33°38′, E 114°40′	> 50 yrs wheat and maize	Fluvo-aquic

Oguike and Mbagwu [17]:

$$\mathrm{MWD} = \sum_{i=1}^{n} \bar{x}_i w_i$$

The percentage of each size fraction of soil aggregate (PSA) was calculated as

$$\mathrm{PSA}_i = \frac{w_i}{w} \times 100,$$

where $\bar{x}_i$ is the mean diameter of each size class, w_i is the mass of aggregate in the size class i, and w is the total mass of all size fractions of the aggregate.

The slaking ratio of the water stable aggregate is defined as the ratio of the water unstable aggregates and the total aggregates, measured by dry and wet sieving methods. The slaking ratio of the water stable aggregate greater than 0.25 mm ($SR_{0.25}$) is applied to evaluate the degree of breakdown during wet sieving.

$$\mathrm{SR}_{0.25} = \frac{m_d - m_w}{m_d} \times 100\%,$$

where m_d and m_w are the mass percent content of the aggregates with the size greater than 0.25 mm by dry and wet sieving methods, respectively.

Data analysis

All statistical analyses were performed using the SPSS Statistical Package 19.0 (SPSS, Inc., Chicago, IL, USA). The differences of MWD, PSA and $SR_{0.25}$ of soil aggregates under different types of land use were determined by the one-way analysis of variance (ANOVA). If the results were statistically significant, the post hoc multiple comparisons were performed with least significant difference (LSD). The correlations between MWD and the soil properties determined were performed, and the Pearson correlation test was carried out.

RESULTS

The soil chemical characteristics from different land-use types

The basic soil properties for the three land-use types were presented in Table 2. The land-use types resulted in significant differences in soil properties. The highest value for soil BD was observed in cropland in the 20–40 cm layer, while the lowest one was in forestland in 0–20 cm layer. The SWC ranged from 14.55% to 16.35% in 0–20 cm layer, and from 19.03% to 25.14% in 20–40 cm layer. Forestland and grassland had higher SWC in 20–40 cm layer. The SOC ranged from 11.84 to 15.63 g/kg in 0–20 cm layer. The higher value for SOC was observed in forestland, and the lowest one was observed in the cropland. A similar trend was observed for the soil TN. The higher pH values were observed in forestland and grassland in 0–20 cm layer, and land-use types showed no significant effect on soil pH values in 20–40 cm layer.

Aggregate distributions in different land-use types

The soil aggregate distributions using wet sieving method in the different land-use types are shown in Table 3. The size of the main fraction was <0.25 mm in the three land-use types. This size fraction accounted for 36.90% to 90.90% of the total soil weight. The lowest value for the size <0.25 mm was found in the forestland, and the highest value was observed in the cropland in both soil layers. Compared with cropland, the decreases of <0.25 mm fractions were 59.4% in forestland and 11.0% in grassland in 0–20 cm layer, respectively. The contents of fraction >5 mm in different land-use types ranged from 1.93% to 13.80%, followed the trend of forestland > grassland > cropland across soil layers. Compared with the values of cropland, increases of >5 mm fractions were 6.15 and 2.42 folds in forestland and in grassland in 0–20 cm layer, respectively.

For the dry sieving method, the >5 and 2–5 mm fractions were the main fractions in the two soil layers of the three different land-use types (Table 4). The content of >5 mm fractions accounted for 20.58% to 78.80%, while the percentage of 2–5 mm fractions ranged from 14.38% to 26.64%. Compared to cropland, the content of >5 mm was much higher in forestland in 0–20 cm layer and higher in grassland in 20–40 cm layer. Differently, the content

Table 2 The basic soil properties of different vegetation systems.

Soil layer (cm)	Land use	BD (g/cm^3)	SWC (%)	pH	SOC (g/kg)	TN (g/kg)
0–20	Forestland	1.11^c	16.35^a	8.08^a	15.63^a	1.40^a
	Grassland	1.35^b	14.55^c	8.01^a	11.84^b	1.13^b
	Cropland	1.42^a	15.88^b	7.78^a	12.22^b	1.10^b
20–40	Forestland	1.30^c	22.01^a	7.82^a	10.28^a	0.95^a
	Grassland	1.41^b	25.14^a	7.86^a	8.82^b	0.80^b
	Cropland	1.56^a	19.03^b	7.78^a	8.54^b	0.78^b

All data are expressed in mean. BD is bulk density; SWC is soil water content; SOC is soil organic carbon; and TN is soil total nitrogen. Different lowercase letters indicate significant differences under different land-use types at $p < 0.05$.

Table 3 Distributions of soil aggregates using wet sieving method in different land-use types.

Soil layer	Land use	Content of different soil aggregate fractions (%)					
(cm)		> 5 mm	2–5 mm	1–2 mm	0.5–1 mm	0.25–0.5 mm	< 0.25 mm
0–20	Forestland	13.80^a	2.47^a	3.13^a	18.60^a	25.10^a	36.90^c
	Grassland	6.60^b	1.97^b	1.67^b	2.73^b	6.13^b	80.90^b
	Cropland	1.93^c	0.70^c	0.70^c	1.47^c	4.30^b	90.90^a
20–40	Forestland	9.63^a	3.80^a	4.60^a	11.57^a	21.17^a	49.23^c
	Grassland	4.73^b	1.43^b	4.23^a	5.33^b	19.93^b	64.33^b
	Cropland	2.67^c	1.27^b	1.87^b	3.93^c	16.20^b	74.07^a

Different lowercase letters indicate significant differences at $p < 0.05$ over the different land-use types in the same soil layer.

of <0.25 mm was significantly the highest in cropland in both soil layers (14.18% in 0–20 cm layer and 19.86% in 20–40 cm layer). The percentages of <0.25 mm fractions for the dry sieving method in 0–20 cm layer were in the order of cropland > grassland > forestland, while the order of cropland > grassland = forestland in 20–40 cm layer.

The land-use types had a significant effect on the MWD (Table 5). In 0–20 cm soil layer, the MWD for the wet sieving method ranged from 0.32 to 1.45 mm. According to the classes of soil aggregate stability based on the MWD values, the forestland, the grassland, and the cropland corresponded to stable, medium stable, and very unstable, respectively. However, MWD for dry sieving method ranged from 2.74 to 6.48 mm, which was higher than that for the wet sieving method. Among the three different land-use types, the forestland had the lowest $SR_{0.25}$ (33.42% and 47.46%) and the cropland had the highest $SR_{0.25}$ (89.40% and 67.64%) in both soil layers.

Relationships between soil properties and aggregate stability

In the present study, there were no significant correlations between soil properties and MWD values for the dry sieving method (Table 6). Significant negative correlation was observed between MWD_{wet}

Table 4 Distributions of soil aggregates using dry sieving method in different land-use types.

Soil layer	Land use	Content of different soil aggregate fractions (%)					
(cm)		> 5 mm	2–5 mm	1–2 mm	0.5–1 mm	0.25–0.5 mm	< 0.25 mm
0–20	Forestland	75.06^a	16.96^b	5.70^b	1.28^c	0.28^b	0.72^c
	Grassland	42.54^b	26.64^a	17.38^a	8.38^b	2.32^b	2.74^b
	Cropland	30.22^c	17.88^b	16.98^a	11.44^a	9.30^a	14.18^a
20–40	Forestland	45.08^b	24.48^a	15.42^b	8.72^a	2.94^b	3.36^b
	Grassland	78.80^a	14.38^b	4.02^c	1.00^b	0.36^c	1.44^b
	Cropland	20.58^c	21.90^a	20.18^a	11.46^a	6.02^a	19.86^a

Different lowercase letters indicate significant differences at $p < 0.05$ over the different land-use types in the same soil layer.

Table 5 The mean weight diameter (MWD) and slaking ratio ($SR_{0.25}$) of the two sieving methods for the different land-use types.

Soil layer (cm)	Land use	MWD (mm) Wet sieving	MWD (mm) Dry sieving	$SR_{0.25}$ (%)
0–20	Forestland	1.45[a]	6.32[a]	33.42[c]
	Grassland	0.73[b]	4.46[b]	80.36[b]
	Cropland	0.32[c]	3.43[c]	89.40[a]
20–40	Forestland	1.15[a]	6.48[a]	47.46[c]
	Grassland	0.66[b]	5.55[a]	63.81[b]
	Cropland	0.66[b]	2.74[b]	67.64[a]

Different lowercase letter indicated significant difference at $p < 0.05$ over the different land-use types in the same soil layer.

Table 6 Correlations between the soil properties and MWD values.

	BD (g/cm^3)	SWC (%)	SOC (g/kg)	TN (g/kg)
MWD_{wet}	−0.814*	0.037	0.513*	0.508*
MWD_{dry}	−0.719	0.454	0.290	0.278

MWD_{wet}, mean weight diameter for the wet sieving method; MWD_{dry}, mean weight diameter for the dry sieving method; BD, soil bulk density; SWC, soil water content; SOC, soil organic carbon; and TN, total nitrogen. * indicated a significant difference at $p < 0.05$.

and soil BD ($r = -0.814$, $p < 0.05$), while MWD_{wet} was positively correlated with SOC ($r = 0.513$, $p < 0.05$) and TN ($r = 0.508$, $p < 0.05$). There were no significant correlations between MWD_{dry} and basic soil properties under dry sieving method.

DISCUSSION

Land use impact on soil aggregates

In our study, the effects of land use on soil aggregates were profound and significant differences of aggregate distribution and stability were observed under different land-use types. The findings were consistent with results in other regions: the Highlands of Northern Ethiopia [18], the South-South Agro-ecological Zone of Nigeria, along the Bonny River [19], and the Loess Plateau of China [8]. The aggregate sizes demonstrated effects of land-use types on soil structural stability. It was believed that macro-aggregate (>0.25 mm) was the best structure in soil and the higher the content, the better soil aggregation and structure [2]. As a result, the soil with more macro-aggregates would be more resistant to soil erosion. In the present study, the highest proportion of macro-aggregates was found in forestland for wet sieving method samples, and the lowest in cropland for both sieving method samples. These results indicated that forestland favored the formation of macro-aggregates, whereas traditional tillage was not conducive to soil aggregation. Moreover, soil aggregate stability was significantly lower in cropland than that in forestland and grassland in the present study. Previous studies also showed that tillage would reduce stability of soil aggregate [20, 21]. This might be due to continuous arable cropping reduced soil aggregates in macro particles and promoted micro ones [19]. Tillage broke up soil aggregates and accelerated decomposition and mineralization of soil organic matter, which might be proved by the lower content of SOC and TN in cropland in this study.

The soil properties, especially SOC, were significantly different in terms of land-use types in our study. Our results showed that SOC was positively correlated with MWD under wet sieving method. These findings agreed with the results of previous studies from various regions [8, 22]. The SOC was significantly affected by land-use types [23, 24], and SOC contributed to stability and distribution of soil aggregates [25]. It is believed that soil organic matter and carbohydrate contents positively linked to aggregate stability [26]. The forestland shared the highest soil aggregate stability, which was significantly higher than those in grassland, in line with results of Zeng et al [8]. This might be attributed to a study result that the forestland had higher levels of polysaccharides and fungi in the rhizosphere [27]. In addition, higher SOC in forestland might be another reason. Previous studies showed that characteristics of plant community depend on land-use types [28] and significantly influence stability of soil aggregates via changing SOC and soil microbial biomass [29]. Zhao et al [10] reported that land-use types contributed to about 67% variation of soil aggregates, which implied that land use was a main factor influencing soil aggregate stability and size distribution. Plant roots might be another factor for the soil aggregate formation and stabilization, as a positive correlation was observed between fine roots and soil aggregate stability [30]. The soil aggregate stability has been believed to be promoted by plant roots generally via enhancing the interaction between roots and mycorrhizal fungi [31]. However, we did not determine the microbial characteristics and plant roots in relation to soil aggregate stability in our present study. Thus, further studies are required to assess the microbial mechanisms of soil aggregation under different land-use types. In addition, this study was limited to Zhoukou City, hence more studies should be taken in other sites in North China Plain to validate the present opinions.

Different methods for soil aggregate stability determination

Selection of an appropriate procedure to determine soil aggregate stability is not straight forward. Our results showed that soil aggregate stability in different land-use types followed the order of forestland > grassland > cropland under both sieving methods. However, significance was observed between the two sieving methods. With dry sieving method, the distribution of aggregates was skewed toward aggregates of >5, 2–5, and 1–2 mm; while proportions of 0.25–0.5 and <0.25 mm aggregates were relatively low. In contrast, with the wet sieving method, micro-aggregate (<0.25 mm) contributed to the highest fractions in all soil studies. The difference between wet sieving and dry sieving methods in terms of aggregate distribution could be mainly on the fact that the energy applied to the soil differs greatly between both methods. Moreover, the proportions of macro-aggregate obtained from wet sieving method were lower than that obtained from dry sieving method. This might suggest that proportions of soil water stable aggregate were relatively low in this given soil, the studied soil tended to suffer from erodibility. Previous studies indicated that the proportions of lager macro-aggregates generally decreased with wet sieving method due to the breakdown of the weak macro-aggregates into smaller aggregates by high disruptive forces of water, and soil aggregates only shocked by a rubbing effect under dry sieving method [32, 33]. Our results showed that MWD_{wet} was positively correlated with BD, SOC, and TN, while no significant correlation was observed between MWD_{dry} and basic soil properties (i.e. BD, SOC, and TN). This might be because the soil aggregates were only water stable aggregate under wet sieving method, while aggregates obtained from dry sieving method concluded water stable and non-water stable aggregates. Our results indicated that the majority parts of aggregates in the agricultural soil were not water stable. The water stable aggregates obtained from wet sieving method can better reflect the size distribution of soil aggregates.

CONCLUSION

The effects of land-use types on soil aggregate stability and size distribution in Central China were determined. The land-use types had significant effect on soil aggregate stability in the present study, and MWD of forestland was the highest in both soil layers under both wet and dry sieving methods. This result suggested that the soil aggregate was more stable in the forestland than in the grassland and the cropland. SOC was positively correlated with MWD, which was a vital factor affecting soil aggregate formation. The wet sieving method was more suitable to evaluate soil aggregate stability for the given soil. The forestland soil was more stable and more resistant to soil erosion in the studied area; however, more attention should be taken in soil management of grassland and cropland. These results would provide guidance for soil ecological construction in Central China. However, further studies in other sites should be conducted to reveal the microbial mechanisms of soil aggregation in different land-use types.

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