Catena 172 (2019) 148–157

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Soil texture determines the distribution of aggregate-associated carbon, nitrogen and phosphorous under two contrasting land use types in the Loess Plateau

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ARTICLE INFO

Keywords:
Land use types
Nitrogen
Organic carbon
Phosphorus
Soil texture
Water-stable aggregates

ABSTRACT

Organic carbon (OC) and nutrient dynamics are closely related to soil texture, but how texture influences the distribution of OC and nutrients in aggregates in various land use types has not been examined. This knowledge gap precludes our mechanistic understanding of soil biogeochemical cycles at large spatial scales. Herein we compared the contents and stoichiometric ratios of OC and nutrients in both bulk soils and aggregates in cropland and woodland across a clay content gradient (7–31%) in the Loess Plateau. The soil metrics that were measured included the proportions of water-stable aggregates, and the contents of OC, nitrogen (N) and phosphorous (P) in bulk soils and each aggregate fraction. The stoichiometric ratios of carbon (C), N and P were calculated. The relationships between soil metrics and clay content were analyzed. We hypothesize that OC, N and P in aggregates increase with clay content, and these relationships are independent of land use types. In partial support of these hypotheses, the proportion of macroaggregates and the contents of OC, N and P in bulk soils and most aggregate fractions linearly increased with clay content. The slopes of these linear relationships were not affected by land use type. The C/N ratio were minimally affected, while the C/P and N/P ratios in both bulk soils and aggregates increased with clay content, and these relationships changed with land use type. Proportion of macroaggregates, contents of OC and N, and ratios of C/N, C/P and N/P were significantly higher in woodland than in cropland across or within sites. Furthermore, the distribution patterns of OC, N and P contents, and C/P and N/P ratios among aggregates varied with site and land use type. These suggested that soil texture determines the distribution of OC, N and P and their stoichiometric ratios within soil aggregates in the Loess Plateau of China, and most of these determining relationships were independent from land use types.

1. Introduction

The distribution and availability of nutrients in soils are vital to the productivity and biogeochemical cycles in terrestrial ecosystems (Wang et al., 2007; Udom and Ogunwole, 2015). The turnover and availability of organic carbon (OC) and nutrients and their response to management are largely related to soil aggregates and thus soil structure (Six et al., 2000; Galantini et al., 2004). For example, aggregates provide physical protection from microbial decomposition and loss of OC and N (Six et al., 2004; Barthès et al., 2008; Wei et al., 2013), and changes in soil OC and N after land-use change mainly result from those associated with macroaggregates (Cambardella and Elliott, 1993; Onweremadu et al., 2007; Wei et al., 2013; Udom and Ogunwole, 2015). According to hierarchy theory, soil OC and N are hypothesized to increase with soil aggregate size because large aggregate-size classes are composed of small aggregate-size classes associated with organic binding agents (Tisdall and Oades, 1982; Oades and Waters, 1991; Six et al., 2000). This theory has been supported by many observations in various ecosystems (Six et al., 2000; Yamashita et al., 2006; Lugato et al., 2010; Qiu et al., 2015). However, the OC and N contents have also been reported to decrease with increasing aggregate size in different ecosystems (Spaccini et al., 2004; Gao et al., 2013; Nweke and Nnabude, 2014). This discrepant observations are mostly due to the different contents of coarse and fine fractions in the soils investigated in previous

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https://doi.org/10.1016/j.catena.2018.08.021
Received 3 October 2017; Received in revised form 9 August 2018; Accepted 21 August 2018
Available online 30 August 2018
0341-8162/

Table 1
Details of the study sites in the Loess Plateau.

Study sites	Location	MAT (°C)	MAP (mm)	Soil type[a]	Clay content (%)[b]	Soil texture
Fufeng28[c]	107°38′E, 34°37′N	12.4	600	Anthrosols	28 (22 – 31)	Loam clay
Yongshou26	108°13′E, 34°43′N	10.8	602	Anthrosols	26 (23 – 31)	Loam clay
Binxian19	108°09′E, 35°04′N	9.7	561	Calcisols	19(15–22)	Clay loam
Yanan14	109°48′E, 36°60′N	9.4	550	Cambisols	14 (11–18)	Sandy loam
Shenmu12	110°51′E, 38°83′N	8.4	437	Cambisols	12 (8–18)	Sandy loam

MAT: mean annual temperature; MAP: mean annual precipitation.
[a] Soil type was identified according to FAO (2014).
[b] Mean and range of clay content.
[c] The number followed the sites represented the averaged clay contents.

reports. Soils with greater proportion of fine particles are more likely to be enriched in C and N than soils with more coarse particles (Mbagwu and Piccolo, 1990).

In addition to OC and N, there are relatively few studies about the phosphorous (P) distribution among aggregates (Green et al., 2005; Wright, 2009; Jiang et al., 2015). Phosphorous plays an important role in plant growth and microbial metabolism (Smith and Prairie, 2004; Singh and Satyanarayana, 2011). Furthermore, the increased C and N availability due to elevated atmospheric CO_2 concentration and N deposition rate (Groenigen et al., 2006; Block et al., 2013) accentuate the P limitations in most ecosystems (Block et al., 2013; Zhang et al., 2014). Improving our understanding of nutrient distribution within soil aggregates is therefore essential for determining the mechanism behind organic carbon and nutrient cycling in soils and ecosystems.

Soil texture is a fundamental property that controls the aggregation of particles, the soil structure, the turnover and availability of nutrients, and the association of OC and nutrients with aggregates. For example, clay particles can act as nuclei capable of generating macro- and microaggregates because of their large specific surface area and chemical association capacity, thus producing a good soil structure (Oades, 1988; Bronick and Lal, 2005). Soil organic matter can be chemically stabilized or physically protected from microbial decomposition through aggregating or intimately associating with clay particles (Six et al., 2002; John et al., 2005), while the availability of soil nutrients has been reported to be higher in coarse-textured soils than fine-textured soils (Franzluebbers et al., 1996; Bronick and Lal, 2005). Moreover, soil texture (usually soil clay content) has been included in most soil models (i.e., Hydrus, DNDC, Biome-BGC, and Century, etc) used to predict the physical, chemical and biological processes that occur in soils and ecosystems (Müller and Höper, 2004; Bricklemyer and Miller, 2007; Bruun et al., 2010). However, although the importance of soil texture has been recognized, how soil texture influences the distributions of OC, N and P in aggregates has not been fully understood. This knowledge is essential for understanding the mechanisms behind soil biogeochemical cycles and for predicting such processes precisely at large spatial scales.

Land use types significantly influence the aggregation of soil particles and the distribution of OC and nutrients within aggregates (Degryze et al., 2004; Qiu et al., 2012; Udom and Ogunwole, 2015). For example, Li and Pang (2010) reported significant differences in the OC and N concentrations and stocks in aggregate fractions among various land use types in the southern Loess Plateau. Adesodun et al. (2007) found higher contents of C, N and P in > 0.5 mm soil fractions but lower contents in < 0.25 mm soil fractions in uncultivated rainforest than those in cultivated soils, while Udom and Ogunwole (2015) reported higher contents of OC and N in each aggregate fraction in forest soils than in cultivated soils in Nigeria. However, current studies have very rarely assessed the impact of soil texture on the nutrient distribution among aggregates at various land use types. The lack of evidence regarding the role of land use types in the effects of texture on nutrient distribution within aggregates hinders our ability to predict biogeochemical cycles under complex landscape conditions.

In this study, we present the results of OC, N and P in bulk soils and water-stable aggregates along a soil clay gradient in different land use types (cropland and woodland) in the Loess Plateau in China to test the following hypotheses: (H1) the contents of OC, N and P increase as aggregate size increases according to hierarchy theory, (H2) soil texture determines the distribution of soil aggregates and the distribution of OC, N and P among aggregates, and the effects of soil texture are not influenced by land use type, and (H3) the distribution patterns of OC, N and P and their stoichiometry among aggregates are independent from land use type.

2. Materials and methods

2.1. Study site and soil sampling

To assess the distribution of OC, N and P among soil aggregates along a soil clay gradient, we selected five paired woodland and cropland sites across the Loess Plateau. The five sites were Fufeng28, Yongshou26, Binxian19, Yanan14 and Shenmu12. Numbers following the site names were the averaged clay contents in soils of the sites. The details of each site are presented in Table 1. For the cropland, the cropping systems were a winter wheat (*Triticum aestivum L*, September to June) - summer maize (*Zea mays Linn*, June to September) rotation (Yongshou26, Fufeng28), winter wheat (September to July) or summer maize (May to September) monoculture (Binxian19, Yanan14), millet (*Panicum miliaceum L*, May to September) or summer maize (May to September) monoculture (Shenmu12). Chemical N fertilizers were applied to the cropland at an annual rate of 307 (± 95), 224 (± 49), 340 (± 40), 350 (± 25), and 360 (± 26) kg N ha^{-1} yr^{-1} at the Fufeng28, Yongshou26, Binxian19, Yanan14, and Shenmu12, respectively. Chemical P fertilizers were applied at an annual rate of 89 (± 34), 95 (± 41), 110 (± 24), 120 (± 20), and 135 (± 17) kg P ha^{-1} yr^{-1}, respectively. No manure fertilizer was applied to the cropland in the past 20 years. The amount and timing of fertilization may influence N and P results in the cropland. However, given that amounts of fertilizers applied in cropland varies with site and year across sites with a distance of 750 km, our approach is appropriate for understanding effects of clay content on N and P in the cropland. Fertilizers were applied at the beginning of seeding season, while soil samples were collected at or near the harvest season. The timing of fertilization has minimal effects on results of N and P in this study. At each site, 3 to 8 plots (10 × 10 m) were established in the cropland for soil sampling. For the woodland, the dominant species were black locust (*Robinia pseudoacacia Linn*) in Fufeng28, Yongshou26, Binxian19 and Yanan14 and peashrub (*Caragana korshinskii Kom*) in Shenmu12. At each site, 9 to 12 plots (20 × 20 m) were established in woodlands with stand ages of approximately 20 years for soil sampling. The sampling size in this study was determined by the area proportion of cropland or woodland in each site. However, given that variation of soil properties in woodland is greater than cropland, the sampling size was larger in woodland than cropland. Each sampling plot was at least 40 m from the boundaries between woodland and cropland to reduce the possibility of effects of