Geoderma 330 (2018) 19–29

Contents lists available at ScienceDirect

Geoderma

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

Control of tillage disturbance on the chemistry and proportion of raindrop-liberated particles from soil aggregates

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ARTICLE INFO

Handling Editor: Morgan Crisitne L.S.

Keywords:
Raindrop
Aggregate mechanical breakdown
Soil organic carbon
Stable isotope
Lignin

ABSTRACT

In most agricultural systems, the raindrop-induced breakdown of soil aggregates is the initial process of surface soil erosion and redistribution of soil organic matter. The physicochemical differences between the liberated and mobilized material and the residual raindrop-stable soil aggregates can be a critical factor controlling landscape-level heterogeneity in soil biogeochemical reactivity. Using an artificial rainfall simulator with soils from southeastern Iowa, we investigated the role of management intensity on the chemical characteristics of soil particles liberated through raindrop-induced breakdown of both small aggregates (0.25–2 mm; SMAGG) and large aggregates (> 2 mm; LGAGG). At all sites LGAGG exhibited lower stability to raindrop energy than SMAGG. Both soil aggregate size classes from a restored prairie and an agricultural site using reduced ridge tillage exhibited higher raindrop stability than conventionally tilled sites. In the restored prairie, the chemical composition (i.e. lignin, substituted fatty acids, SOC and TN, $\delta^{15}N$ values) of raindrop-liberated particles was nearly indistinguishable from raindrop-stable aggregates. Among all tilled sites, with the exception of SOC in the conservation tillage site, the raindrop stable particles had relatively higher concentration of measured chemical components versus raindrop-liberated particles. Additionally, the liberated particles in all tilled sites contained higher concentration of oxidized lignin phenols, a lower proportion of cinnamyl to vanillyl lignin, and, as evidenced by the $\delta^{15}N$ values, a trend toward a higher proportion of microbially-processed nitrogen, indicating more decomposed microbial processed organic matter. These results are important for understanding the biogeochemical impacts and resulting spatial heterogeneity of raindrop liberated and transported soil particles among landscapes with different management intensity and efforts toward soil conservation.

1. Introduction

Intensive agricultural land management practices put soil at risk for erosion and have resulted in the redistribution and loss of soil organic matter from hillslopes, leading to significant degradation of soil structure and soil quality (Six et al., 2000; Berhe et al., 2007; Ryals et al., 2014; Papanicolaou et al., 2015; Paul, 2016). In addition to direct mechanical fragmentation of the aggregates by tillage, soil aggregates in intensively managed landscapes are at increased risk of disaggregation by runoff and raindrop impacts, as soil lacks plant cover for over half of the year (Rieke-Zapp and Nearing, 2005; Hu et al., 2013). This raindrop-induced disruption of aggregates can result in a local depletion of soil organic matter as organic fragments, both free and clay/silt-bound, are detached from the larger protective aggregate structures, redistributed across the landscape, and exposed to microbial-driven degradation (Wacha et al., 2014). Ultimately, the spatial heterogeneity in biogeochemistry of surface and buried soil across a landscape may be strongly controlled by how management intensity controls the susceptibility of soil aggregates to raindrop-induced release and redistribution of soil particles of distinct chemical character (Six et al., 2000; Berhe et al., 2012).

Soil aggregates have incredibly complex internal particle structures with a great degree of spatial heterogeneity in organic chemistry, mineralogy, and microbiology that is evident upon physical breakdown of

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https://doi.org/10.1016/j.geoderma.2018.05.013
Received 30 September 2017; Received in revised form 3 February 2018; Accepted 11 May 2018
0016-7061/

aggregates into component sub structures (Lugato et al., 2010a; Chacón et al., 2015; Regelink et al., 2015; Erktan et al., 2016; Liu et al., 2016). This internal variability, however, manifests itself as characteristic trends in physicochemical properties upon aggregate breakdown into particles that vary by size and density (Six et al., 2001; Baldock, 2002). In general, laboratory separation of soils by size and density reveals that progressively smaller, denser particles tend to exhibit decreased elemental C and N abundances and a lower proportion of plant-derived organic matter and an accumulation of microbial residues (Castellano et al., 2015).

Organic geochemical measures of soil organic matter are commonly used to investigate soil aggregate and particle dynamics in response to environmental stressors and natural variation in soil forming processes (Grandy and Neff, 2008; Crow et al., 2009; Sollins et al., 2009b). Plant-derived biopolymers commonly used as biomarkers for plant input and processing, e.g. lignin and substituted fatty acids from cutin and suberin, have been shown to vary in concentration and chemistry across soil particle size and density reflecting distinctive source and alteration by biological and chemical-sorbtive means (Sollins et al., 2006; Filley et al., 2008a; Hernes et al., 2013; Ma et al., 2014). Although lignin exhibits poor long-term protective capacity in agricultural soils (Schmidt et al., 2011), it serves as a powerful tool in studies of soil organic matter dynamics (Routh et al., 2014; Paul, 2016) and connectivity of eroded soil to streams (Dalzell et al., 2005). Trends in stable isotopes of C and N are also observed with particle size and provide indications of plant source, land use, and biogeochemical processing (Liao et al., 2006; Sollins et al., 2006; O'Brien and Jastrow, 2013). The relationship between land use and the $\delta^{15}N$ of soil is complex. Within soil fractions (both size and density separated in-laboratory) $\delta^{15}N$ values tend to increase with decreased soil particle size and increased density (Liao et al., 2006; Sollins et al., 2006), which is often attributed to an increase in the proportion of microbially-processed, or microbial necromass-derived, nitrogen (Kleber et al., 2007; Kleber and Johnson, 2010). Such trends in the organic geochemistry of soil fractions, which are primarily revealed in analytical laboratory aggregate separation processes (Baldock and Skjemstad, 2000; Baldock, 2002; Sollins et al., 2009a), suggest that soil-fractions liberated and mobilized by the kinetic energy of raindrops on soil aggregates will create smaller soil particles that are chemically distinct from the initial or raindrop stable soil aggregates and manifest into chemical variability across the landscape (Ellerbrock et al., 2016).

Soil aggregates in the size range of 0.25 to 2 mm are particularly responsive to agricultural tillage and mechanical breakdown from rainfall (Blanco-Canqui and Lal, 2004; Moebius et al., 2007). Particles within this size range facilitate short-term microbial transformation of plant detritus and create the conditions to form new micro- and macro-aggregated structures (Baldock, 2002; Allison and Jastrow, 2006; Grandy and Neff, 2008). These aggregates help modulate the biogeochemical engine of soil by localizing plant matter in conditions that can either slow or accelerate decay depending upon soil factors such as texture, clay type, microbial community structure and activity (Jastrow, 1996; Six et al., 2000; Six et al., 2002; Kleber and Johnson, 2010; Paul, 2016). Greater aggregate stability against environmental or management-induced breakdown positively affects the quantity and chemistry of soil organic matter, the soil's resilience to water and wind erosion, and long-term soil health (Edwards and Bremner, 1967; Barthes and Roose, 2002; Kleber et al., 2007).

Although there is an extensive body of literature on the geochemistry of soil aggregates under a variety of management intensities, significant work is still needed to assess the chemical transformation and differentiation of soil fractions generated by direct raindrop breakdown in order to inform both landscape and in-stream erosion studies (Dalzell et al., 2005; Berhe et al., 2012). We used a multiproxy geochemical approach to characterize soil aggregates and particles liberated by raindrop impact using a rainfall simulator on a series of hillslopes under different tillage intensity in southeastern Iowa, U.S. Our goal was to evaluate how land management controls the geochemical signature and generation potential of raindrop-liberated soil particles. We hypothesized that (1) the ability of soil aggregates to withstand raindrop mechanical breakdown decreases with increasing tillage disturbance; (2) raindrop-stable aggregates will have greater organic carbon, plant-derived lignin phenols, and substituted fatty acids as plant-derived particulate organic matter and newly-formed intra-aggregates and micro-aggregates are concentrated therein; and (3) raindrop liberated particles contain more microbially-processed SOC and N, more closely reflecting mineral-associated/bound soil organic matter.

Table 1
General site characteristics.

Site	RP	RT	CT-1	CT-2	CT-3
Management					
Tillage	n/a	Reduced ridge till	Conventional tillage	Conventional tillage	
Tillage intensity	n/a	Reduced	Moderate	Intensive	
Tilth depth	n/a	5 cm	20 cm	20 cm	
Crop rotation	Restored prairie	Corn-corn-bean	Corn-bean	Corn-bean	Corn-bean
Soil physical and chemical properties					
Sand%	2.63	1.87	4.10	19.10	7.85
Coarse silt%	42.32	43.57	41.95	33.09	33.64
Fine silt%	29.25	27.43	27.58	25.61	33.41
Clay%	25.80	27.13	26.38	22.20	25.11
Bulk density (g/cm^3)	0.92	0.95	1.19	1.00	1.04
Total carbon (%)	3.88	2.05	2.17	2.05	2.21
Total nitrogen (%)	0.36	0.20	0.20	0.20	0.20
pH	6.18	5.95	6.63	5.55	6.07
Landscape					
Slope (%)	15.21	6.52	5.71	0.07	0.57
Elevation (m)	235–243	240–261	237–242	201–211	210–211

2. Materials and methods

2.1. Study sites

This study was conducted using soils collected from five fields in the Intensively Managed Landscapes Critical Zone Observatory (IML-CZO) within the 270 km^2 Clear Creek Watershed in the southeastern Iowa, U.S. The area was converted from native prairie-savannah-forest to agriculture over the last 140 years (Bettis et al., 2003) (see Table 1 for site-specific characteristics). Clear Creek is now dominated by agriculture (~80%), especially corn-soybean rotations with combinations of conservation and conventional tillage. The climate is humid-continental with a mean annual temperature of 9 °C and abundant freeze-thaw cycles in early Spring and late Autumn. The mean annual precipitation is 889 mm/year, with ~50% of annual water delivered between March and June (Papanicolaou et al., 2009).

The field sites are representative of U.S. Midwest agricultural sites in terms of corn-soybean cropping rotations, as well as broadly geomorphic and edaphic properties. The field sites span three geographic zones within Clear Creek, which are differentiated by topography, geomorphology, and land management (Table 1). The restored prairie site (RP), in the central region of the watershed, was taken out of intensive management nearly 50 years ago and then grazed as pasture. It was reseeded in 2003 and managed as a restored prairie with a five-year burn frequency that was last performed 2 years prior to sampling in 2014. A reduced tillage (RT) site near the headwaters is under a three-year rotation of corn-corn-soybean with reduced tillage (contour