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Factors influencing soil aggregation and particulate organic matter responses to bioenergy crops across a topographic gradient

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ABSTRACT

Bioenergy crops have the potential to enhance soil carbon (C) pools from increased aggregation and the physical protection of organic matter; however, our understanding of the variation in these processes over heterogeneous landscapes is limited. In particular, little is known about the relative importance of soil properties and root characteristics for the physical protection of particulate organic matter (POM). We studied short-term (3-year) changes in aggregation and POM-C pools under three cropping systems (switchgrass, a triticale/sorghum double crop, continuous corn) replicated across five landscape positions along a topographic gradient in Iowa, USA. We isolated POM associated with three aggregate fractions (>2 mm, 0.25–2 mm, and 0.053–0.25 mm) to determine the relative influence of ten soil and three root properties. Aggregation increased in all cropping systems and was greatest under switchgrass; however cropping system effects were not consistent among positions. Total soil organic C stocks did not change, but C within both physically protected (iPOM-C) and unprotected (frPOM) C pools increased. Shifts in iPOM-C were concurrently influenced by soil properties and root traits. Soil texture had the strongest influence (65% relative importance), with finer-textured soils showing greater gains in total iPOM-C, while greater root biomass influenced (35% relative importance) accrual of total iPOM-C. Aggregate fractions varied in their iPOM-C response to soil and root variables, however individual pools similarly showed the importance of soil texture and root biomass and annual root productivity (BNPP). Changes in frPOM-C were strongly correlated with BNPP. Our data suggest that macroaggregate formation drives short-term responses of POM, which are influenced by both soil and root system properties. Crops that maximize root biomass and BNPP will lead to the largest increases in protected soil C stocks. However, C storage rates will vary across landscapes according to soil conditions, with texture as the primary influence.

1. Introduction

Purported environmental benefits of bioenergy often highlight the increased stabilization and subsequent storage of carbon (C) as soil organic matter (SOM) within agricultural soils (Gelfand et al., 2013; Lemus and Lal, 2005). Maximizing this C storage benefit necessitates understanding how cropping systems that produce bioenergy feedstocks alter belowground C cycling across agroecosystems (Anderson-Teixera et al., 2013; Blanco-Canqui, 2010; Tiemann and Grandy, 2015). Perennial crops, such as switchgrass and short-rotation woody crops, are expected to influence carbon cycling and the overall potential environmental benefits of bioenergy much differently relative to annual crops (Chimento et al., 2014; Robertson et al., 2011), with the realized improvements to ecosystem functioning likely dependent on the location of crops within landscapes (Dale et al., 2011). Sites poorly suited for annual row crops due to edaphic limitations or susceptibility to erosion and flooding have the potential to produce significant biomass from perennial vegetation (Campbell et al., 2008; Gelfand et al., 2013; Tilman et al., 2006). Still uncertain, however, is the relative capacity for improving soil C storage in annual versus perennial bioenergy crops within both productive and marginal areas that comprise heterogeneous agroecosystems, as well as the duration of time necessary to realize these changes. Understanding the potential of bioenergy cropping systems to stabilize SOM across both productive and marginal locations is necessary for maximizing ecosystem benefits as well as establishing realistic expectations of SOM accrual across diverse agricultural landscapes.

Soil aggregation and particulate organic matter (POM) are key indicators of soil quality and the environmental sustainability of agricultural management practices. Aggregate formation stabilizes organic material within soil microsites, physically protecting POM from microbial decomposition (Golchin et al., 1994; Balesdent et al., 2000) and increasing the mean residence time (MRT) relative to inter-aggregate (unprotected) organic matter (Puget et al., 2000). For example, Liao et al. (2006)

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showed that unprotected POM had shorter average MRTs (30 years) than POM protected within aggregates (60 years) using natural abundance $\delta^{13}C$ signatures in grasslands invaded by woody shrubs. Because physical protection from microbial activity contributes to the persistence of soil C regardless of the biochemical recalcitrance due to the chemical structure of organic matter (Dungait et al., 2012; Kleber et al., 2011; Torn et al., 2009; Trumbore, 2009), practices that promote the formation of soil aggregates—such as no-till management (Elliott, 1986) and establishment of perennial vegetation (Jastrow, 1996)—ultimately lead to greater soil carbon stocks.

According to the conceptual model of Six et al. (2000), recent inputs of organic matter induce macroaggregate (>250 μm) formation, while the decomposition of SOM within these macroaggregates leads to the formation of stable microaggregates (Gale et al., 2000b) and organo-mineral complexes. Microaggregates (<250 μm) turn over slower relative to macroaggregates from increased stability with smaller size (De Gryze et al., 2005). Consequently, macroaggregate formation leads to longer MRTs of SOM in soil over time through the formation of smaller, more stable soil fractions with increasingly intimate associations between organic matter and mineral surfaces (Martens et al., 2003; Poirier et al., 2005). In aggrading systems, macroaggregate formation may be a good predictor of potential future C stabilization responses due to their importance for protecting recently deposited SOM (Angers and Giroux, 2006; Jastrow et al., 1996) and promoting the formation of stable organo-mineral complexes.

The biophysical drivers of soil aggregation have been a focus within the scientific literature for decades (Six et al., 2004). Early theoretical and experimental work identified the importance of inorganic binding agents, organic residues, soil mineral particles, soil organisms, and the effects of environmental variables (Kemper and Koch, 1966). In particular, the significance of interactions between SOM and silt and clay particles for the formation of highly stable microaggregates was recognized (Edwards and Bremner, 1967). In agricultural soils, soil disturbance from tillage destabilizes aggregates, releasing intra-aggregate organic matter and increasing decomposition (Balesdent et al., 2000; Beare et al., 1994; Blanco-Canqui and Lal, 2007; Cambardella and Elliott, 1992, 1993; Grandy and Robertson, 2006; Six et al., 1999, 2000). Establishment of perennial vegetation following cultivation showed the positive effects of root length, microbial biomass, and mycorrhizae on aggregate formation (Jastrow et al., 1996; Jastrow et al., 1998; Miller and Jastrow, 1990). Based on much of the experimental work done to date, additional biological factors influence aggregation, including the positive influences of microbial biomass and by-products (Zhang et al., 2012), mycorrhizae (Wilson et al., 2009), and soil fauna such as Collembola (Siddiky et al., 2012a,b) and nematodes (Zhang et al., 2013). Recent work has shown strong positive links between root biomass and the abundance of nematodes and several taxa of mesofauna (Eisenhauer et al., 2013), suggesting that changes in root biomass alters the structure of soil food webs, changing belowground C cycling and the mean residence time of different SOC pools (Reid et al., 2012).

With the development of the aggregate hierarchy concept, Tisdall and Oades (1982) suggested that the factors important for aggregate formation differed according to aggregate size. Microaggregates are bound together by persistent binding agents such as humified SOM interactions with clay particles, while macroaggregates are formed from transient (microbial- and plant-derived polysaccharides) and temporary (roots, fungal hyphae) binding agents. Despite the recognition of the importance of multiple factors influencing physical protection, very few studies have considered their interactive effects on aggregation and SOM changes (Six et al., 2004). Particularly important is the need to assess the significance of soil physiochemical and biotic factors simultaneously (Barto et al., 2010) to predict soil C storage in response to changes in management across heterogeneous landscapes (Viaud et al. 2010). It is well understood that SOM levels vary at landscape scales, particularly across topographic gradients (Schimel et al., 1985) in response to soil redistribution (Pennock et al., 1994) and biological factors affecting C cycling, such as variation in plant C inputs and decomposition (Yoo et al., 2006). Further, topographical influences on soil C can interact with management, resulting in altered responses to management such as tillage (Senthilkumar et al., 2009) and land use (Tan et al., 2004) depending on position in the landscape. Although many of the abiotic and biotic factors important for aggregation and physical protection of POM are known to vary across topographic gradients and in response to land use—and coincide with spatial patterns of soil C stocks—little work has been done to identify the relative influence of these factors and their interactions across heterogenous landscapes.

In this study, we address the need for understanding both the impacts of topography and bioenergy cropping systems on short-term variation in POM pools, and the relative importance of multiple ecosystems drivers of aggregation in bioenergy cropping systems. We measured changes in aggregation and physically protected SOM among three cropping systems and five landscape positions along a topographic gradient providing variation in numerous soil properties during the initial years following conversion from a conventionally-tilled corn soybean rotation to production of no-till bioenergy cropping systems. The objectives of this study were to (i) assess the interactions between cropping system and landscape position/soil properties on soil aggregation and unprotected (also known as free POM; frPOM) and physically protected (intra-aggregate POM; iPOM) C pools associated with aggregate fractions, and (ii) evaluate the relative importance of multiple cropping system and soil properties on short-term (3 year) changes in unprotected and physically protected SOM.

2. Materials and methods

2.1. Site description and design

This study was conducted between 2009 and 2012 as part of the Landscape Biomass Project (http://www.nrem.iastate.edu/landscapebiomass/), located in Boone County, IA, at Iowa State University's Uthe Research and Demonstration Farm. Prior to the establishment of experimental plots, the entire 35 ha site was managed for annual row crop production since the 1970s; all but the floodplain soils have been in continual production since before the 1930s. Soils were managed with conventional tillage practices since at least the 1980s (Lynn Henn, CAD farm manager, personal communication); however, all plots were managed as no-till following establishment in 2008. A complete description of the site including the experimental design, site soil conditions, and cropping systems evaluated can be found in Wilson et al. (2014). Briefly, the three cropping systems included in this study were randomized within three blocks across each of five landscape positions (summit, shoulder, back slope, toe slope, floodplain) situated along a topographic gradient in a randomized complete block design ($n = 3$, 45 plots total). Soils on the site are comprised of two Mollisols consisting of five soil series (see Ontl et al., 2013). All soil series have high cation exchange capacity relative to clay content, consist of mixed mineralogy, and were formed in calcareous glacial till—except the floodplain soils—which were formed in alluvium (Soil Survey Staff, 2013). Three cropping systems were included in the study, 1) switchgrass (*Panicum virgatum* L., cultivar: "Cave-In-Rock"), 2) a double crop system consisting of a winter annual crop (triticale, ×*Triticosecale* Wittm.) seeded in the fall following the harvest of sorghum (*Sorghum bicolor* L. Moench), and 3) continuous corn (*Zea mays* L.). Fertilization rates were determined according to crop needs. Nitrogen was added as urea; annual N addition rates were 134 kg N ha^{-1} for switchgrass, 168 kg N ha^{-1} for triticale/sorghum (34 kg N ha^{-1} prior to triticale, 134 kg N ha^{-1} prior to sorghum) and 168 kg N ha^{-1} for continuous corn. In 2011, sorghum received 112 kg urea–N ha^{-1}, while in 2012 sorghum plots were not fertilized due to drought conditions. All plots received 112 kg KCl ha^{-1} and 56 kg P_2O_5 ha^{-1} of Triple Super phosphate in 2010 and 2011.