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Long-term tillage, rotation and perennialization effects on particulate and aggregate soil organic matter

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ABSTRACT

Perennialization and reducing tillage have increased soil organic matter (SOM) in both aggregate and particulate organic matter (POM) in short-term and small scale experiments, but there is a need for investigations into the long-term effects of agroecosystems on these dynamic pools of SOM. The objectives of this study were to investigate how management varying in crop rotation, tillage intensity and organic management from 1990 to 2013 has affected POM and aggregate C and N, and assess the relationship between these SOM fractions and biomass C inputs. We hypothesized that tillage, low biomass inputs, and annual crops in rotation would be associated with decreased POM and aggregate C and N. Soil from six systems from the Wisconsin Integrated Cropping Systems Trial (WICST) on a Phaeozem, or Mollisol, was sampled in 2013: Continuous Maize (*Zea mays* L.), Maize–Soybean [*Glycine max* (L.) Merr.], Organic Grain (including maize, soybean, and wheat [*Triticum aestivum* L.] sequentially seeded with oats [*Avena sativa* L.] and berseem clover [*Trifolium alexandrinum* L.]), Conventional Forage (three years alfalfa [*Medicago sativa* L.] followed by maize), Organic Forage (two years' alfalfa with oats nurse crop followed by maize), and Pasture (rotationally grazed, seeded to a mixture of red clover [*Trifolium pratense* L.], timothy [*Phleum pretense* L.], smooth bromegrass [*Bromu sinermis* L.] and orchardgrass [*Dactylis glomerata* L.]). Among all systems at 0–25 cm depth, we found significantly greater concentrations of POM-C in the Pasture (4.4 g C kg^{-1} soil) and POM-N in Pasture (0.30 g N kg^{-1} soil) and Organic Forage (0.25 g N kg^{-1} soil). The Organic Grain system had lower concentrations of macroaggregates and lower stocks of C and N within macroaggregates. Across all systems, belowground biomass C input was significantly positively correlated with POM-C, POM-N, and aggregate C and N. The data supported our hypothesis in part, as results indicate that frequent cultivation in the form of tine weeding and rotary hoeing for weed control in Organic Grain rotation is likely disrupting formation of aggregates and storage of C and N therein. However, in systems that were chisel plowed every one to three years, high biomass C inputs maintain POM-C and POM-N and soil aggregation equivalent to the fully perennial system.

1. Introduction

There is immense interest in adjusting agricultural management to increase concentrations of soil organic carbon (SOC) for environmental benefits including climate change mitigation, improved soil fertility, erosion prevention and improved infiltration (Lal, 1993, 2001; Sanchez et al., 2004). Since SOC may be preserved due to its chemical characteristics, physical protection in aggregates, or immobilization in microbial biomass, it is difficult to predict which agricultural practices may increase SOC over the long term. Many soil processes can take decades to reach equilibrium (Six et al., 2004a,b), and so consistent management over time is needed to explore the long-term implications of adoption of cropping systems (Dick, 1992; Drury et al., 1998). The Wisconsin Integrated Cropping Systems Trial (WICST), established in 1990, was designed with input from farmers, researchers and extension agents, and applies six sets of management practices as whole systems (Table 1,Posner et al., 1995). No one practice can be tested by itself, e.g. tillage intensity across a range of rotations, but the strength of WICST is that each treatment represents a management system (grain vs. forage based, conventional vs. organic) and the long-term effects of these systems can be

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Table 1
Wisconsin Integrated Cropping Systems Trial (WICST) details including crop rotations, yield, tillage regime, and biomass C input estimates, 1993–2013. (Adapted and updated from Sanford et al., 2012 and Jokela et al., 2011).

Type	System	Crop phase	Average yield[a]	Primary tillage equipment	Estimated annual C input[b] ($kg\ ha^{-1}$)	
			$Mg\ ha^{-1}$		Belowground	Aboveground
Grain	Continuous Maize	Maize	10.7	Chisel plow	4030	2355
	Maize–soybean	Soybean	3.6	No till	2007	1061
		Maize	11.1	Strip-till	4192	2450
		System mean			3093	1751
	Organic Grain	Soybean	3.2	Chisel plow	1774	938
		Winter wheat/clover-oats mixture	3.9	Field cultivator	1742	840
		Maize	8.9	Chisel plow	3732	1944
		System mean			2416	1241
Forage	Conventional Forage	Alfalfa seeding	5.8	Chisel plow	3143	734
		Alfalfa	11.0	None	822	2644
		Alfalfa	9.8	None	1183	7456
		Maize	12.0	Chisel plow	6731	2603
		System mean			2976	3361
	Organic Forage	Oat–alfalfa seeding	8.2	Chisel plow	2773	1649
		Alfalfa	11.2	None	1291	6671
		Maize	10.2	Chisel plow	5601	2182
		System mean			3221	3501
	Pasture	Mixed pasture	8.3	None	1606	4437

[a] Forage yields are reported at 100% dry matter (DM), corn yields at 84.5% DM, soybean yields at 87% DM, and wheat yields at 86.5% DM.
[b] Biomass C inputs to soil were estimated based on 1993–2013 WICST yields and harvest indices and shoot/root ratios from Bolinder et al., 2007. Post-harvest residue, cover crop biomass, cow or chicken manure, roots and root exudates are included in estimates.

compared in the same environment. The WICST occurs on a Typic Argiudoll, a productive silt loam which covers over 12 million ha of the United States Corn Belt, where management may have an enormous impact on SOC stocks (Lal, 2001). Agricultural management, variation in crop physiology and yields at WICST create an ecological gradient of biomass C inputs, which may affect both free and protected SOC (Table 1, Culman et al., 2010; Kong and Six, 2010; Rasse et al., 2005). We measured particulate organic matter (POM) and aggregate C and N, which have been proposed as potential indicators of management effects on SOC storage (Denef et al., 2007; Marriott and Wander, 2006b), after 23 years of varying tillage, rotation and inputs at WICST.

The inclusion of forage perennials, grazed or harvested, in a cropping system has important effects on storage of SOC due to a shift in timing and type of organic inputs, a greater root/shoot ratio, and a reduction in disturbance (lack of tillage). Soil under perennial vegetation has been shown to store more C than under annual crops, as the increased root presence and associated microbial activity provides SOC around which aggregates are formed (Culman et al., 2010; DeLuca and Zabinski, 2011; O'Brien and Jastrow, 2013). DuPont et al. (2010) showed that root production was halved by the no-tillage conversion of perennial grassland to annual wheat and microbial biomass C was significantly reduced in the top 40 cm of soil; changes in SOC after conversion to annual crop production are due to crop physiology as well as lack of disturbance. Many field studies have shown that reducing tillage increases storage of SOC (Halvorson et al., 2002; Havlin et al., 1990; Lal, 1984; Six et al., 1999), but there is also evidence that tillage regime does not change total SOC in some conditions, and that tilled systems may redistribute SOC lower in the soil profile (Baker et al., 2007; Gál et al., 2007). The variation in SOC response to tillage may be due to the variation in mechanism of SOC storage. Tillage reduces soil aggregation, promoting decomposition of the SOM within aggregates which is essential for long-term SOC storage (Denef et al., 2004; Six et al., 2000a; Yoo et al., 2011). Given the equivocal conclusions of past studies, it is important to take into account soil type, tillage frequency and type, and both free and protected SOC pools when assessing the impact of tillage on SOC storage.

By separating the large-size, labile POM and associated C and N, researchers have been better able to track a fast-cycling pool of SOC, which is vulnerable to loss upon shifts in management. The POM-C has been shown to be easily decomposed (Mirsky et al., 2008) and reflective of inputs (Marriott and Wander, 2006a). The POM-C and POM-N were increased in continuous maize compared with maize–soybean rotation (Coulter et al., 2009), and decreased in tilled soils compared with native sod more drastically than did SOC or total nitrogen (TN) (Cambardella and Elliott, 1992). Rotations with livestock, prairie and manure treatment have also increased POM-C compared with maize fields (Hernandez-Ramirez et al., 2009; Maughan et al., 2009). The sensitivity to management shown in these studies suggests that POM is a biologically labile but somewhat physically protected pool of SOM, so when management disrupts soil structure, POM-C and POM-N are affected more dramatically than are SOC or TN (Marriott and Wander, 2006b).

Soil aggregates have proven to be a useful, measurable tool for investigating SOC in natural and agroecosystems (Six and Paustian, 2014). Aggregate hierarchy theory as defined by Tisdall and Oades (1982) maintains that aggregates form around particles of SOM, and that stability of aggregates increases as size decreases due to the nature of the SOM acting as aggregate binding agents. Work using physical fractionation and C isotope analysis has revealed that organo-mineral associations with silt and clay are the most stable, followed by binding into microaggregates (53–250 μm) by persistent binding agents such as mycorrhizal byproduct glomalin, and finally binding into macroaggregates (<250 μm) by fungal hyphae, roots, and more temporary organic compounds such as polysaccharides (Denef et al., 2001; Gunina and Kuzyakov, 2014; Jastrow, 1996; Kleber et al., 2007; Six et al., 2004a; Tisdall and Oades, 1982). Physical protection prevents decomposition of simple bioavailable C compounds like proteins and glucose for