RESEARCH LETTER

Systems with greater perenniality and crop diversity enhance soil biological health

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Abstract

Soil health has received heightened interest because of its association with long-term agricultural sustainability and ecological benefits, including soil carbon (C) accumulation. We examined the effects of crop diversity and perenniality on soil biological health and assessed impacts on mineralization and C stabilization processes across 10 systems including four no-till annual row crops, two monoculture perennials, and four polyculture perennials. Crop diversity increased soil biological health in both annual and perennial systems. Rotated annuals with a cover crop increased permanganate oxidizable C (POXC) and soil organic matter relative to continuous corn (*Zea mays* L.). Perennial polycultures also had 88% and 23% greater mineralizable C relative to the annual and monoculture perennial systems, respectively. All polyculture perennials had significantly greater POXC relative to switchgrass (*Panicum virgatum* L.) and annual systems, with the exception of restored prairie. Of the systems assessed in this study, incorporating perennial polycultures into rotations is the most effective way to increase soil biological health and enhance C stabilization.

1 | INTRODUCTION

The degree to which different management practices influence soil organic matter (SOM) has been a central discussion within agriculture for decades due to the importance of SOM for crop production and long-term soil health (Jarecki & Lal, 2003). Guiding principles on how to best manage for improved soil health include (a) reduced soil disturbance, (b) diversifying soil biota with plant diversity, (c) living roots throughout the year, and d) year-round groundcover (Moebius-Clune et al., 2016; Williams, Colombi, & Keller, 2020). Numerous examples from the

scientific literature demonstrate that continuous SOM inputs combined with reduced soil disturbance results in soil carbon (C) accumulation (Minasny et al., 2017; West & Post, 2002). Syswerda, Corbin, Mokma, Kravchenko, and Robertson (2011) found that annual cropping systems under no-till and organic management sequestered more C relative to conventionally managed systems. Recent meta-analyses demonstrated that increased crop rotational diversity lead to greater soil C and N pools (McDaniel, Tiemann, & Grandy, 2014; Tiemann, Grandy, Atkinson, Marin-Spiotta, & McDaniel, 2015), and multiple studies demonstrated that perennial cropping systems are effective at increasing soil C relative to annual systems (King & Blesh, 2018; Sprunger, Oates, Jackson, & Robertson, 2017). Moreover, plant diversity combined with

Abbreviations: POXC, permanganate oxidizable carbon; SOM, soil organic matter.

perenniality is especially effective at enhancing soil C sequestration largely because of greater root systems created from plant complementarity (Fornara, Tilman, & Hobbie, 2009; Sprunger & Robertson, 2018; Weisser et al., 2017). While there is a strong consensus regarding which management practices increase SOM pools, questions still remain on the mechanisms that control soil C cycling and accumulation (Cates & Ruark, 2017).

Emerging soil health indicators that are sensitive to recent changes in management and have the ability to reflect short- and long-term soil C dynamics that could enable researchers to further understand the mechanisms that drive soil C accumulation. For instance, the amount of CO_2 released from the soil after drying and rewetting is highly correlated with mineralization from anaerobic microbes (Franzluebbers, Haney, Honeycutt, Schomberg, & Hons, 2000; Haney, Brinton, & Evans, 2008). Soil respiration, hereafter referred to as mineralizable C, reflects the pool of C that is most accessible to microbial activity and is strongly associated with nutrient mineralization (Haney et al., 2008; Hurisso et al., 2016). In contrast, permanganate oxidizable C (POXC) reflects the theoretical active C pool and has consistently been shown to provide an early indication of soil C stabilization (Culman et al., 2012; Hurisso et al., 2016). A third indicator, soil protein, assesses the labile pool of nitrogen (N) and has a strong association with SOM and nutrient mineralization (Hurisso et al., 2018; Sprunger, Culman, Palm, Thuita, & Vanlauwe, 2019).

These soil health indicators are relatively new and several questions remain regarding how management practices influence POXC, mineralizable C, and soil protein. Determining how different management practices affect soil biological health indicators is a critical step in assessing mineralization and C stabilization processes across various agroecosystems, which has important implications for short- and long-term soil C dynamics (Hurisso et al., 2016).

Here we examine the effect that crop diversity and perenniality have on soil biological health and shallow soil C dynamics in order to understand how different systems affect mineralization and stabilization processes. We hypothesize that (a) crop diversity will increase soil biological health in both annual and perennial cropping systems and (b) perennial crops will have a greater impact on C stabilization relative to annual cropping systems.

2 | MATERIALS AND METHODS

We examined soil biological health indicators in the Biofuel Cropping System Experiment located at the W.K Kellogg Biological Station in southwestern Michigan. The soils at this site are well-drained, moderately fertile, fine-loamy mixed, semiactive, mesic Typic Hapludalfs primarily of the

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> **Core ideas**
> - Soil biological health was examined across a diversity and perenniality gradient.
> - Crop diversity increased POXC and mineralizable C in annual and perennial systems.
> - Differences in SOM among the systems were less apparent compared with other indicators.
> - Perennial polycultures have the ability to stabilize soil C.

Kalamazoo and Oshtemo soil series (Robertson & Hamilton, 2015). Mean annual precipitation and temperature are 1,005 mm and 10.1 °C, respectively (Robertson & Hamilton, 2015).

2.1 | Experimental design

The experiment was established in fall 2008 as a randomized complete block design with five replicates. The 10 treatments included in this trial are different biofuel systems that include annual row crops, monoculture perennial grasses, and polyculture perennials. The four annual systems consist of continuous corn (*Zea mays* L.) a corn + cover crop, and each phase of a corn–soybean [*Glycine max* (L.) Merr.] + cover crop rotation. The cover crop is a winter cereal rye (*Secale cereale* L.) that is planted every fall. Cover crops are then mowed and removed prior to planting. The monoculture perennial systems consist of switchgrass (*Panicum virgatum* L.) and miscanthus (*Miscanthus × giganteus*). The polyculture perennials consist of a system dominated by a hybrid poplar (*Populus* sp.) + a vigorous understory of herbaceous species (Sprunger & Robertson, 2018), a five-species native grass mix [*Andropogon gerardii* Vitman, *Elymus canadensis* L., *P. virgatum, Schizachyrium scoparium* (Michx.) Nash, and *Sorghastrum nutans*], an early successional community, and an 18 species restored prairie consisting of C3, C4, and legume species. All systems except the restored prairie system received N fertilizer.

2.2 | Soil sampling

Soils were collected in mid-November 2017, when the perennial crops were in their ninth year of establishment. Soils were collected from blocks 1–5 with a hydraulic sampler (Geoprobe). Three 1-m-deep cores (7.6-cm diam.) were taken within each plot and separated by four depth
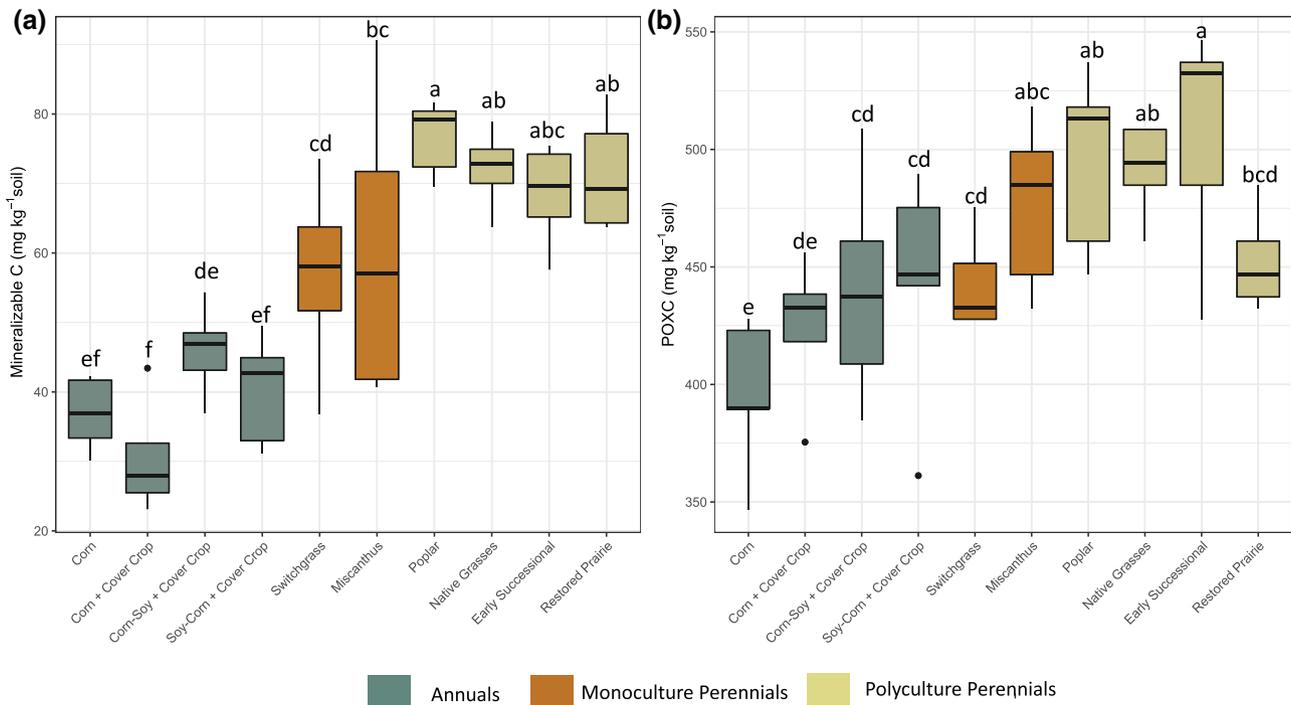
FIGURE 1 (a) Mineralizable C and (b) permanganate oxidizable C (POXC) across 10 systems reflecting a diversity and perenniality gradient on fine loam soils ($n = 5$). Boxplots with different letters are significantly different at $p < .05$

intervals (0–10, 10–25, 25–50, 50–100 cm). Cores within each plot were composited by depth interval and sieved to 4 mm.

2.3 | Soil health indicator analysis

Biological soil health indicators of SOM, POXC, protein, and mineralizable C were conducted on the surface 0-to-10-cm depth layer. Before analysis, soils were sieved to 2 mm and air dried. The POXC measurements were adapted from Culman et al. (2012) and Weil, Islam, Stine, Gruver, and Samson-Liebig (2003). Mineralizable C was determined via a 24-h assay that measures CO_2 respired from rewetted soils using methods adapted from Franzluebbers et al. (2000) and Hurisso et al. (2018). Soil protein was measured through methods adapted from Hurisso et al. (2018) and Moebius-Clune et al. (2016), and SOM was determined via loss on ignition (Combs & Nathan, 1998).

2.4 | Statistical analyses

Analysis of variance (ANOVA) was performed on all soil health indicators using PROC GLIMMIX in SAS v.9 (SAS Institute, 1994). We adopted a framework developed by Hurisso et al. (2016) that calculates the average residuals of

a linear regression model to determine which systems are most closely associated with POXC versus mineralizable C. In our model, mineralizable C was designated as the predictor variable and POXC was designated as the response variable. Residuals were then extracted from the model output (https://github.com/jordon-wade/POXC-chapter). Model observations with greater than predicted POXC values had positive residuals (system trending toward C stabilization), whereas observations with greater than predicted mineralizable C values had negative residuals (system trending toward mineralization).

3 | RESULTS AND DISCUSSION

3.1 | Mineralizable carbon

Mineralizable C values for perennial polycultures were 88 and 23% greater than that of the monoculture perennials and annuals (Figure 1a). This demonstrates that 9 yr post establishment, perennial polycultures had a large capacity to build nutrient pools that are highly associated with mineralization processes. Similar findings from this site are reported in Sprunger and Robertson (2018), who found that 5 yr postestablishment, polyculture perennials had active C pools that were 2.5 times larger than monoculture and annual cropping systems. A larger biologically

TABLE 1 Mean (and SE) soil organic matter, soil protein, and residuals from surface soils (0–10 cm) across the diversity and perenniality gradient. Average residuals from linear regression models used to assess field type effects on permanganate oxidizable C (POXC) versus mineralizable C. A positive residual indicates that field type was more associated with POXC, whereas negative residues were more associated with mineralizable C

System	Soil organic matter	Soil protein	Residuals
	g kg^{-1} soil	mg g^{-1} soil	
Corn	14.4 (1)f	3.67 (0.2)ef	−31.4 (15)
Corn + cover crop	16.2 (2)ef	3.92 (0.2)def	8.14 (16)
Corn–soy + cover crop	18.2 (2)cde	3.62 (0.2)ef	−1.14 (20)
Soy–corn + cover crop	19.2 (1)bcde	3.43 (0.2)f	10.7 (19)
Switchgrass	18.0 (0)def	4.23 (0.2)cde	−15.4 (17)
Miscanthus	22.4 (2)ab	4.95 (0.2)bc	12.2 (12)
Poplar	25.0 (2)a	5.89 (0.3)a	5.49 (17)
Native grasses	21.8 (1)ac	4.56 (0.2)cd	16.5 (8)
Early successional	21.6 (1)abcd	5.42 (0.4)ab	29.0 (22)
Restored prairie	20.4 (1)bcd	4.49 (0.3)cd	−29.1 (9)

Note. Different letters reflect statistical significance at $p = .05$.

available pool of C within the polyculture perennial systems is likely the result of greater fine root production (Sprunger et al., 2017) and enhanced microbial activity (Tiemann & Grandy, 2015). Among the annual systems, the corn–soy + cover crop system had the greatest mineralizable C value, which demonstrates that increasing diversity through crop rotation and the addition of cover crops is important for increasing soil health.

3.2 | Permanganate oxidizable carbon

Differences in POXC across the diversity and perenniality gradient were muted relative to mineralizable C; however, noteworthy differences were still visible (Figure 1b). The poplar, native grasses, and early successional systems had significantly greater POXC values relative to switchgrass and the annual systems. Given that POXC reflects a more stabilized pool of C (Hurisso et al., 2016), this demonstrates that the majority of polyculture perennials and miscanthus are able to stabilize greater amounts of C relative to the annual cropping systems and switchgrass. Enhanced diversity through the addition of cover crops and rotations among the annual systems also resulted in greater POXC (Figure 1b).

3.3 | Trends in carbon mineralization and stabilization processes

To assess soil C trends across the cropping system gradient, we calculated residuals from linear regression, whereby positive residuals indicate that a system is trending toward (or more closely associated with) POXC and C stabilization

and negative residuals indicate that a system is trending toward mineralizable C (mineralization processes) or soil C use (Hurisso et al., 2016; Wade et al., 2019).

Continuous corn had the largest negative residuals across the entire system, indicating that it is heavily associated with mineralizable C (Table 1). The monoculture perennials were split; switchgrass appeared to be more closely associated with mineralizable C (negative residuals) and miscanthus was more closely associated with POXC (positive residuals). Of the polyculture perennials, the poplar, native grasses, and early successional systems all appeared to be more closely associated with POXC and therefore trend more toward C stabilization. Most noteworthy is that the restored prairie system had a large negative residual, indicating that restored prairie trends more heavily toward mineralization processes. This finding coupled with lower POXC values, indicates that the restored prairie is not as effective at stabilizing C relative to the other perennial polycultures. Despite being the most diverse system with greater fine root production (Sprunger et al., 2017), the restored prairie system continues to lose large amounts of bioavailable C through time (Szymanski, Sanford, Heckman, Jackson, & Marín-Spiotta, 2019). Furthermore, the restored prairie system has reduced soil protein because it has never been fertilized (Table 1) which could also hinder C stabilization (Ludwig et al., 2011).

3.4 | Implications for soil health promoting practices

Overall, our findings demonstrate that crop diversity enhanced soil health in both annual and perennial systems. Generally, SOM, mineralizable C, POXC, and soil

protein were lowest in the continuous corn relative to the other annual systems. This corroborates findings that demonstrate that lengthening crop rotations and implementing cover crops increase soil nutrient pools in annual row crops (McDaniel et al., 2014). Even larger gains in soil health were visible in the perennial systems, especially among the perennial polycultures. This indicates that planting perennial polycultures could be an effective strategy for increasing nutrient pools and stabilizing soil C, except when systems are N limited. Perennial polycultures are often incorporated into row crop agriculture via integrated livestock systems, where mixed species pastures are used for grazing (Weißhuhn, Reckling, Stachow, & Wiggering, 2017). Ultimately, our study demonstrates that designing systems that include all four pillars of soil health management (increased diversity, year-round cover, living roots, and reduced soil disturbance) is the most effective way to enhance soil health that leads to important nutrient mineralization and C stabilization processes.

CONFLICT OF INTEREST

The authors declare no conflict of interest associated with the preparation of this manuscript.

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