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Reconciling opposing soil processes in row-crop agroecosystems via soil functional zone management

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ABSTRACT

Sustaining soil productivity in agricultural systems presents a fundamental agroecological challenge: nutrient provisioning depends upon aggregate turnover and microbial decomposition of organic matter (SOM); yet to prevent soil depletion these processes must be balanced by those that restore nutrients and SOM (soil building processes). These nutrient provisioning and soil building processes are inherently in conflict; management practices that create spatial separation between them may enable each to occur effectively within a single growing season, thereby supporting high crop yield while avoiding soil depletion. Soil functional zone management (SFZM), an understudied but increasingly adopted strategy for annual row-crop production, may help meet this agroecological challenge by creating spatial heterogeneity in biophysical conditions between crop rows and inter-rows. However, the process-level effects of this spatial heterogeneity on nutrient provisioning and soil building processes have not been characterised. We assessed the magnitude and spatial distribution of nutrient provisioning and soil building processes in model SFZM (ridge tillage) and conventional tillage (chisel plough) systems in four US states encompassing a major global agricultural production region. For soil building we measured bulk density, aggregation and permanganate oxidisable carbon (POXC); for nutrient provisioning we measured microbial decomposition activity, nutrient mineralisation and plant-available nitrogen. After two years, POXC increased under ridge tillage (0–20 cm depth) compared with chisel plough. Ridge tillage also enhanced nutrient provisioning processes in crop rows, increasing plant-available nitrogen in synchrony with maize peak nitrogen demand. Structural equation modelling revealed that improvement in soil building processes under ridge tillage caused rapid enhancement of nutrient provisioning processes in SOM-poor soils. Increases in crop row POXC stimulated microbial decomposition activity, which was associated with increased plant-available nitrogen during the phase of maize peak nitrogen demand. The decimetre-scale spatial heterogeneity created by ridge tillage enables reconciliation of nutrient provisioning and soil building processes in row-crop agroecosystems. In doing so, ridge tillage promotes critical soil processes necessary for increasing the range of ecosystem services provided by intensive production systems. SFZM approaches may have particular value in regions with SOM-poor soils, which would benefit from rapid increases in surface organic carbon. Also, by concentrating and promoting nutrient provisioning processes around crop roots during crop peak nitrogen demand, ridge tillage may enhance nitrogen-use efficiency and reduce current fertiliser requirements.

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1. Introduction

Sustaining soil productivity in agroecosystems presents a fundamental ecological challenge: nutrient provisioning depends upon the disruption of soil aggregates and microbial decomposition of organic matter (SOM); yet to prevent soil depletion these processes must be balanced by processes that restore nutrients and SOM (henceforth soil building processes) (Janzen, 2006). In natural ecosystems, this balance is achieved in part by plant-scale spatial segregation of SOM accumulation and decay processes. For example, differences in litter quality between plant species leads to horizontal spatial heterogeneity in microbial communities and decomposition processes, affecting the nature and location of SOM dynamics (Ettema and Wardle, 2002). In contrast, the predominant commercial tillage practices in agroecosystems, i.e. conventional ploughing and no-tillage, minimise soil horizontal spatial heterogeneity, creating homogenous soil environments geared towards nutrient provisioning or soil building, respectively (Ettema and Wardle, 2002; Williams et al., 2016c). In conventional plough (henceforth conventional tillage) systems the predominance of nutrient provisioning processes contributes to inefficient resource use and soil depletion (Robertson and Vitousek, 2009; Varvel and Wilhelm, 2011). Conversely, the predominance of soil building processes in no-tillage systems can promote excessive nutrient immobilisation that inhibits crop development (Martens, 2001). Soil functional zone management (SFZM), an understudied strategy for row-crop production, attempts to restore soil spatial heterogeneity by creating interacting zones of SOM accumulation and decay (Williams et al., 2016c). In doing so, SFZM aims to reconcile opposing soil processes to optimise productivity and the delivery of soil ecosystem services.

In SFZM, spatial heterogeneity is created over decimetre-scales by managing crop rows and inter-rows as distinct functional zones. These zones are subject to varying degrees of disturbance at different times, promoting nutrient provisioning processes in one zone and soil building processes in the other zone (Williams et al., 2016c). One widely practiced application of SFZM is ridge tillage. In ridge tillage, rows are tilled in early spring to promote a warm, dry seedbed and residues from the previous crop are moved to the surface of inter-rows (Hatfield et al., 1998). As summer progresses, these residues are sequestered, gradually being converted to labile SOM (i.e. a soil building process). This SOM is then moved back to the crop row at the onset of crop peak nitrogen (N) demand, stimulating microbial decomposition activity and enhancing nutrient availability close to the majority of crop roots (i.e. a nutrient provisioning process) (Kaspar et al., 1991; Williams et al., 2016c).

The SFZM practice of ridge tillage can increase N mineralisation and plant-available N in crop rows relative to inter-rows, and in synchrony with crop developmental needs (Kane et al., 2015; Müller et al., 2009). Surface soil organic C (SOC) is also often greater in SFZM systems compared with conventional tillage, and similar to no-tillage (Fernández et al., 2015; Shi et al., 2012; Varvel and Wilhelm, 2011). These findings support the hypothesis that SFZM can jointly enhance nutrient provisioning and soil building processes. In particular, the spatiotemporal patterns of formation and provision of labile SOM in ridge tillage may support high levels of microbial extracellular enzyme activity, a critical component of nutrient provisioning processes. High levels of extracellular enzyme activity are strongly dependent on substrate availability, e.g. labile SOM (Sinsabaugh et al., 2008). Thus, spatiotemporal patterns of labile SOM availability can drive similar patterns of soil enzyme activity and subsequent nutrient availability (Baldrian, 2014). Consequently, we expect that the movement of sequestered SOM from inter-rows to rows is what drives observed increases in N mineralisation and availability in ridge tillage systems. Relative to predominant tillage practices (conventional and no-tillage), we hypothesise a complementary relationship between improvement in soil building processes in ridge tillage and enhancement of nutrient provisioning during a critical phase of crop development (Williams et al., 2016c).

However, a joint assessment of soil processes in SFZM systems has hitherto not been done. Such process-level assessments are essential to understanding the value of SFZM in mitigating the conflict between soil building and nutrient provisioning processes that is present in conventional and no-tillage systems. Moreover, any reductions in crop yields associated with SFZM must be identified (e.g. Pittelkow et al., 2015). Given increasing global demand for agricultural products (Godfray et al., 2010; Tilman et al., 2011), any declines in yield will strongly deter adoption of SFZM. If yields are comparable with conventional tillage, then SFZM may offer a viable pathway to ecological intensification, by maintaining intensive crop production while maintaining or regenerating the soil resources upon which such production depends (Bommarco et al., 2013).

We assessed the magnitude and spatial distribution of soil building and nutrient provisioning processes in model SFZM (ridge tillage) and conventional tillage (chisel plough) systems. We hypothesised: (1) by separating soil building and nutrient provisioning processes into adjacent row and inter-row spaces at different times, i.e. by creating spatial heterogeneity, ridge tillage enhances both processes compared with chisel plough; (2) the movement of labile SOM to crop rows increases microbial decomposition activity, enhancing nutrient availability at the onset of crop peak N demand, i.e. enhancement and management of soil building processes has a positive effect on nutrient provisioning processes; (3) ridge tillage maintains agricultural productivity at levels comparable to chisel plough. We conducted our assessment across four US states that provided wide variation in climates and soil types. This allowed us to move beyond local comparisons of tillage systems in order to identify consistent effects of soil management applicable across a wide range of environments.

2. Materials and methods

2.1. Experimental sites and design

The study was conducted across four US states that encompass a major global agricultural production region: Illinois (IL), Michigan (MI), Minnesota (MN) and Pennsylvania (PA). This large geographic area provided wide variation in soil types and climates; baseline soil properties and climate data are provided in Table 1

Table 1
Baseline (2011) soil properties (0–10 cm depth) for each site and coordinates of their locations. Precipitation and temperature figures are 30-year growing season means (April–October in IL; May-October for MI, MN and PA). SOM: soil organic matter.

Location	Soil series	Soil texture	SOM (g kg^{-1})	pH	Precipitation (cm)	Temperature (°C)	Location
IL	Drummer	Silty clay loam	47.9	6.0	61.6	18.3	40° 3′, −88° 15′
MI	Marlette	Sandy loam	19.0	6.2	48.0	17.3	42° 24′, −85° 24′
MN	Waukegan	Silty clay loam	42.5	6.4	69.0	16.9	44° 44′, −93° 7′
PA	Hagerstown	Coarse silt loam	33.8	6.3	55.0	17.9	40° 47′, −77° 51′