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′

(see Williams et al. (2016a) for complete soil profile information). At each site the experiment was established as a randomised complete block design with four blocks. Within each block were eight plots: four conventional tillage and four SFZM ($4 \times 8 = 32$ plots per site). For each tillage system two plots were planted with maize (*Zea mays* L.) and two with soybean (*Glycine max* (L.) Merr.); crops were rotated annually. Of the two plots planted to the same crop, one was planted with a winter rye (*Secale cereale* L.) cover crop following maize/soybean harvest; the other was left fallow over winter.

Plots at all four sites were established in 2011 and planted with maize. Prior to 2011, IL, MI and MN were managed under maize-soybean rotations using conventional tillage; PA was under sorghum (*Sorghum bicolor* L. Moench). The two tillage treatments and crop rotations were established in 2012. Chisel plough was chosen as a model conventional tillage system; ridge tillage as a model SFZM system. A detailed description of ridge tillage is provided by Hatfield et al. (1998).

In the ridge tillage system, permanent ridges were formed with maize/soybean planted into the centre of ridge tops; rows were re-ridged – approximately 2–5 cm of furrow surface soil and plant residues scraped onto the row – shortly after the maize six leaf stage (V6). Management varied at each site following local best management practices (see Table S1 for detailed management information). All plots were treated with glyphosate three weeks prior to maize/soybean planting.

2.2. Soil sampling and analyses

Soil samples were taken from maize plots during the 2012 and 2013 growing seasons (eight site-years). Within each growing season, two sets of soil samples were collected. The first set, taken 10 days after maize planting, was used to estimate soil building processes: bulk density, water-stable macro- and micro-aggregates, and permanganate oxidisable C (POXC). Bulk density was measured to investigate whether conversion to ridge tillage was associated with increases in soil compaction, which has been highlighted as a concern amongst farmers converting from conventional to reduced or no-tillage systems (Logsdon and Karlen, 2004). The second set was collected shortly after maize V6 (seven days after re-ridging), coinciding with the onset of maize peak N demand (Karlen et al., 1987). This was used to track nutrient provisioning processes: extracellular enzyme activity, potentially mineralisable N (PMN) and C (PMC), and plant-available N. Samples for soil building processes were collected prior to the re-ridging event in the ridge tillage system to avoid residue and soil redistribution confounding POXC measurements. In each plot, within each position (crop row and inter-row) thirty 2.5 cm diameter soil cores were taken from 0 to 20 cm depth and bulked to form a composite sample; inter-row composite samples included cores from both tracked and untracked inter-rows.

Soil aggregates were isolated using 100 g of air-dried soil sieved to 8 mm while still field-moist (Grandy and Robertson, 2006). Macro-aggregates (>250 μm) were separated from micro-aggregates (<250 μm) by wet-sieving (Elliot, 1986). POXC within macro- and micro-aggregates was determined following Weil et al. (2003), with modifications as described by Culman et al. (2012). Bulk density was calculated following Robertson et al. (1999).

Inorganic N available for plant uptake was expressed as the sum of 2 M KCl extractable ammonium (NH_4^+) and nitrate (NO_3^-) (Keeney and Nelson, 1982). PMN was calculated as the difference in available N before and after incubation of soil samples at 37 °C for 10 days (Drinkwater et al., 1996). PMC was calculated as basal respiration (CO_2 flux rate) after incubation for 24 h at 22 °C (Borken et al., 2002).

Extracellular enzyme activity rates were determined for 1,4-β-cellobiohydrolase (CBHase, EC 3.2.1.91), β-*N*-acetylglucosaminidase (NAGase, EC 2.4.1.255) and acid phosphatase (Pase, EC 3.1.3.2). Activity rates were determined following Peoples and Koide (2012). In summary, 100 g of frozen (−20 °C) soil was homogenised in water. Enzyme substrates were added to homogenates and incubated. The methylumbelliferone (MUB)-linked substrates used were 4-methylumbelliferyl-β-ᴅ-cellobioside (MUB-CB, M6018, Sigma), 4-methylumbelliferyl *N*-acetyl-β-ᴅ-glucosaminide (MUB-NAG, M2133, Sigma), and 4-methylumbelliferyl phosphate (MUB-P, 69607, Fluka), respectively. Enzyme activities were expressed as nmol MUB produced $min^{-1} g^{-1}$ soil dry weight.

2.3. Maize yields

Maize was harvested at full physiological grain maturity, designated by the development of a black abscission layer at the base of kernels. Within two 3 m long rows in each plot, all maize ears were hand harvested. Kernels were mechanically separated from cobs, and fresh grain mass determined. Grain was then dried to constant mass in a forced air oven, and dry mass determined. Maize yields were expressed in $kg\,ha^{-1}$ at 15.5% moisture content.

2.4. Statistical analyses

For each soil variable, linear mixed effects models were fitted to investigate the main and interactive effects of tillage (chisel plough vs ridge tillage), cover cropping (rye vs none) and sample position (crop row vs inter-row); models were simplified for parsimony. To account for differences between site-years, a random effects structure was fitted with block nested within site nested within year (year/site/block). Effects of tillage and cover cropping on maize yields were assessed using a linear mixed effects model with a year/site/block random effects structure. We also conducted a *post hoc* power analysis of maize yields, to account for possible Type II errors.

To test our second hypothesis, of a positive effect of soil building processes on nutrient provisioning processes in the crop row at the onset of maize peak N demand, we fitted multigroup structural equation models (SEM) (Smith et al., 2014), using data from row positions. Multigroup SEM aims to fit a single, global model across data from all sites, and identifies how relationships between variables differ between sites (Grace, 2006). The conceptual model underpinning our SEM is shown in Fig. 1. Within this model, macro-aggregate abundance and POXC were fitted as exogenous manifest variables representing soil microbial habitat; microbial decomposition activity was fitted as a latent endogenous variable comprised of enzyme activities (CBHase, NAGase and Pase); nutrient mineralisation rates were represented by PMC and PMN; and available N was fitted as the final endogenous variable (Fig. 1). To gain further understanding of site-specific differences revealed by SEM, we examined the relationship between baseline SOM and 2013 macro-aggregate POXC, and how this was affected by tillage, using a linear mixed effects model with a site/block/position random effects structure.

All statistical analyses were carried out in R 3.2.2 (R Core Team, 2015). Linear mixed effects models were fitted in *nlme* (Pinheiro et al., 2015); power analysis in *nlmeU* (Galecki and Burzykowski, 2013); SEMs in *lavaan* (Rosseel, 2012); *ggplot2* was used for plotting (Wickham, 2009).
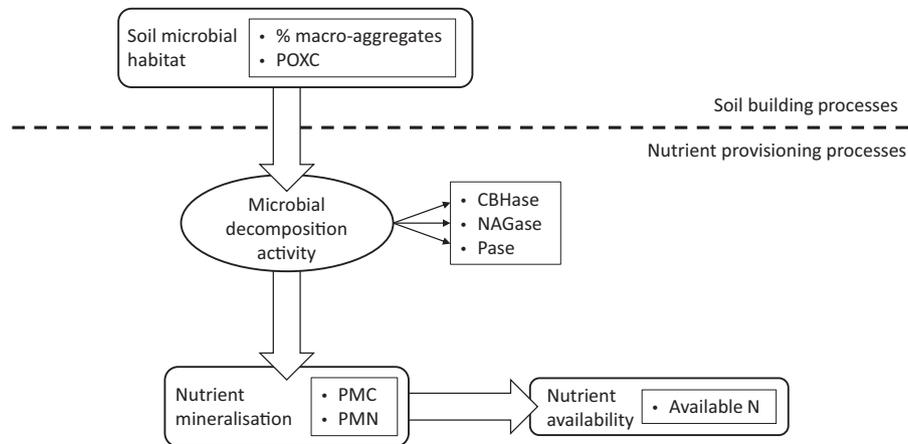
Fig. 1. Conceptual model representing the effect of soil building processes on nutrient provisioning processes within crop rows. Improvements in soil structure and carbon resources provide conditions for increased microbial decomposition activity. Greater microbial decomposition activity elevates nutrient mineralisation rates, increasing plant-available N. White arrows show direction of influence. Square boxes indicate manifest variables; circular box indicates latent variable. POXC: permanganate oxidisable C; CBHase, NAGase and Pase: enzyme activities of 1,4-β-cellubiohydrolase, β-*N*-acetylglucosaminidase and acid phosphatase, respectively; PMC and PMN: potentially mineralisable C and N, respectively.

3. Results

3.1. Soil building and nutrient provisioning processes

Overall, macro-aggregate POXC was greater under ridge tillage ($F_{1,221} = 6.77$, $P = 0.010$; Fig. 2) and with rye cover cropping ($F_{1,221} = 5.10$, $P = 0.025$, Fig. S1) compared with chisel plough and no cover cropping. Above-ground rye biomass (dry weight) averaged 687, 242, 1903 and 471 kg ha^{-1} at IL, MI, MN and PA, respectively. In addition, macro- and micro-aggregate POXC were greater in crop rows compared with inter-rows, irrespective of tillage (macro-aggregate: $F_{1,221} = 6.44$, $P = 0.012$, Fig. 2; micro-aggregate: $F_{1,219} = 5.94$, $P = 0.016$, Fig. S2). The relative abundances of macro- and micro-aggregates did not differ between any of the treatments. Bulk density was unaffected by tillage and cover cropping, but was greater in inter-rows compared with rows in both tillage systems ($F_{1,231} = 12.08$, $P < 0.001$, Fig. S3).

Activity rates for all three enzymes were greater with cover cropping (CBHase: $F_{1,205} = 9.24$, $P = 0.003$; NAGase: $F_{1,206} = 12.73$, $P < 0.001$; Pase: $F_{1,206} = 20.51$, $P < 0.001$). Enzyme activity also showed a strong tillage × position effect (CBHase: $F_{1,205} = 20.29$, $P < 0.001$; NAGase: $F_{1,206} = 20.64$, $P < 0.001$; Pase: $F_{1,206} = 28.70$, $P < 0.001$), being greater in ridge tillage rows compared with ridge tillage inter-rows (Figs. 3, S4, S5).

PMC was greater with cover cropping in both tillage systems ($F_{1,248} = 20.77$, $P < 0.001$), but was highest overall under ridge tillage ($F_{1,248} = 421.44$, $P < 0.001$). PMC also showed a strong tillage × position effect, with ridge tillage rows having greatest PMC ($F_{1,248} = 54.80$, $P < 0.001$, Fig. 4). PMN was greater in ridge tillage rows compared with ridge tillage inter-rows, and conversely greater in chisel plough inter-rows compared with chisel plough rows. However, this trend was not statistically significant.

Plant-available N showed a strong tillage × position effect, with concentrations in chisel plough inter-rows approximately double that in chisel plough rows; conversely, plant-available N in ridge tillage rows was greater than in ridge tillage inter-rows ($F_{1,207} = 585.91$, $P < 0.001$, Fig. S6). Cover cropping had no effect on available N.

3.2. Effect of soil building on nutrient provisioning

Multigroup SEM revealed a strong positive effect of soil building processes on crop row nutrient provisioning processes at two of the four sites (Fig. 5). Specifically, at MI and PA, macro-aggregate POXC had a positive effect on microbial decomposition activity, which in turn increased plant-available N. Macro-aggregate abundance had no effect on microbial decomposition activity at any site. Nutrient mineralisation rates (PMC and PMN) were fitted
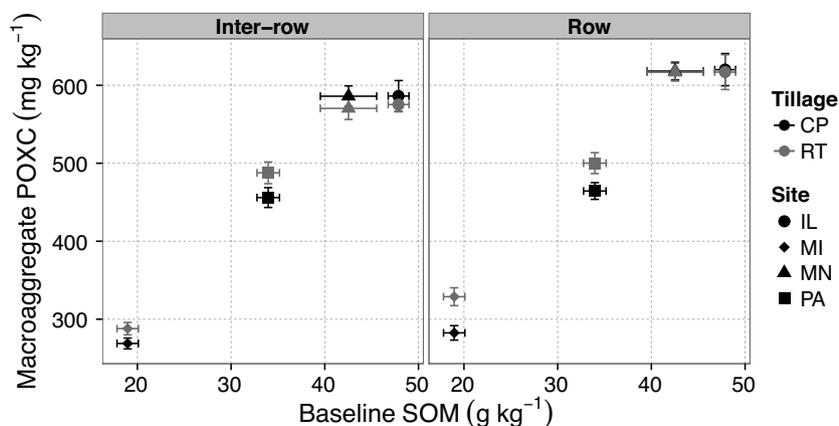

Fig. 2. Macro-aggregate permanganate oxidisable carbon (POXC) in 2013 against baseline (2011) soil organic matter (SOM). Error bars show ± 1 SE. CP: chisel plough; RT: ridge tillage.
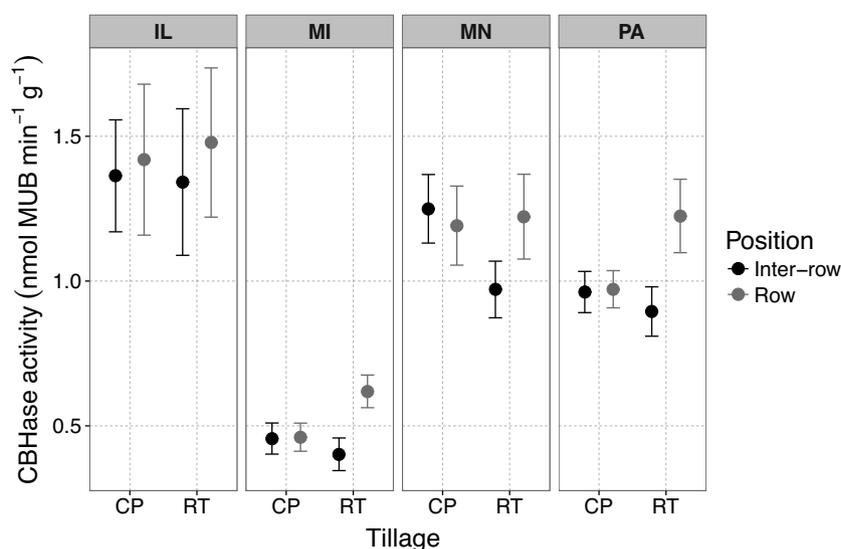
Fig. 3. 1,4-β-cellobiohydrolase (CBHase) enzyme activity by tillage and sample position at each site. CP = chisel plough; RT = ridge tillage. Data are means averaged across 2012 and 2013 ± 1 SE.
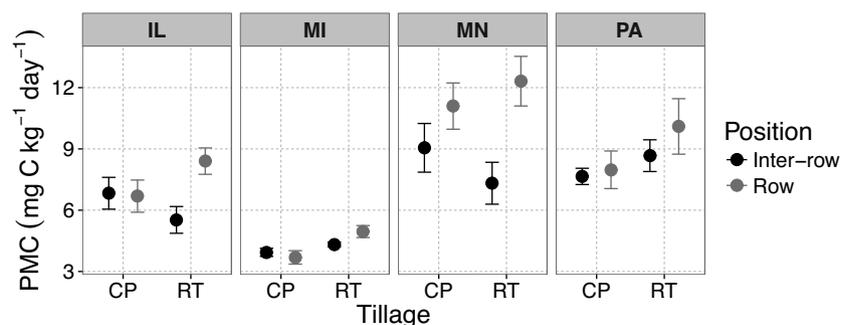

Fig. 4. Potentially mineralisable carbon (PMC) by tillage and sample position at each site. CP = chisel plough; RT = ridge tillage. Data are means averaged across 2012 and 2013 ± 1 SE.

in the initial model (Fig. 1), but were poorly explained by microbial decomposition activity and themselves provided little explanatory power for available N; they were removed from the model for parsimony. We found no evidence that changes in soil building processes were linked to changes in nutrient provisioning processes at IL or MN (Fig. 5).

Given the site-specific association of POXC with microbial decomposition activity, we examined the relationship between baseline SOM and POXC, and how this was affected by tillage. Baseline levels of SOM were substantially greater at both IL and MN compared with MI and PA ($F_{3,9}$ = 62.92, P < 0.001; Fig. 2). Differences in macro-aggregate POXC as a result of tillage were only apparent at MI and PA, where both showed increases with ridge tillage ($t_{1,634}$ = 4.02, P < 0.001; Fig. 2).

3.3. Maize yields

Across site-years, maize grain yields ranged between 3500 and 13000 kg ha^{-1}, and were greatest in IL and lowest in MI ($F_{3,21}$ = 3.72, P = 0.027). No difference in yields was detected between tillage or cover crop treatments ($F_{1,93}$ = 2.50, α = 0.05, power = 0.35; Fig. 6). For our level of replication, a power of 0.80 (a power 'rule of thumb') would have required a yield difference of approximately 700 kg ha^{-1}. In reality, such a difference seems improbable based on previous comparisons of maize yields in these tillage systems: thirty-year maize yield data from the US state of Iowa (also in the

US Corn Belt, and neighbouring IL and MN) showed average yields under chisel plough were approximately 200 kg ha^{-1} greater than under ridge tillage (Karlen et al., 2013). Our data is near this range (mean difference = 281 kg ha^{-1}); thus, the insignificant yield difference observed in our experiment between chisel plough and ridge tillage is representative of these systems under the prevailing climatic conditions.

4. Discussion

Our study provides strong evidence for our first hypothesis: that ridge tillage can facilitate joint enhancement of soil building processes within inter-rows and nutrient provisioning processes in crop rows by creating spatial heterogeneity. This suggests that ridge tillage has broad potential to improve agricultural sustainability, as demonstrated at these four study sites with contrasting climates and soil types. Furthermore, we found evidence supporting our second hypothesis: that improvement in soil building processes leading to increased microbial substrate availability has a positive effect on nutrient provisioning processes occurring in the crop row. This indicates greater utilisation of soil ecosystem services to maintain agricultural productivity under ridge tillage, which is a key component of ecological intensification (Bommarco et al., 2013).

Despite no observable impact of tillage on soil aggregation, the ridge tillage system accumulated more macro-aggregate POXC
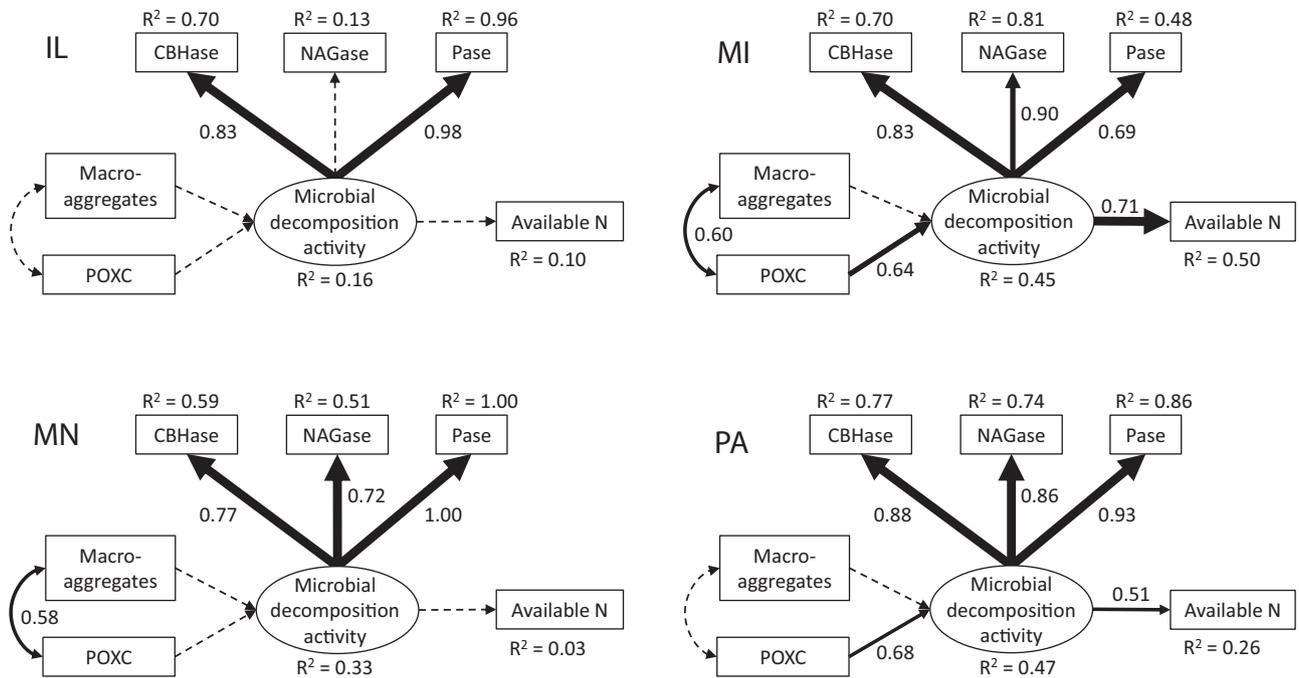
Fig. 5. Multigroup structural equation model showing relationships between soil building and nutrient provisioning processes at each site. Path coefficients are standardised regression coefficients. Arrow widths indicate strength of effect. Bold and dashed lines indicate significant and non-significant pathways, respectively. The model was well-supported by the data: $\chi^2 = 36.6$, df = 32, $p = 0.27$. POXC: permanganate oxidisable C; CBHase, NAGase and Pase: enzyme activities of 1,4-β-cellubiohydrolase, β-N-acetylglucosaminidase and acid phosphatase, respectively.
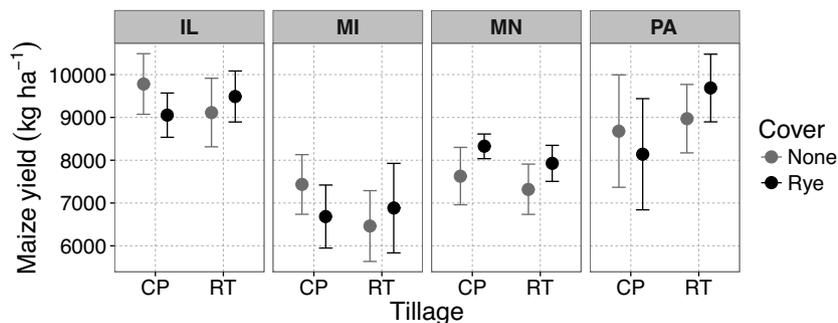

Fig. 6. Maize yields by site, tillage and cover cropping, averaged over 2012–2013. Error bars show ± 1 SE. CP: chisel plough; RT: ridge tillage.

than the chisel plough system, in both crop rows and inter-rows. Increased physical protection of SOM within macro-aggregates is a primary driver of SOC accumulation under reduced soil disturbance (Balesdent et al., 2000; Grandy and Robertson, 2007). However, we found macro-aggregate abundance to be equivalent across tillage systems. This corroborates previous findings showing equivalent levels of soil aggregation in conventional and reduced or no-tillage systems, but with greater SOC accumulation in macro-aggregates in reduced or no-tillage systems (Panettieri et al., 2015; Zibilske and Bradford, 2007). We found a strong tillage × position effect on PMC, indicating the presence of a substantial labile SOC pool and microbial activity in ridge tillage rows. Greater microbial activity and biomass have been observed in ridge tillage rows in previous studies (Müller et al., 2009; Zhang et al., 2013). Over time, the continuous and rapid turnover of microbial biomass can produce considerable quantities of necromass (Liang and Balser, 2011), which accounts for a large proportion of stabilised SOM (Grandy and Neff, 2008; Kallenbach et al., 2015; Schmidt et al., 2011). Thus, increased microbial activity, biomass and necromass may explain the increase in macro-aggregate POXC observed in crop rows under ridge tillage, despite no difference in aggregate

structure between tillage systems. If so, this would represent a positive effect of nutrient provisioning processes on soil building processes (Williams et al., 2016c); this requires further investigation. The reduction in soil disturbance in ridge tillage inter-rows may enable accrual of the readily oxidisable POXC fraction that would otherwise be lost under higher disturbance management regimes, i.e. conventional tillage.

Likewise, rye cover cropping increased macro-aggregate POXC and PMC compared with no cover cropping. Cover cropping increases plant residue, root and exudate production, as well as crop rotational diversity, all of which increase microbial biomass and activity (Kong and Six, 2012; McDaniel et al., 2014; Tiemann et al., 2015). Such increases in microbial activity and resultant necromass should contribute positively to SOC in the same way as described above. Thus, we predict that in the mid- to long-term, the combination of rye cover cropping with a SFZM approach will lead to substantial increases in SOC and soil aggregation compared with soils under conventional tillage with no cover crops.

The observed increase in macro-aggregate POXC under ridge tillage was confined to MI and PA, both of which had lower baseline SOM relative to IL and MN. Thus, we found that ridge

tillage can deliver rapid and significant gains in labile soil C pools; preferentially in SOM-poor soils. This finding is important not only because SOM plays a critical role in improving soil structure (Bronick and Lal, 2005), but also because our results show enhanced soil C can lead to improvements in soil fertility via enhanced microbial decomposition activity. Increasing the pool of labile SOC alleviates microbial C-limitation, enhancing microbial activity and biomass (Blagodatskaya et al., 2014; Ninh et al., 2015). Soil extracellular enzymes are critical for microbial breakdown of SOM, thus we would expect an increase in SOC to be accompanied by an increase in enzyme activity (Grandy et al., 2007). Our SEM results support this, as increases in crop row POXC at MI and PA resulted in increased enzyme activity rates. As such, ridge tillage may have direct and indirect effects on soil properties, but be specifically valuable for delivering rapid improvements in surface soil quality in SOM-depleted and degraded soils. Importantly, such complementarity suggests that soil building processes in ridge tillage have beneficial effects on crop production on a range of time scales. The effects noted above are consistent with the hypothesis that conversion to SFZM will have immediate benefits for nutrient provisioning, while also driving longer-term processes that support future crop production via improvements in soil quality.

Nutrient provisioning, with a focus here on soil inorganic nitrogen availability, varied spatially under ridge tillage relative to chisel plough. Extracellular enzyme activity, PMC and available N were all greatest in ridge tillage rows, concentrated around the maize root zone. Moreover, the timing of our soil samples revealed that this concentration of nutrient provisioning processes coincided with maize peak N demand, indicating greater temporal synchrony of soil microbial processes and nutrient availability with crop physiological needs. The redistribution in ridge tillage of composted crop residues from inter-rows to rows creates a favourable environment for microbial activity (Grigera et al., 2007), resulting in increased rates of N mineralisation and availability, and improved crop N uptake (Kane et al., 2015; Müller et al., 2009; Williams et al., 2016b). This suggests that ridge tillage has potential to improve agricultural N-use efficiency, reducing fertiliser requirements and N loss (Xu et al., 2012). The greater environmental exposure of ridge tillage rows (raised ridges) can lead to higher soil temperatures relative to ridge tillage inter-rows and chisel plough positions (Cox et al., 1990). It is possible this exposure may have stimulated the observed increase in nutrient provisioning processes. However, analysis of soil temperatures within the same experimental plots used in this study and over the same time period revealed no difference in row temperatures between chisel plough and ridge tillage at maize V6 (Williams et al., 2016a).

The increase in nutrient provisioning processes in ridge tillage rows compared with ridge tillage inter-rows contrasts with the chisel plough system, where nutrient provisioning processes were greatest in inter-rows and lowest in rows. This demonstrates a fundamental difference between conventional tillage systems and ridge tillage. In ridge tillage, soil building and nutrient provisioning processes are intentionally managed in both space and time to maximise resource-use efficiency: by first storing nutrients in labile SOM within inter-rows before redistributing this SOM to the crop row, where the majority of crop roots are located (Kaspar et al., 1991), in synchrony with crop developmental needs (Williams et al., 2016c). In tillage systems that do not attempt to create spatial heterogeneity (e.g. conventional and no-tillage systems), soil processes cannot be managed according to crop physiological demand, resulting in microbial processes occurring in the wrong place and time, encouraging inefficient resource-use. This is potentially the reason for the spatial distribution of available N under chisel plough: maize roots have been shown to

be concentrated in the crop row at 0–15 cm depth in both ridge tillage and chisel plough systems during the maize V6 stage (the same time we collected soil samples), with significantly lower root lengths in inter-rows (Kaspar et al., 1991). Root uptake of soil nutrients would lead to depletion of available N in the crop row in both tillage systems, leaving residual available N in inter-rows. This pattern was evident in the chisel plough system but absent from the ridge tillage system, where nutrient resources were transferred from the inter-row to the crop row.

Despite the benefits for surface soil quality associated with reduced and no-tillage systems (Hobbs et al., 2008), yields in such systems are often lower compared with conventional tillage (Giller et al., 2009; Pittelkow et al., 2015). This is in part due to surface residue in crop rows reducing seedling emergence by maintaining excessively cool and moist seedbed conditions (Dwyer et al., 2000; Mehdi et al., 1999). SFZM may avoid this drawback because residues are concentrated into inter-rows prior to planting, leaving an uncovered seedbed that can warm and dry rapidly in early spring (Williams et al., 2016a, 2016c). Studies in addition to ours have found little difference in maize yields between conventionally tilled systems and those managed under some form of SFZM (Griffith et al., 1973; Karlen et al., 2013; Licht and Al-Kaisi, 2005). This augurs well that SFZM will not impose a yield penalty in return for improvements in soil quality.

5. Conclusions

We present a range of evidence that SFZM may offer a path towards overcoming major trade-offs inherent in the predominant commercial tillage systems used today, which is vital for ecological intensification. By creating spatial heterogeneity, ridge tillage was shown to mediate simultaneous functioning of opposing soil processes: that of soil building and nutrient provisioning processes in row-crop agroecosystems. Ridge tillage was also shown to enhance each process relative to non-zonal management. The enhancement of soil quality via increases in SOC improves soil water holding capacity (Franzluebbers, 2002; Zibilske and Bradford, 2007). Such changes in soil functional attributes are likely to become more important as drought frequency and intensity increase with climate change in major crop producing regions (Trenberth et al., 2014). Furthermore, the spatial heterogeneity provided by SFZM aims to promote ecological processes provided by soil biodiversity (Williams et al., 2016c). Such "ecological engineering" should increase resource-use efficiency, reducing fertiliser requirements and nutrient losses, and thereby enhance agricultural sustainability (Bender et al., 2016). While our study was limited to maize-soybean systems, various implementations of SFZM are used for a wide range of crops, including cereal, vegetable and fruit production systems (Balota and Auler, 2011; Haramoto and Brainard, 2012; Müller et al., 2009). Further research is urgently needed to test the capacity of SFZM to provide these benefits across these different systems, and to develop novel methodologies that encourage greater adoption of SFZM systems.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.11.012.

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