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A comparison of soil hydrothermal properties in zonal and uniform tillage systems across the US Corn Belt

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ABSTRACT

Zonal tillage (e.g. ridge tillage, RT) separates management of row and inter-row positions, while non-zonal tillage (e.g. chisel plough, CP) applies management uniformly across a field. This may have large effects on soil hydrothermal properties, affecting soil processes and crop development. We examined the effects of RT versus CP on soil hydrothermal conditions under maize (*Zea mays* L.) at four sites spanning the US Corn Belt over two growing seasons (2012–2013). We also investigated whether RT, as a result of changes in hydrothermal conditions, could stimulate greater soil nitrogen (N) availability during peak maize N demand. We captured wide variation in soil types and climates, allowing us to generalise tillage effects across a large environmental gradient. Continuous hydrothermal measurements were taken in the centre of row and inter-row positions. Soil cores collected shortly after maize six leaf stage (V6) were analysed for plant-available N and potentially mineralisable N (PMN). We hypothesised: 1) in spring CP and RT both produce warm, dry seedbeds with equivalent accumulations of growing degree days (GDD), but later in season RT holds greater soil moisture, providing better conditions for cover or relay crop establishment; 2) Hydrothermal properties of RT rows are distinct from RT inter-rows, while CP rows and inter-rows are indistinguishable; 3) RT promotes greater soil N mineralisation and availability in crop rows compared with CP. Results largely confirmed all hypotheses. In early spring, rows were drier in RT than CP, and both were similar in warmth (i.e. in accumulated GDD). From V6 to tasselling, CP accumulated more GDD than RT in inter-rows, while row positions remained similar; RT maintained greater soil moisture across both positions. From tasselling to harvest, RT inter-rows held greater soil moisture than CP, but accumulated fewer GDD. Both tillage systems showed zonation of soil moisture between planting and harvest (inter-rows moister than rows); the magnitude of zonation was greatest in RT. Plant-available N and PMN were greater in RT compared with CP at V6, suggesting RT increases synchrony of soil N availability with crop requirements. The results demonstrate that zonal tillage can integrate the seedbed benefits of conventional tillage with increased soil moisture retention across a wide range of climates and soil types. Increased moisture retention may help buffer agricultural systems against drought, and improve seedbed conditions for cover and relay crops in late summer and early autumn, thus potentially improving both sustainability and production in these systems.

1. Introduction

A primary goal of tillage is to create optimal soil conditions for seed germination and seedling development, particularly in terms of soil moisture and temperature (hydrothermal properties). Tillage practices are typically uniform, with disturbance applied homogeneously across a field, e.g. mouldboard and chisel ploughing (conventional tillage) and no-tillage. Conventional tillage allows soil to warm and dry more rapidly in spring, compared to no-tillage, facilitating earlier crop planting (Griffith et al., 1973); but as concerns about soil degradation from excessive disturbance and lack of residue cover have increased

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(Grandy and Robertson, 2007), no-tillage has become more popular (Lal, 1997). However, no-tillage can inhibit soil warming and maintain excessively high soil moisture at planting time, particularly in fine-textured soils in cool, humid environments (Licht and Al-Kaisi, 2005; Shi et al., 2012). Zonal tillage, such as ridge and strip tillage, may offer a compromise between conventional tillage and no-tillage by integrating the benefits of both while avoiding their respective drawbacks (Pierce and Burpee, 1995; Pierce et al., 1992; Vyn et al., 1990; Williams et al., 2016).

The basic concept of zonal tillage is to separate soil management over small spatial scales, specifically over row and inter-row positions, to create contiguous and complementary soil functional zones. For example, ridge tillage (RT) creates a raised seedbed (ridge), which can dry and warm rapidly in spring (Cox et al., 1990; Hatfield et al., 1998). The ridge is truncated prior to seeding, with surface soil displaced to the inter-row (furrow); the furrow remains covered with crop residues. After crop establishment, ridges are reformed by scraping the displaced surface soil and crop residues from the furrow back onto the ridge (Hatfield et al., 1998; Lal, 1990). Strip tillage, while not creating a raised seedbed, operates under the same principle of spatial separation of row and inter-row operations (Vyn and Raimbault, 1992). As such, the ridge/row is managed to optimise seedbed hydrothermal properties for rapid seed germination and seedling development; the furrow/inter-row is managed to accumulate soil organic matter and maintain soil structure, thereby enhancing soil water holding capacity and reducing erosion potential (Drury et al., 2003; Hatfield et al., 1998; Pierce et al., 1992). These dual effects of RT may be particularly important for increasing the resilience of agricultural systems to climate change, where greater soil water holding capacity may help buffer crops against summer droughts (Pittelkow et al., 2015; Trenberth et al., 2014). Increased furrow/inter-row soil moisture during summer may also improve the success of inter-seeded cover or relay crops (Gesch and Johnson, 2015; Williams et al., 2016).

Previous studies have compared soil hydrothermal properties in zonal and uniform tillage systems, and have generally found that zonal systems are intermediate between conventional tillage and no-tillage (e.g. Drury et al., 2003, 2006; Licht and Al-Kaisi, 2005; Zibilske and Bradford, 2007). Kovar et al. (1992) also found that zonal tillage resulted in crop rows with soil temperatures similar to those under conventional tillage, while soil in zonal inter-rows was cooler than conventional inter-rows. In this report, we expand functional understanding of zonal tillage systems by examining the hydrothermal properties of RT between ridge and furrow zones, and across the growing season. Additionally, we extend knowledge by assessing functional effects that may be significant to development of summer annual crops, and of cover or relay crops. For example, previous studies have not determined whether differences in soil temperatures result in functionally significant differences in accumulation of growing degree days (GDD).

In addition, few studies have determined whether zonal management actually creates distinct zones, for example whether soil hydrothermal properties of RT ridges are distinct from RT furrows. Where studies have found that zonal tillage creates distinct zones [e.g. that inter-rows maintain higher soil moisture than crop rows (Fan et al., 2014; Müller et al., 2009; Shi et al., 2012)], most did not also demonstrate that differences were specific to zonal systems, i.e. that the same differences did not also exist under uniform tillage. Therefore, it is unclear whether zonal tillage results in uniquely differentiated hydrothermal zones, as is necessary if it is to provide integrated hydrothermal benefits; that is, a warm and dry seedbed combined with moisture retentive inter-rows. Moreover, the temporal dynamics of zonal differentiation are currently poorly characterised. Such characterisation is important, as zonal differentiation that creates a warm, dry seedbed combined with moisture retentive inter-rows may be favourable for early season growth (Waddell and Weil, 1996); whereas in mid-summer, a more even distribution of water across the root zone may be more beneficial.

Similarly, zonal tillage systems may affect soil hydrothermal properties of crop rows so as to enhance beneficial microbial activity (Hatfield et al., 1998). Enhancement of microbial activity can contribute to agricultural sustainability through improvements in nutrient-use efficiency (de Vries and Bardgett, 2012). Recent studies have found evidence for such effects, with rows in RT supporting greater microbial biomass and inorganic nitrogen (N) than rows in uniform systems (Kane et al., 2015; Müller et al., 2009). Increases in soil N were most noticeable in July, after the RT re-ridging event, and correlated positively with increased crop tissue N (Kane et al., 2015).

In this study we explicitly tested the hypotheses that zonal tillage: 1) Provides a functionally equivalent spring seedbed to conventional tillage, in terms of hydrothermal properties and GDD accumulation, but a more optimal summer seedbed for inter-seeded cover and relay crops by holding greater soil moisture; 2) Creates distinct hydrothermal soil zones (row vs inter-row) when compared with conventional tillage; and 3) Promotes greater soil N mineralisation and availability in crop rows compared with conventional tillage, coinciding with peak maize N demand. We measured continuous soil moisture and temperature in row and inter-row positions within two tillage systems: ridge tillage (RT) and chisel plough (CP), as model zonal and uniform systems, respectively. Tillage treatments were established in four states across the US Corn Belt – Illinois (IL), Michigan (MI), Minnesota (MN) and Pennsylvania (PA) – providing a large geographic range encompassing multiple soil types and climates. This allowed us to move beyond previous studies that have focussed on local comparisons of zonal and non-zonal tillage systems, and attempt to identify consistent effects on soil hydrothermal properties that are generalisable across a wide environmental gradient.

2. Materials and methods

2.1. Experimental sites and design

The study was conducted at four sites spanning the US Corn Belt: IL, MI, MN and PA. Baseline soil properties and climate data for each site are provided in Table 1 (see Table S1 in Supplementary Material for complete soil profile information). At each site the experiment was established as a randomised complete block design with four replicates (blocks). Within each block there were four plots: two CP and two RT. For both CP and RT plots, one plot was under maize (*Zea mays* L.) and one was under soybean (*Glycine max* (L.) Merr.); crops were rotated annually. This gave a total at each site of $4 \times 4 = 16$ plots. Soil moisture and temperature readings were taken only from plots planted with maize.

The plots at all four sites, for both tillage treatments, were established in 2011 and planted with maize. Prior to 2011, IL, MI and MN were managed under maize-soybean rotations using conventional, uniform tillage, while PA was under sorghum (*Sorghum bicolor* L. Moench). From 2012 onwards the tillage treatments were established and managed under the annual maize-soybean rotation described above, with all entry points included in each year. Thus, the RT plots are in an early stage of transition from conventional to reduced tillage. Permanent ridges were formed in RT, and in both rotations maize and soybean were planted at the centre of ridge tops. Crop residues were concentrated onto the soil surface of furrows during planting. RT ridges were re-ridged [furrow surface soil scraped back onto ridge (Hatfield et al., 1998)] shortly after the maize six leaf stage (V6). In CP, maize and soybean were planted into level, cultivated soil, i.e. no ridges, and crop residues were ripped and incorporated into the soil during cultivation. In both tillage systems, weeds were sprayed with glyphosate three weeks prior to planting. Row/ridge widths varied by site, being 30 cm at IL, 57 cm at MI, 25 cm at MN, and 30 cm at PA. Management varied at each site in accordance with local best management practices (Table 2). Soil moisture and temperature readings were taken throughout the 2012 and 2013 growing seasons.

Table 1
Baseline soil properties (0–10 cm depth) of the four experimental farms in 2011 and coordinates of their locations. Complete soil profile information is provided in Table S1 (Supplementary Material). Precipitation (cm) and temperature (°C) figures are the 30-year means for the growing season (April–October in IL; May–October for MI, MN and PA).

Location	Soil series	Soil texture	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	SOM (g kg^{-1})	Bulk density (g cm^{-3})	pH	Precip.	Temp.	Location
IL	Drummer	Silty clay loam	170	560	270	47.9	1.1	6.0	61.6	18.3	40° 3′, −88° 15′
MI	Marlette	Sandy loam	600	280	120	19.0	1.1	6.2	48.0	17.3	42° 24′, −85° 24′
MN	Waukegan	Silty clay loam	280	560	160	42.5	1.3	6.4	69.0	16.9	44° 44′, −93° 7′
PA	Hagerstown	Coarse silt loam	100	650	250	33.8	1.1	6.3	55.0	17.9	40° 47′, −77° 51′

2.2. Soil moisture and temperature

Soil moisture in the centre of ridge/row and furrow/inter-row positions was measured using volumetric soil moisture sensors (Decagon ECH2O™, S-SMC-M005, Onset Computer Corporation, Bourne, MA; two sensors per plot, one in ridge/row position, one in furrow/inter-row position) which were read every minute and integrated hourly using a miniature data logger (HOBO micro-station logger; #H21-002; Onset Computer Corporation, Bourne, MA). Hourly readings were aggregated to form daily means. Measurements were taken at 0–10 cm depth, in both row and inter-row positions in both tillage treatments. Continuous soil moisture measurements were supplemented with soil core sampling, which occurred at four sampling events annually at each site. At each sampling event, 30 cores per plot were taken from the centre of row/ridge and inter-row/furrow positions, down to 10 cm depth. The 30 cores in each position were bulked to give a representative sample. The first set of soil cores was taken prior to seed planting; the second prior to maize six leaf stage (V6); the third prior to tasselling (VT); the fourth post-harvest. Volumetric soil moisture was calculated for each bulked set of soil cores and compared against sensor readings at time of sampling. If the sensor readings fell outside the 95% confidence interval (CI) of the soil cores, the continuous measurements were rectified by the difference to the mean of the soil cores. When it was necessary to rectify the data, it was done for all sensor readings between soil core sampling dates. Soil moisture content was converted to water-filled pore space (WFPS) by dividing it by soil porosity. Soil porosity was calculated as 1 − (bulk density/2.65). The particle density of mineral soils was assumed to be 2.65 (Linn and Doran, 1984). Bulk density measurements were taken twice in each year: prior to seed planting and after harvest. Comparisons of WFPS were preferred to volumetric soil moisture due to the additional functional insight WFPS provides in relation to water or aeration limiting conditions that affect microbial activity, and because it normalises moisture data across the different soil textures at each site (Dobbie and Smith, 2001; Franzluebbers, 1999; Linn and Doran, 1984). However, statistical analyses were conducted on both volumetric soil moisture and WFPS; as the results were qualitatively similar, and to avoid repetition, only the results of WFPS are shown.

Soil temperatures were measured continuously between 0 and 10 cm depth in the centre of ridge/row and furrow/inter-row positions (Onset Pendant Logger; UA-001-64). Hourly readings were aggregated to form daily means. Daily growing degree days (GDD) were calculated by $T_{avg} - T_{base}$, where T_{avg} is the daily mean temperature and T_{base} is the temperature below which maize growth does not occur, which was taken as 10 °C (Cross and Zuber, 1972; McMaster and Wilhelm, 1997). Temperature and moisture sensors were removed during tillage operations, creating data gaps; additional data gaps were created due to unforeseen events, e.g. rodents chewing through sensor wires.

2.3. N availability

Given the importance of soil N availability from V6 to VT (period of maize peak N demand) (Mengel, 1995; Sawyer et al., 2006), the set of soil cores collected from RT ridges and CP rows after V6 was also analysed for available inorganic nitrogen ($NH_4^+ + NO_3^-$) and potentially mineralisable N (PMN). For PMN, soil samples were incubated at 25 °C for 21 days. Total NH_4^+ and NO_3^- (2 M KCl extraction) were measured before and after incubation (Keeney and Nelson, 1982).

Table 2
Information on equipment/machinery, timing of operations and plot sizes. Operations at each site followed local best management practices.
CP = chisel plough; RT = ridge tillage; UAN = urea ammonium nitrate.

Site	Tillage	Tractor	Tillage implements	Pre-plant soil prep.	Planter	Timing of tillage	Re-ridging soil depth displacement	Fertiliser N (kg ha^{-1}); form	Fertiliser placement (timing)	Plot size (m × m)
IL	CP	John Deere 9410	John Deere 2410 chisel plough, 20 ft width	Sunflower soil finisher	John Deere Max Emerge 4-row planter	Fall	NA	200; UAN	Broadcast (pre-planting)	100 × 20
	RT	John Deere 9410	Buffalo 6000 high residue cultivator	Besler root slicer	John Deere Max Emerge 4-row planter	Spring	~3 cm	200; UAN	Broadcast (pre-planting)	100 × 20
MI	CP	John Deere 7810	John Deere 714 chisel plough	Kongskilde Vibro Till 2900	John Deere Max Emerge 6-row planter	Spring	NA	170; UAN	Side-dress surface band (V6)	30 × 30
	RT	New Holland 8360	Buffalo 6000 high residue cultivator	Besler root slicer	John Deere Max Emerge 6-row planter	Spring	~3–5 cm	170; UAN	Side-dress surface band (V6)	30 × 30
MN	CP	John Deere 7230	John Deere 1610 chisel plough, 10 ft width	John Deere 960 field cultivator	John Deere 7100 6-row planter	Spring	NA	95; UAN	Side-dress surface band (V6)	60 × 10
	RT	John Deere 7230	Hiniker Econ-O-Till ridge cutter	Hiniker 6-row ridge cultivator	John Deere 7100 6-row planter	Spring	~5 cm	95; UAN	Side-dress surface band (V6)	60 × 10
PA	CP	John Deere 7700	John Deere 714 chisel plough	Taylor Pittsburgh disc harrow and Brillion Cultimulcher	John Deere 1780 6-row planter	Spring	NA	170; urea with Agrotain	Broadcast (pre-emergence)	30 × 10
	RT	John Deere 7330	John Deere 886 row crop cultivator	Taylor Pittsburgh disc harrow	John Deere 1780 6-row planter	Spring	~5 cm	170; urea with Agrotain	Broadcast (pre-emergence)	30 × 10

2.4. Statistical analysis

The growing season for each year was divided into four phases: pre-planting to planting, planting to V6, V6 to VT, and VT to harvest. The pre-planting to planting phase allowed investigation of whether either tillage system offered potential benefits in terms of earlier spring planting. For both years the pre-planting phase was taken to begin on the 70th day of the year (mid-March), as snow cover had typically melted and soil was consistently thawed by that date. The planting to V6 phase covers the critical period of seed germination and seedling establishment. The V6 to VT phase encompasses the period of maize peak N demand. The VT to harvest phase is vulnerable to late season drought, when soil moisture is important for ongoing kernel development and for inter-seeded cover or relay crop establishment.

For each of the phases, linear mixed effects models (LMEs) were fitted to investigate the effects of tillage (fixed effect) on soil WFPS, temperature and GDD. By using LMEs we were able to combine all site-years into a single model, maximising our statistical power while still allowing for differences between site-years (Zuur et al., 2009). This enabled us to move beyond previous studies that have focussed on local comparisons, and instead attempt to identify consistent tillage effects that can be generalised across a wide environmental gradient. For each model, a priori contrasts were established to separately analyse CP row versus RT ridge, and CP inter-row versus RT furrow. To account for potentially large differences in moisture and temperature from week to week, daily values were nested within week of year, and models were fitted with autocorrelation structures such that residuals in one week correlated with residuals of the preceding week. The random intercept structure nested week within site within year.

To assess whether distinct zonation occurred within the tillage systems, delta (Δ) values were analysed. Δ values were calculated as (row value − inter-row value), and as (ridge value − furrow value), for CP and RT, respectively. A positive Δ indicated that rows/ridges were significantly warmer or moister than inter-rows/furrows, while negative Δ indicated the opposite. Daily Δ values were calculated for soil moisture and temperature, and analysed using the same LME fixed and random effects structure described above. In addition, model-calculated 95% CIs were used to determine whether the Δ values for each phase differed significantly from zero. Zonation only occurred when 95% CIs did not overlap zero.

To investigate why the different positions might have dissimilar hydrothermal properties between tillage systems, additional LMEs were run regressing daily mean soil temperature and WFPS against daily mean air temperature and precipitation, with tillage fitted as a fixed effect. In these analyses, differences in tillage regression slopes identified how responsive the soil environments in the different tillage treatments were to daily weather events; e.g. a steeper regression slope for RT ridges compared with CP rows, for soil temperature against air temperature, indicated that soil temperatures in RT ridges responded more to changes in air temperature than CP rows. Similarly, differences in intercepts indicated greater or lower minimum bounds to low air temperatures or precipitation.

Lastly, available N and PMN from RT ridges and CP rows were analysed against tillage using LMEs with year and site fitted as random effects. A random variance structure was also fitted to account for differences in variation between sites and years (Zuur et al., 2009). All LMEs were fitted with restricted maximum likelihood estimations (REML), using the *nlme* package (Pinheiro et al., 2015) in R 3.1.1 (R Core Team, 2015). All figures were created using *ggplot2* (Wickham, 2009).

3. Results

3.1. Hypothesis 1: seedbed properties

Across our multi-state study, we found strong support for our hypothesis that zonal tillage provides a functionally equivalent spring seedbed as conventional tillage, and holds great soil moisture in the summer seedbed. Spring seedbed (i.e. RT ridge and CP row) temperatures were similar in RT and CP over the growing season, while summer seedbed (i.e. RT furrow and CP inter-row) temperatures differed. Seedbeds also differed in moisture over the growing season, with RT ridges being initially dryer, then becoming wetter during the middle stages of growth, and drying again at the end of the growing season. RT furrows were wetter than CP inter-rows over most of the growing season.

Soil temperatures differed between tillage treatments during the pre-planting to planting phase. Temperatures in RT were lower than CP by an average of 0.24 °C in ridges compared with rows ($t_{1,1416} = -6.25$, $p < 0.001$), and by 0.40 °C in furrows compared with inter-rows ($t_{1,1477} = -10.19$, $p < 0.001$; Fig. 1). The modest difference in CP row and RT ridge temperatures did not manifest in differences in GDD accumulation, with both tillage systems accruing an average of 269 GDD during this phase. The reason differences in ridge/row temperatures did not carry through into GDD is likely because temperature differences, in real terms, were so small and were lost in measurement noise as the daily values were summed to calculate GDD. CP inter-rows accumulated 269 GDD from pre-planting to planting, while RT furrows accumulated 250 GDD ($t_{1,45} = -11.00$, $p < 0.001$).

Through planting to V6, RT was again cooler than CP. Temperature differences were small between ridge and row positions (0.13 °C; $t_{1,1462} = -2.89$, $p = 0.004$), and larger between furrow and inter-row positions (0.49 °C; $t_{1,1378} = 7$–9.95, $p < 0.001$; Fig. 1). Differences in temperature between RT ridges and CP rows were too small to affect GDD, and both tillage systems accrued a mean of 464 GDD. RT furrows accumulated fewer GDD than CP inter-rows (463 in RT furrows vs 475 in CP inter-rows) ($t_{1,45} = -3.31$, $p = 0.002$).

From V6 to VT, when furrow and inter-row hydrothermal properties become important for inter-seeding cover and relay crops, RT furrows were cooler than CP inter-rows by 0.21 °C ($t_{1,1273} = -5.41$, $p < 0.001$) (Fig. 1). This manifested into fewer GDD in RT furrows (510 GDD) compared with CP inter-rows (519 GDD) ($t_{1,1077} = 7.36$, $p < 0.001$). CP rows and RT ridges both accumulated a mean of 519 GDD. During the VT to harvest phase, RT furrows accumulated 740 GDD compared with 753 GDD in CP inter-rows ($t_{1,43} = -13.15$, $p < 0.001$). GDD accumulation was similar in RT ridges and CP rows, with both averaging 733 GDD.

In terms of soil moisture, we found strong support for our hypothesis as RT ridges dried faster than CP rows in early spring, while RT furrows held greater soil moisture than CP inter-rows later in summer. During pre-planting to planting, RT ridges were significantly drier than CP rows, with mean WFPS in each tillage system being 43% and 53%, respectively ($t_{1,930} = 18.16$, $p < 0.001$; Fig. 2). This was despite RT furrows having 3% greater WFPS than CP inter-rows over the same period ($t_{1,930} = 4.37$, $p < 0.001$; Fig. 2). The differences in ridge/row soil moisture were substantial. When converted to volumetric soil moisture, 53% WFPS in CP rows exceeded soil field capacity in both IL and MI, and was at or near field capacity in PA and MN, respectively (data not shown). In contrast, 43% WFPS in RT ridges was below field capacity in IL, MN and PA, and was at field capacity in MI (data not shown).

Through the planting to V6 phase, mean WFPS did not differ between CP and RT in rows/ridges (overall mean = 37%) or inter-rows/furrows (overall mean = 43%; Fig. 2). From V6 to VT, RT maintained greater WFPS than CP in both ridges/rows (33% vs 28%; $t_{1,801} = 9.20$, $p < 0.001$) and furrows/inter-rows (42% vs 31%; $t_{1,687} = 16.98$, $p < 0.001$; Fig. 2). In the last phase of the season, VT to harvest, RT furrows held more soil moisture than CP inter-rows (45% vs 40%; $t_{1,802} = 9.82$, $p < 0.001$), while ridge/row positions were undifferentiated at 36% WFPS (Fig. 2).

3.2. Hypothesis 2: hydrothermal zonation across positions

RT showed no strong evidence for zonation (difference between ridge/row value and furrow/inter-row value) in soil temperatures

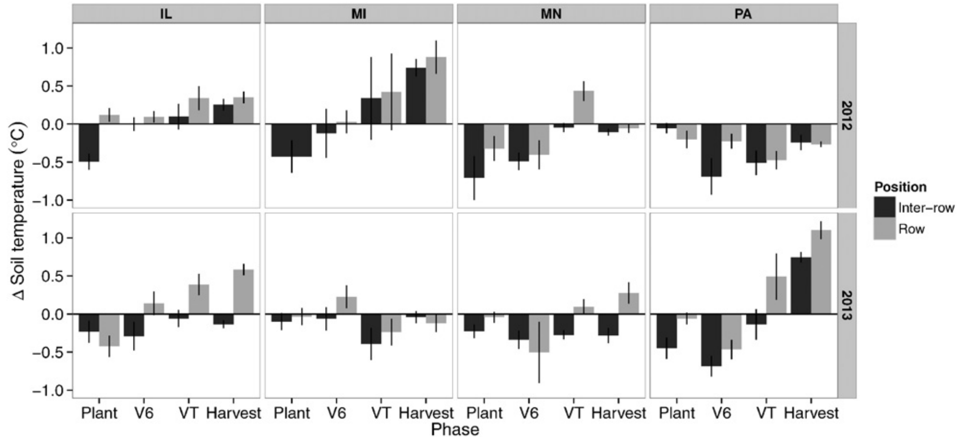

Fig. 1. Mean Δ soil temperature for each phase of the growing season by site, year and position. The end of each phase is marked on the *x*-axis, thus values for "Plant" show mean Δ for the pre-planting to planting phase; values for "V6" show mean Δ for the planting to maize six leaf phase, etc. Δ = ridge tillage soil temperature − chisel plough soil temperature. Bars show 95% CI.

throughout the growing season, despite a trend of warmer temperatures in RT ridges compared with furrows from pre-planting to planting (Table 3). CP showed zonation from planting through to VT, with CP inter-rows warmer than CP rows ($t_{1,1261} = 2.79$, $p = 0.005$; Table 3).

For WFPS, neither tillage system showed strong evidence for zonation during pre-planting to planting (Table 4), although RT showed a trend of greater WFPS in furrows compared with ridges. From planting to V6, both tillage treatments showed zonation, with furrow/inter-row positions being wetter than ridge/row positions (CP: $t_{1,362} = -2.85$, $p = 0.005$; RT: $t_{1,362} = -6.45$, $p < 0.001$); this pattern was repeated in CP from V6 to VT ($t_{1,346} = -3.10$, $p = 0.002$) (Table 4). From VT to harvest, both tillage systems again showed zonation, with furrows/inter-rows holding greater soil moisture than ridges/rows (CP: $t_{1,640} = -2.71$, $p = 0.007$; RT: $t_{1,640} = -16.41$, $p < 0.001$); the magnitude of the difference was more than two times greater in RT (Table 4).

3.3. Relationship between weather and soil properties

Soil temperatures in both tillage systems were strongly correlated with air temperatures (Table 5). However, the regression slope of the relationship differed significantly by tillage and position. RT ridge had the steepest slope, meaning its temperatures were most sensitive to changes in air temperature (higher thermal diffusivity). CP row and RT furrow had the shallowest regression slopes, showing increased buffering to changes in air temperature (smaller thermal diffusivities).

Soil WFPS in both tillage systems was positively correlated with precipitation (Table 6). The slope of the relationship did not differ between CP row, CP inter-row or RT ridge positions. However, the slope of RT furrow was less than for both CP positions, indicating reduced sensitivity of RT furrows to precipitation. The position intercepts of CP and RT differed significantly (Table 6), as RT consistently maintained higher levels of soil moisture than CP.

3.4. Hypothesis 3: N availability

Concentrations of plant-available N and PMN, measured between V6 and VT, were significantly greater in RT ridges compared with CP rows (available N: $F_{1,63} = 33.67$, $p < 0.001$, Fig. 3a; PMN: $F_{1,63} = 39.64$, $p < 0.001$, Fig. 3b). Across sites and years, RT ridges had on average 20 mg N kg^{-1} soil more than CP rows. Using bulk density (Table 1), this converts to approximately 24 kg N ha^{-1} in the upper 10 cm of soil. Maize is typically fertilised with 100 to 200 kg N ha^{-1}, thus 24 kg N ha^{-1} represents an appreciable portion of annual maize N requirements.

4. Discussion

In this multi-state field study, we found compelling evidence that distinct soil microenvironments developed under zonal management, compared with conventional, uniform management. These microclimates differed among zones in zonal management, with potential

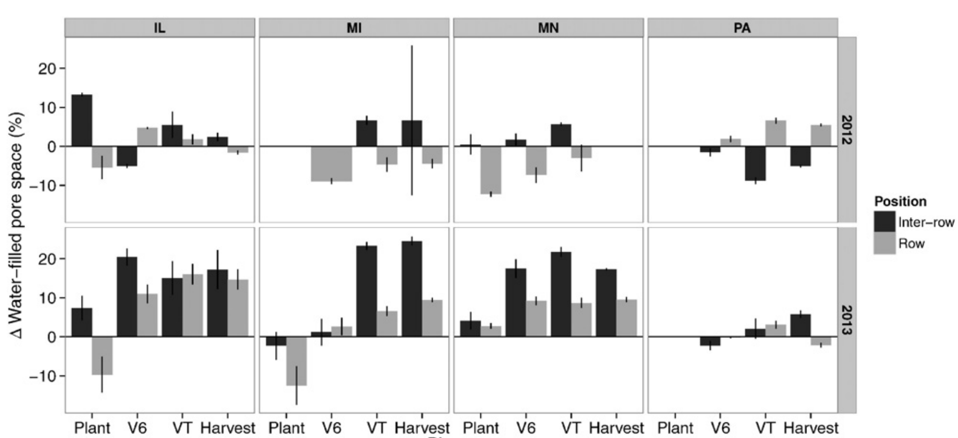

Fig. 2. Mean Δ water-filled pore space (WFPS) for each phase of the growing season by site, year and position. The end of each phase is marked on the *x*-axis, thus values for "Plant" show mean Δ for the pre-planting to planting phase; values for "V6" show mean Δ for the planting to maize six leaf phase, etc. Δ = ridge tillage WFPS − chisel plough WFPS. Bars show 95% CI.

Table 3
Mean Δ soil temperature (mean ± 95% CI) by tillage for each phase of the growing season, as estimated by linear mixed effects models. Δ values with 95% CIs that do not overlap zero (i.e. show significant zonation) are highlighted in bold. Δ = row position − inter-row position. CP = chisel plough; RT = ridge tillage.

Phase	Tillage	
	CP	RT
Pre-planting to planting	−0.04 ± 0.24	0.26 ± 0.33
Planting to maize six leaf stage (V6)	**−0.16 ± 0.11**	0.18 ± 0.19
V6 to tasselling (VT)	**−0.26 ± 0.23**	0.11 ± 0.32
VT to harvest	−0.13 ± 0.16	0.06 ± 0.21

implications for crop development and the integration of summer-annual crops with cover and relay crops.

Soil WFPS was greater within CP rows relative to RT ridges from pre-planting to planting, by an average of ten percentage points (53% in CP vs 43% in RT) across three of the four sites (no pre-planting data from PA due to repeated damage to sensors). This is consistent with increased drying of RT ridges early in the season. The difference in soil moisture is relevant to seedling growth. In CP rows, soils were either at or had exceeded field capacity. Such excessive soil moisture early in the season can create unsuitable conditions for seedling emergence and reduce yields (Drury et al., 2003; Dwyer et al., 2000; Eckert, 1990; Fausey, 1990; Kladivko et al., 1986). Soil moisture levels in no-tillage systems are typically even higher than in CP systems (Alvarez and Steinbach, 2009), which could exacerbate negative impacts on seedling health and crop establishment. In contrast, soils were moist but unsaturated in RT ridges, which is a very favourable condition for seedling recruitment. However, in climates experiencing greater aridity than our range of sampling, early season soil moisture loss from the crop row may represent a drawback rather than a benefit. RT furrows held greater soil moisture than CP inter-rows, indicating development of distinct functional zones for soil moisture.

Our data are consistent with the hypothesis that thermal properties of soils are altered as a function of tillage and position. From the weeks prior to planting up until V6, CP rows and RT ridges were functionally equivalent, accumulating similar amounts of GDD. This similarity provides evidence that zonal tillage can provide the same functional spring seedbed thermal properties as CP. Such properties affect crop growth directly (Cross and Zuber, 1972), as well as agronomically important soil processes affecting N availability (Griffin and Honeycutt, 2000; Honeycutt et al., 1991). This contrasts with no-tillage, which can produce sub-optimal seedbed temperatures more than 2 °C cooler than CP and RT around the time of planting (Beyaert et al., 2002; Johnson and Lowery, 1985).

It is worth noting that GDD accumulation during the pre-planting to planting phase in row/ridge positions of both tillage systems was the same (269 GDD). This quantity of GDD is sufficient for maize to develop to the two-leaf stage (V2) (Neild and Newman, 1987). This thermal resource could be utilised by planting maize earlier in the season. The reason that maize is not currently planted earlier may be due to excessive seedbed soil moisture in conventional and no-tillage systems (Fan et al., 2014; Shi et al., 2012). Indeed, within our multi-state experiment, earlier planting in RT would have been possible for this reason (pers. obs.), but we constrained planting dates to match CP to ensure comparability across tillage treatments. Therefore, as RT ridges have significantly reduced soil moisture during the pre-planting phase, RT may allow earlier planting to capture early-season GDD and consequently extend the growing season. This may contribute positively towards increases in both sustainability and production by enhancing opportunities for cover and/or double cropping (Brooker et al., 2015; Heaton et al., 2013; Williams et al., 2016).

Table 4
Mean Δ water-filled pore space (mean ± 95% CI) by tillage for each phase of the growing season, as estimated by linear mixed effects models. Δ values with 95% CIs that do not overlap zero (i.e. show significant zonation) are highlighted in bold. Δ = row position − inter-row position. CP = chisel plough; RT = ridge tillage.

Phase	Tillage	
	CP	RT
Pre-planting to planting	3.1 ± 13.0	−12.6 ± 15.7
Planting to maize six leaf stage (V6)	**−4.8 ± 3.3**	**−5.8 ± 3.9**
V6 to tasselling (VT)	**−5.7 ± 3.6**	−5.4 ± 5.4
VT to harvest	**−3.9 ± 2.8**	**−10.8 ± 3.6**

Table 5
Intercepts and slopes of relationship between daily mean soil temperatures and daily mean air temperatures for chisel plough (CP) and ridge tillage (RT) by position. Different superscript letters within rows indicate significant differences.

	CP row	CP inter-row	RT ridge	RT furrow	Test statistic	*p*-Value
Intercept	3.69^{a}	3.31^{ab}	2.81^{b}	3.61^{a}	$F_{3,27466} = 5.23$	0.001
Slope	0.89^{b}	0.91^{ab}	0.94^{a}	0.89^{b}	$F_{3,27466} = 6.67$	<0.001

That being said, the regression slope of RT ridge temperatures to air temperatures was steeper than for CP rows. This suggests that RT ridges have greater sensitivity to air temperatures compared with CP rows. This property has both positive and negative implications for crop development: while the increased exposure of the ridge allows it to warm rapidly with rising air temperatures, it also results in lower ridge temperatures if air temperatures drop. Conversely, CP rows showed greater temperature buffering. This may explain the lower temperatures observed in RT ridges prior to V6 compared with CP rows. Therefore, while zonal management may confer seedbed benefits during warm springs, it may impose costs during cold springs.

From V6 to VT, RT ridges maintained higher WFPS relative to CP rows, as well as warmer soil. This demonstrates how the zone function within zonal systems changes with crop development (RT ridges were cooler and drier than CP rows earlier in the season). Increased warmth and moisture from V6 onwards may help RT ridges provide a more amenable environment for microbial activity compared with CP rows. This could provide crop benefits in terms of increased organic matter turnover and nutrient release for plant uptake. Certainly, increases in WFPS such as that observed between CP rows and RT ridges (increase from 28% to 33%) from V6 to VT can result in a doubling of relative microbial activity, increasing ammonification and nitrification (Linn and Doran, 1984). The soil cores analysed between V6 and VT add support to this, as levels of plant-available N and PMN were significantly higher in RT ridges than in CP rows. Furthermore, recent studies have demonstrated that the RT re-ridging process, which occurs around maize V6, concentrates microbial biomass and PMN on the ridge, increasing soil inorganic N and maize N uptake (Kane et al., 2015; Müller et al., 2009). Thus, zonal management appears to create conditions that enhance microbial nutrient turnover processes (Grigera et al., 2007) in synchrony with peak maize N demand (Nielsen, 2000).

The RT system also showed significant zonation from VT to harvest, having greater WFPS in furrows compared with ridges. Over the same period, RT furrows consistently had greater WFPS than CP in inter-rows. These results indicate greater potential buffering capacity in RT compared with CP to summer drought, which can cause significant yield reductions (Ciais et al., 2005; Dickin and Wright, 2008). Zonal tillage has also been shown to increase water-use efficiency relative to conventional tillage and no-tillage (He et al., 2010; Sarkar et al., 2007).

Table 6
Intercepts and slopes of relationship between daily mean water-filled pore space (WFPS) and daily mean precipitation for chisel plough (CP) and ridge tillage (RT) by position. Different superscript letters within rows indicate significant differences.

	CP row	CP inter-row	RT ridge	RT furrow	Test statistic	*p*-Value
Intercept	28.4^{b}	28.5^{b}	32.4^{a}	33.6^{a}	$F_{3,7521} = 288.5$	<0.001
Slope	0.36^{a}	0.31^{a}	0.29^{ab}	0.25^{b}	$F_{3,7521} = 3.2$	0.02

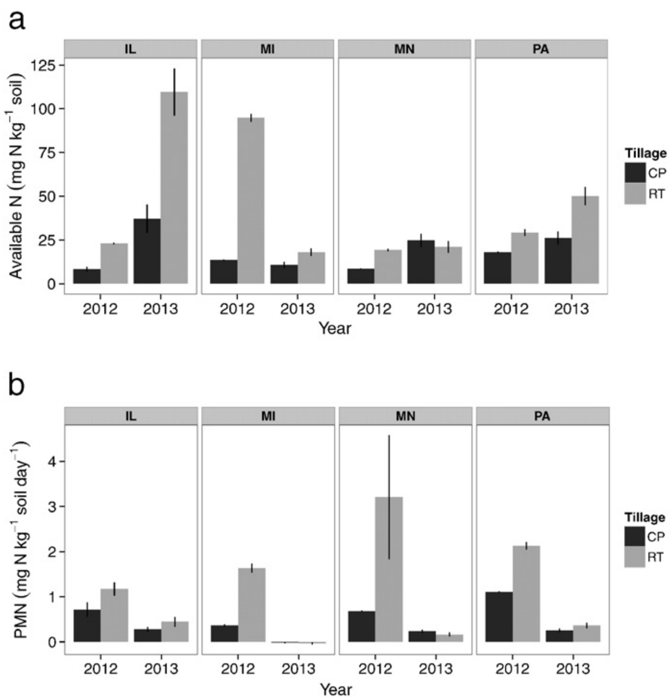

Fig. 3. Nitrogen (N) availability and turnover between maize six leaf stage (V6) and tasselling (VT) in row positions of each tillage system. (a) Plant-available N ($NH_4^+ + NO_3^-$). (b) Potentially mineralisable N (PMN).

The ability of RT to maintain greater soil moisture than CP, even during periods of reduced precipitation, may arise from lower rates of evaporation due to residue cover (Hatfield et al., 1998), alterations in soil surface geometry to increase infiltration (Larson, 1964), and/or from greater soil structural qualities that simultaneously enhance water infiltration rates and water holding capacity (Alvarez and Steinbach, 2009; Katsvairo et al., 2002; Zibilske and Bradford, 2007).

5. Conclusions

This study provides evidence that the temporal and decimetre-scale spatial zonation produced by zonal tillage can integrate the hydrothermal benefits of conventional tillage and no-tillage. These results are consistent across a wide range of soil types and climates. The ability of zonal systems to capture and store water more effectively than conventional tillage may impart zonal systems with capacity to buffer against precipitation shortfalls. Given that droughts are predicted to increase in intensity, last for longer periods and become more extensive (Cook et al., 2015; Trenberth et al., 2014), adopting management practices that build climate buffering capacity may be prudent. Furthermore, the alterations in soil hydrothermal properties may improve seedbed conditions at both the beginning and end of the traditional summer growing season. Improvements at both stages of the season may promote both earlier planting and harvest of summer-annual crops, and improve establishment of cover and relay crops. Thus, zonal systems may enhance opportunities for cover and relay cropping, and thus contribute positively towards increases in both sustainability and production (Williams et al., 2016). Lastly, by creating optimal environments to elicit desirable microbial functions at appropriate times and places (e.g. N mineralisation), zonal management may increase nutrient-use efficiency in field crops and reduce fertiliser requirements.

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