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

Alwyn Williams [a],*, Adam S. Davis [b], Patrick M. Ewing [a], A. Stuart Grandy [c], Daniel A. Kane [d], Roger T. Koide [e], David A. Mortensen [f], Richard G. Smith [c], Sieglinde S. Snapp [d], Kurt A. Spokas [g], Anthony C. Yannarell [h], Nicholas R. Jordan [a]

[a] Department of Agronomy and Plant Genetics, University of Minnesota, St. Paul, MN 55108, USA
[b] USDA-ARS, Global Change and Photosynthesis Research Unit, Urbana, IL 61801, USA
[c] Department of Natural Resources and the Environment, University of New Hampshire, Durham, NH 03824, USA
[d] Department of Plant, Soil and Microbial Sciences, Michigan State University, East Lansing, MI 48824, USA
[e] Department of Biology, Brigham Young University, Provo, UT 84602, USA
[f] Department of Plant Science, The Pennsylvania State University, State College, PA 16802, USA
[g] USDA-ARS, Soil and Water Management Unit, St. Paul, MN 55108, USA
[h] Department of Natural Resources and Environmental Sciences, University of Illinois, Urbana, IL 61801, USA

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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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* Corresponding author.
E-mail address: alwyn.williams@outlook.com (A. Williams).

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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.