SPATIAL AND TEMPORAL NITROGEN SYNCHRONY IN RIDGE TILLAGE SYSTEMS AS COMPARED TO CHISEL PLOW SYSTEMS

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ABSTRACT

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Ridge tillage (RT) is a Precision Zonal Management (PZM) system, most commonly used in corn-soybean rotations, that creates raised beds for planting through the repeated relocation of soil and residues from between rows. Several studies have found that with long-term management, the ridge and furrow spaces develop distinct biological and physical profiles. The creation of these zones has important implications for nitrogen (N) availability in RT systems.

To examine how RT might alter patterns of N distribution and mineralization, we conducted experiments in a tillage study fully replicated at two sites in Urbana, Illinois (IL) and Mason, Michigan (MI). Over the 2012 growing season, fine resolution soil monitoring was done in zero-fertilizer sub-plots for inorganic N, potentially mineralizable N, particulate organic matter, ion exchange N, and plant N status. Consistent with previous research, we found that RT increased labile N pools, as well as in situ measurements of N mineralization by ion exchange resins in the ridge positions relative to the furrow. As well, mean cumulative NO_3 adsorption summed across all positions, depths, and sampling points was greater in RT treatments than in CP treatments. Higher per plant yields and total plant and grain N concentrations also indicated that the effect of RT on soil N pools may have increased N uptake in RT plants relative to CP plants. Results were consistent with RT having the potential to create distinct soil functional zones with the potential to improve spatial N synchrony.

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LIST OF ABBREVIATIONS

PZM: Precision Zonal Management

RT: Ridge tillage

CP: Chisel plow

CP-fallow: Chisel plow with winter fallow

CP-rye: Chisel plow with winter rye cover crop

RT-fallow: Ridge tillage with winter fallow

RT-rye: Ridge tillage with winter rye cover

C: Carbon

N: Nitrogen

NO_3: Nitrate

NH_4: Ammonium

POM: Particulate Organic Matter

POM-N: Particulate Organic Matter Nitrogen

POM-C: Particulate Organic Matter Carbon

GWC: Gravimetric Water Content

VWC: Volumetric water content

INTRODUCTION:

Ecosystem services in agriculture:

Agroecosystems are primarily managed for provisioning ecosystem services – the production of food, fiber, and fuel for human and animal consumption. While major gains in global agricultural productivity have generally been a boon, the pursuit of ever-increasing production goals has resulted in a number of simultaneous, unintended ecosystem disservices. Synthetic fertilizers have vastly increased the productive capacity of agriculture in the past century by providing farmers with a cheap and abundant source of soluble nitrogen (N) for crop growth, replacing nitrogen-fixing legumes and existing soil N pools as primary sources of fertility (Robertson and Vitousek 2009). But despite its benefits to productivity, the use of N fertilizer in current practice comes at a variety of well-documented external costs. Nitrate leaching to groundwater can lead to eutrophication in inland fresh water and hypoxia in coastal marine waters, severely compromising the integrity of aquatic ecosystems (Robertson and Vitousek 2009). Recent research has also determined that high N application rates often result in higher rates of denitrification that lead to greater emissions of N_2O, a potent greenhouse gas (Hoben et al. 2011). Though accurate estimates are difficult to make, it's possible only 47% of fertilizer N applied to agricultural fields makes its way into crop plants, while the rest is lost to the environment (Galloway and Cowling 2002).

Similarly, decades of extensive tillage and disadoption of practices such as summer fallow and crop rotation have led to major declines in soil carbon (C) stocks and a concomitant loss of soil quality. Globally, soils are an important terrestrial C sink. Lal (2004) estimates that the conversion of soils to agricultural production accounts for as much as 50 – 66% of the loss

of stored C from terrestrial ecosystems. The mechanism for soil C loss by tillage is well understood, as the mechanical action of tillage destroys soil aggregates that protect organic matter from microbes and decomposition (Six et al. 1998 and 2004). Janzen et al. (1998) and Grandy and Robertson (2006) both found that tillage of previously uncultivated soils can severely reduce soil C due to the destruction of aggregates. As inputs to soil C stocks are outpaced by tillage-induced losses to respiration, agricultural soils lose their capacity to act as sinks (Schlesinger and Andrews 2000). This loss of soils as a C sink has important implications for global climate change (Lal 2004), but from an agronomic perspective the loss of soil C should also be alarming to farmers. Soil C plays a crucial role in creating and maintaining adequate soil structure, acting as a substrate for soil microbia that produce compounds that cement aggregates (Bronick and Lal 2004, Reeves 1997). Plus, it is a useful source of nutrients for crops, particularly N, that should be considered as an alternative or a complement to the use of synthetic fertilizers (Janzen 2006, Drinkwater and Snapp 2007).

A growing interest among scientists and producers in mitigating these disservices on-farm has led to a proliferation of technologies, management strategies, and research. Some of these strategies tend to place costs on growers through increased seed, labor, and equipment costs, but they often have the added incentive of enhancing other ecosystem services, particularly those related to increasing soil organic matter. One example of an on-farm strategy is the use of winter cereal cover crops, which has been widely demonstrated to reduce N leaching while increasing soil organic matter (Snapp et al. 2005). Similarly, a review of research on leguminous cover crops by Tonitto et al. (2006) found that their nitrogen fixation potential could displace a significant amount of the recommended fertilizer in some cases. Long-term use

of cover crops and increased rotational complexity have been demonstrated to both mitigate disservices from agriculture, stabilize and improve yields, and increase soil quality (Davis et al. 2012).

Similarly, years of research on conservation tillage systems have shown that reducing disturbance can increase soil C pools while also protecting beneficial soil microbes (Reeves 1997). By reducing disturbance, conservation tillage systems encourage the physical protection of organic matter in microaggregates (Balesdent et al. 2000, Six et al. 1998 and 2004). This protection enhances soil stability (Bronick and Lal 2004), reducing erosion and concomitant pollution (Phillips et al. 1980). Several studies of no-till and conservation tillage systems have also found that they are capable of increasing nutrient availability at surface depths (Varvel and Wilhelm 2011, Tebrugge and During 1999, Doran 1994, Yang and Wander 1999). Reductions in disturbance also protect soil microbial communities, particularly fungal communities by preventing the destruction of fungal hyphae (Helgason et al. 2009, Frey et al. 1999). Protecting microbial communities can improve the capacity of plants to obtain nutrients from soils as fungal colonization of roots increases (Jansa et al. 2003), fungi translocate nutrients to surface soils (Frey et al. 1999), and overall rates of N cycling can be enhanced (Muruganandam et al. 2010). A long-term study of conservation tillage systems at the Kellogg Biological Station also found that these systems can be economically viable, as yield averages and variability is comparable to more conventional tillage schemes (Smith et al. 2007).

With their focus on capturing or fixing N in organic forms through the use of cover crops and protecting existing soil organic matter pools by reducing disturbance, these strategies are often characterized by soil scientists and agroecologists as a re-coupling of C and N cycles.

Nitrogen associated with organic matter is generally less mobile and reactive than nitrate, giving these pools a longer mean residence time in soils and reducing the possibility of loss through leaching or denitrification (Drinkwater and Snapp 2007). At the same time, increased organic matter provides its numerous, well-documented benefits to soil structure and microbial communities. Approaches such as these have powerful potential and are essential in low-input systems such as organic operations, but they can also entail some risks that should be carefully considered.

Re-coupling strategies, risk and N synchrony:

Organic matter nitrogen must be converted into plant available forms via microbially-mediated processes before plant uptake is possible. These processes are strongly influenced by a number of soil conditions, including temperature and moisture (Zak et al. 1999, Miller and Johnson 1964), and the ratio of C to N in SOM at a given time (Robertson and Vitousek 2009). In systems with high residue inputs, microbes metabolizing the carbon in residues will uptake mineral N reducing its availability to crop plants – a process known as N immobilization. Incorporation of cover crops results in a particularly strong immobilization effect early in the season that can dissipate but does reduce N availability in the early season (McSwiney et al. 2010). Rice and Smith (1984) and Lupwayi et al. (2006) also found that no-till systems had increased rates of N immobilization in surface soils as residues accumulate there. Similarly, Smith et al. (2007) found in the study at Kellogg Biological Station that contrary to the findings of Davis et al. (2012), exclusive reliance on cover crops introduced yield variability across several years, despite other soil enhancements. Relying on organic nitrogen pools could entail opportunity costs for growers as crop demand for N and its mineralization from organic matter,

which is highly dependent upon conditions at the time, are not always well synchronized. If N deficits in the soil occur at a time when plant demand for N is high, plant growth can be affected, impacting yields. Synchronizing these processes of supply and demand are essential to ensuring the efficacy of conservation strategies.

Precision Zonal Management (PZM):

Arguably, some conservation strategies promote the enhancement of long-term regulating services to the detriment of services that support short-term production goals, such as timely nutrient turnover. In his 2006 review, Janzen argues that the recent interest in conservation tillage strategies has overshadowed the benefits of utilizing soil C resources through tillage, which generally enhances conditions for nutrient turnover by increasing aeration, soil temperature, and releasing physically protected SOM from aggregates. Although his argument is valid, a widespread return to more extensive, conventional tillage strategies without a simultaneous re-adoption of rotational complexity or fallow periods would only mean a return to previous patterns of soil degradation. But given recent advancements in agricultural technology, such as GPS guidance systems, it may be possible to achieve adequate regulating and provisioning ecosystem services in the same field using a strategy of Precision Zonal Management (PZM).

PZM is a management approach centered on strategic tillage and residue management. Conceptually, these systems strike an optimal balance between regulating and provisioning ecosystem services by creating zones with different soil biological and physical characteristics. Typically, there is a planting zone, managed to optimize nitrogen turnover and soil physical

conditions for crop growth, and an adjacent zone of protected soil, managed to increase soil organic matter pools and reduce water and nutrient losses (Overstreet and Hoyt 2008). The most prominent examples of PZM systems in current use are strip-till and ridge till. Although neither is a new technology, their ability to create zones in the row/inter-row space and the implications for both production and ecosystem services make them an interesting alternative to more popular conservation tillage strategies like no-till. In this study, we focused on ridge tillage in the corn-soybean system.

Ridge tillage:

Historically, ridge tillage (RT) has been used in the smallholder farmer context, with ridges being made by hand to concentrate soil and improve root growth (Lal 1990). At an agronomic scale, RT involves creating permanent raised beds for planting and is primarily used in corn-soybean rotations, although analogous systems with non-permanent ridges are used in the production of cotton and potatoes. Before planting, the ridge crest is either minimally disturbed to create a seedbed or left undisturbed. Ridges are then rebuilt every season using a ridge cultivator that moves soil from the furrow onto the ridge when plants are at a sufficient growth stage to withstand disturbance, typically around V6 in corn. In terms of production, RT is comparable to other conservation tillage schemes overall (Pikul et al. 2001) but may enhance production in systems with heavy, poorly-drained soils (Cox et al. 1990). In recent years RT has been disadopted in some locations as no-till has increased in popularity and efficacy, but it was a popular conservation tillage scheme in the 1980's and early 1990's and was the focus of a fair amount of research then.

Important field research on RT includes several long-term tillage studies that investigate RT effects on soil properties as compared to other conservation and conventional disturbance tillage practices such as chisel or moldboard plough. In three separate experiments on three different soil types RT was found to support gains in soil C and N relative to conventional tillage, though slightly less in magnitude than no-till practices (Zibiliske et al. 2002, Varvel and Wilhelm 2010, and Shi et al. 2012). These increases are likely due to increases in aggregation and microbial activity/biomass brought about by reduced disturbance (Zhang et al. 2012 and 2013). With higher levels of soil C, RT also provides some of the same soil physical and microbial benefits as no-till and other conservation tillage systems. Zibilske and Bradford (2007) found that RT increased water-holding capacity of soils, while Miller et al. (1995) found it increased fungal colonization of roots and Neave and Fox (1998) found it increased spring invertebrate populations relative to conventional tillage by moldboard plow.

A key difference that RT offers from no-till and other types of conservation tillage is in its alteration of the three-dimensional structure of soil by the repeated translocation of soil from the furrow space to the ridge. The creation of ridges is thought to have pronounced effects on soil physical characteristics and organic matter pools, leading to the creation of zones in RT systems. Although there is a limited amount of research on what characterizes these hypothesized zones, a handful of studies have demonstrated clear soil physical and biochemical differences between the ridge and furrow spaces in RT systems

Among the most touted benefits of RT are its unique effect on soil water distribution in the row/inter-row space and the creation of temperature gradients. Chen et al. (2011) demonstrated in a simulated laboratory experiment that water preferentially flows to furrows

but is then horizontally distributed by the negative water potential of the ridge. Similar results were seen in the field by Waddell and Weil (1996). This pattern leaves the ridge space dry and warm but not droughty, providing optimal conditions for planting (Stone et al. 1990). Combined with the increased water-holding capacity of protected soil in the furrow, RT is a moisture conservative system that can still avoid issues of waterlogging in poorly drained soils (Cox et al. 1990). This moisture gradient can also have a unique effect on roots, drawing their growth into soil beneath the furrow space (Kovar et al. 1992) where they can access soil moisture and nutrients.

The repeated movement of soil and residues from the furrow to the ridge could also have strong effects on the spatial distribution of soil C and N, creating gradients across the row/inter-row space. Despite multiple studies characterizing long-term changes in these pools overall in RT systems, there is limited research on whether or not the ridge and furrow develop unique soil biological profiles. The strongest evidence for zones with unique chemical profiles was found by Shi et al. (2012), who sampled soils from several positions across the row/inter-row space of a long-term ridge tillage field and found that soil C and N were higher in the ridge relative to the furrow. A number of more short-term studies have found functional differences between zones, including differences in CO2 respiration (Liebig et al. 1995, Müller et al. 2009a) and soil inorganic N concentrations (Müller et al. 2009b).

Given evidence for zonation of both soil physical and chemical properties, as well as results from several long-term studies demonstrating its carbon sequestration capacity, RT has potential as a PZM system that can balance both long-term regulating ecosystem services, such as carbon sequestration, and more short-term services, such as N mineralization, that support

production goals. Detailed studies of N turnover and availability to support crop growth have not been studied in RT, particulalrly at a fine scale of resolution. Interaction of tillage and cover crop presence is expected to influence N dynamics, as temporary immobilization from cover crop residues has been shown to have marked effects on inorganic N status in corn (McSwiney et al., 2010). Perhaps surprisingly, Eadie et al. (1992) demonstrated that rye cover had no effect on yield in RT systems, but we found no studies examining how within-season N dynamics might change in RT systems when a cover is introduced. Further research into characterizing ridge and furrow zones, as well as understanding how those zones may impact within-season nitrogen dynamics will be important to understanding RT potential alone or combined with winter cover to support high grain yield and efficient use of N.

Objectives:

We focused this study on within-season N dynamics of RT systems as compared to chisel plow (CP) systems. In addition, we investigated interaction of tillage systems with cover crop versus fallow management over the winter. More specifically, we sought to:

1.) Characterize how the process of re-ridging redistributes residues, organic matter, and associated nutrients in the row/inter-row space.

2.) Examine how RT might mitigate the effects of early season N immobilization, especially where a winter cover crop is used.

3.) Verify if possible effects on N pools, both spatial and temporal, affect patterns of N availability in situ, and examine how those patterns may be influenced by soil physical characteristics.

4.) Quantify plant N uptake in all experimental treatments.

CHAPTER ONE

Spatial patterns of labile nitrogen in ridge tillage systems with and without cover crop as compared to chisel plow

Abstract:

Ridge tillage (RT) has been shown to increase soil carbon (C) and (N) at surface depths over long periods of time by reducing disturbance in a manner similar to other conservation tillage systems (Zibiliske et al. 2002, Varvel and Wilhelm 2010). The repeated movement of residues and soil organic matter from the furrow to the ridge space also results in elevated levels of C in the ridge space relative to the furrow (Shi et al. 2012), creating soil functional zones across the row/inter-row space. The creation of these zones and the rebuilding of them every season may have important implications for spatial and temporal patterns in N pools, especially in systems that employ winter cover crops. Several studies have found that RT systems exhibit higher levels of microbial respiration and inorganic N levels in the ridge position at different points in the season (Clay et al. 1995, Müller et al. 2009a and 2009b, Liebig 1995).

To test how RT may alter the spatial distribution of N pools of different turnover times, we sampled a tillage study fully replicated at two sites in Urbana, Illinois (IL) and Mason, Michigan (MI) that included chisel plow (CP) and ridge tillage treatments both with and without rye winter cover crop and planted to corn (Zea mays) in the 2012 growing season. Sampling was conducted at fine spatial resolution to better characterize gradients across the row/inter-row space. Differences in spatial patterns of N pools were not seen during the early season (10 d after planting). But following re-ridging, potentially mineralizable nitrogen (PMN) and particulate organic matter carbon and nitrogen (POM-C and POM-N) were both increased in the

ridge position of RT treatments while values decreased in the furrow. Similar spatial redistribution of N was not seen for CP treatments. This result is consistent with previous studies and is strong evidence for RT's utility as a Precision Zonal Management system (PZM) that has the potential to improve spatial N synchrony in agricultural systems.

1.1. Introduction:

Ridge tillage (RT) is a Precision Zonal Management (PZM) scheme that is unique in how it manages residues, leaving them on the surface in the furrow during the spring, then concentrating and incorporating them in the ridge space at re-ridging. This spatially explicit method of management has been shown to create zones in soil C and N pools, with higher levels of C and N in the ridge space than in the furrow (Shi et al. 2012). The creation of these zones and their re-establishment every year has important implications for both spatial and temporal N synchrony and the distribution of N pools of varying turnover rates across the row/inter-row space. Concentrating residues to the in-row space after a period of decomposition in the furrow may make their associated nutrients more available to plants, especially since the re-ridging process has been shown to both increase microbial activity (Grigera et al. 2007) and nodal root growth (Thomas and Kaspar 1995 and 1997) in the ridge. Additionally, since the re-ridging process occurs when corn is at the V6 growth stage, just as it is beginning exponential growth, increases in N mineralization due to the re-ridging process could improve temporal N synchrony.

A handful of studies have investigated differences in functional signals of microbial turnover of residues. Liebig et al. (1993 and 1995) demonstrated differences in a variety of soil physical measurements between ridge and furrow spaces and that greater porosity in the ridge

space led to higher rates of CO_2 respiration. Similarly, Clay et al. (1995) and Müller et al. (2009a and 2009b) demonstrated that labile C and N and associated respiration tends to be higher in the ridge space at different points in the growing season. Finally, Zebarth and Milburn (2003) found that after hilling in a zero-fertilizer potato system, a system analogous to RT in corn-soybean, NO_3 was increased in the hill. These studies suggest that these zones do indeed exhibit functional differences and that the ridge zone is characterized by higher levels of microbial activity and SOM turnover.

Given this evidence, we sought to investigate the effects of zonation on N synchrony both temporally and spatially. In particular, we were interested in the possible interactions of RT with the use of winter cover crops. In some systems, rye cover has been shown to cause net N immobilization, especially in the early season, suppressing plant growth (Rosecrance et al. 2000, Burger and Jackson 2003, Hu et al. 1997). Although systems may eventually recover from this immobilization as residues are decomposed, resulting in net N mineralization (McSwiney et al. 2010), it poses a risk to which many growers are averse. Similar problems are possible with previous corn residue (Rice and Smith 1984), so a similar effect would be advantageous in cases where corn residue inputs are high. Given the way RT manages residues, it could have the potential to mitigate immobilization problems by relocating the site of immobilization away from plants into the furrow.

Using a spatially resolute sampling design we took soil cores from multiple positions across the row/inter-row space from field sites in IL and MI at points throughout the growing season that correlated with points of high N uptake in plants and important management

events. Soil samples were then analyzed for inorganic nitrogen (NO_3 and NH_4), potentially mineralizable nitrogen (PMN), and particulate organic matter carbon and nitrogen (POM-C and POM-N).

While conventional soil extractions for inorganic forms of N are informative, inorganic pools are highly ephemeral and soil samples can only provide a snapshot of soil N levels at the time of sampling. PMN and POM measurements provide a more integrated assessment of soil N, quantifying what may not be available at the time of sampling but could be available soon thereafter. Gregorich et al. (1994) suggest that PMN represents a labile pool of organic N that can readily supply N to crops and is a good indicator of short-term fertility. Similarly, POM is a collection of pools of organic matter at various levels of decomposition, typically distinguished or fractionated by size or density, that have been well-associated with labile pools of organic nitrogen (Hassink 1995, Wander and Bidart 2000). An analysis of POM fractions can provide insight into the capacity of a soil for organic matter turnover and associated N mineralization. An increase in both PMN and POM would suggest improvements in nutrient cycling/availability, and these measures may help shed light on C-N linkages in study systems.

We hypothesized that RT would improve temporal N synchrony by delaying turnover in the early season when plant demand is low and increasing it when corn enters the exponential growth phase and demand is highest. We also hypothesized that RT would improve spatial N synchrony by relocating labile forms of N from the furrow space to within rows through re-ridging, increasing inorganic N, PMN, and POM-N in the crop row. Finally, we hypothesized that the site of early-season N immobilization would be relocated to the furrow space from the ridge

in RT treatments, mitigating some of the early season N immobilization problems associated with the use of cover crops and high amounts of residues.

1.2. Objectives:

1.) Characterize differences in both inorganic and labile organic soil N pools across experimental treatments and different row/inter-row positions at important points throughout the growing season.

2.) Characterize differences in POM-C pools across experimental treatments and different row/inter-row positions for surface soils just after re-ridging.

1.3. Methods:

1.3.1 Site description:

The study was conducted at two sites participating in a long-term, multi-university tillage experiment, one in Mason, MI owned by Michigan State University and the other in Champaign, IL owned by the University of Illinois Champaign-Urbana. Hereafter the sites will be referred to using the abbreviations for either state: IL and MI. The IL site is dominated by Drummer silty clay/loam (mesic Typic Endoaquoll) with 3-3.5% OM and pH of 6.4, while the MI site is dominated by Marlette sandy loam soils (mesic Oxyaquic Glossudalf) with 1-2% OM and pH of 6.2. The thirty-year average growing season (May-October) precipitation at IL is 61.59 cm, while in MI it is 48.02 cm (Table 1.1). Summer daytime temperatures have historically ranged from 20 – 25 C at both sites with periodic highs near 30 C.

1.3.2. Experimental design:

Sites were established in 2011 and had previously been planted to field crops (corn, soybean, and wheat). The experimental setup is a corn-soybean rotation with sampling

conducted only in plots in the corn phase of the rotation. The experimental design is a randomized complete block design with four blocks and one split-plot factor. The whole plot factor is tillage and consists of two levels, chisel plow and ridge tillage. The sub-plot factor is cover crop and also consists of two levels, winter rye cover and winter fallow. Plots at MI are sized 30 x 30 ft with 30 x 10 ft zero fertilizer sub-plots, and plots at IL 20 x 100 ft with 20 x 40 ft zero fertilizer sub-plots. Zero fertilizer sub-plots were established to allow for monitoring of plant N uptake in the absence of fertilization. We chose to conduct a sub-study in these zero fertilizer subplots because they allow us to examine N turnover from organic matter exclusively.

1.3.3. Soil sampling:

We collected soil samples at a series of time points that coincided with important crop growth stages and field operations (Table 1.2). Soil sampling I was conducted at both sites as plants were emerging (~2 weeks after planting) to document early season conditions. Soil sampling II was conducted at both sites ~10 d after the re-ridging operation was conducted in the ridge till plots. Around the time of this operation, corn plants in both treatments had achieved growth stage V6 and were entering the exponential growth stage, when nitrogen demand is highest. Soil sampling III was conducted at just the Mason site when the corn was at the grain-filling stage R3.

To gain a better understanding of the spatial distribution of nitrogen and the spatial differences in turnover in each system, we chose a sampling approach with high degree of spatial resolution . Soil cores were taken at three different positions in the row-interrow space: in-row/ridge (ridge); 7.5 in from the row (shoulder); and 15 in from the row (furrow). Five cores were taken at each position to a depth of 20 cm and divided into three depth increments: 0-5,

5-10, and 10-20 cm. Depth increments were composited across the five cores, sieved to 6 mm while still field-moist, and stored at 4 C until analysis.

1.3.4. Inorganic nitrogen and potentially mineralizable nitrogen (PMN):

Soil moisture was determined gravimetrically (subsamples were weighed fresh, oven dried to no change in weight, and weighed to calculate percent moisture), and NH_4 and NO_3, were extracted from another subsample using a 1M KCl solution. For each subsample, 10 g +/- 0.1 g of fresh soil was weighed into a 50 mL centrifuge tube, mixed with 40 mL 1M KCl, and shaken at 240 rpm on an orbital shaker for 1 hour. After samples had settled, 15 mL of KCl extractant was then filtered from each sample into scintillation vials through Whatman #42 qualitative filter paper to remove soil. Extracts were then analyzed for both NH4 and NO3 concentrations by the procedure described in section 1.3.5.

At the same time, a duplicate set of 50 mL centrifuge tubes containing 10 g +/- 0.1 g soil from each sample was prepared for a potentially mineralizable nitrogen (PMN) assay as described in Waring and Bremmer (1964). These samples were mixed with 10 mL water and allowed to incubate for 7 days at 30 C. After incubation, samples were extracted by the same process as the samples described above but using 30 mL 1.33 M KCl to achieve the same molarity. Extracts were then analyzed for NH_4 only since the anaerobic condition created during the incubation inhibits nitrification, meaning nitrogen turnover from SOM effectively stops after mineralization

1.3.5. Plate method:

To measure the concentrations of NO_3 and NH_4 of extracts, we used the method described in Doane and Horwath (2003). This method employs colorimetric reagents, different reagents for either NO_3 or NH_4, that are combined with extracts on a 96-well microplate. Once the reaction was complete, plates were read on a Multi-Skan Ascent 96-well plate reader (MTX Lab Systems, Inc.) for absorbance values at 630 nm for NH_4 and 540 nm for NO_3. Standard curves were created on each plate using standards of known parts per million values. Slope and intercept terms of the standard curves were then used to convert absorbance values to concentrations.

Since extracts came from samples taken at several time points and positions, concentrations of both NO_3 and NH_4 varied greatly. To account for variability, the ratio of reagent to sample/standard can be adjusted to fit the range of concentrations of a given set of samples. Combining a high volume of sample with a low volume of reagent is useful for samples in the lower concentration range, while the opposite is useful for samples of higher N concentrations. To understand the upper and lower limits of sensitivity for a number of dilutions (ratio of sample to reagent), we ran several different dilutions with broad standard curves (i.e., 0.1 ppm – 70 ppm). The values between which these standard curves remained linear represented the range in which we considered the dilution to be accurate.

All samples were first analyzed in duplicate for NH4 and NO3 using a “mid-range” dilution that encompassed most likely values. After initial analysis, samples for which values were out of the range of the dilution or for which duplicate error was greater than 10% were

re-analyzed using a more appropriate dilution. Concentrations were then converted from ppm to mg kg soil^{-1}.

1.3.6. Particulate organic matter:

We used a size fractionation POM method modified from Cambardella and Elliot (1993) on soil samples from the 0-5 cm depth increment taken in Soil Sampling II. Unground soil samples were first dried in a forced-air oven at 30 C and 10 g +/- 0.1 g was weighed into a 50 mL centrifuge tube. Samples were mixed with 30 mL of a 5% aqueous solution of sodium-hexametaphosphate and shaken at 120 rpm on a reciprocal shaker for 4-6 hours to disperse all particulate matter in the samples. Shaken samples were poured onto a pair of stacked sieves with mesh sizes of 213 µm and 53 µm. Distilled water was used to gently wash samples through the sieves, capturing particulate matter ≥ 213 µm on the first sieve and particulate matter of 53-213 µm on the second. Particulates collected on the sieves were transferred to aluminum weighing dishes and dried in a forced-air oven at 55 C for 24 h, weighed, and pulverized in a ShatterBox® (SPEX® SamplePrep®) until homogenized. Particulate organic matter C and N determinations were made by dry combustion of the samples, using a Carlo-Erba NA 1500 CNS (Carlo-Erba, Milan, Italy).

1.3.7. Data analysis:

For analysis, data were treated as having one main plot factor, tillage, and three split plot factors, cover, position, and depth. Although position and depth cannot be considered as treatments, we chose to analyze them as fixed, split-plot factors since we were specifically interested in their possible effects on data. Site was either included as a random factor or data were separated by site and analyzed separately according to the following procedure.

For Soil Sampling 1 and Soil Sampling 2, data from both sites were initially combined for analysis by a mixed effects model ANOVA. Initial analysis was performed with tillage, cover, position, and depth as fixed factors, as well as site to determine if site had a significant effect ($\alpha = 0.05$) on results. If site had a significant effect, or a significant interaction with a treatment effect of interest, data from either site was separated and re-analyzed with tillage, cover, position, and depth as fixed factors. If site did not have a significant effect or interaction with a treatment effect of interest, it was changed to a random factor, while tillage, cover, position, and depth remained fixed. Since soils were collected only at MI for Soil Sampling 3, data were analyzed with tillage, cover, position, and depth as fixed factors.

1.4 Results:

1.4.1. 2012 Weather:

The 2012 growing season was exceptionally hot and dry across the American Midwest. At the IL site, total precipitation in the months of May, June, and July was 22.63 cm below the thirty-year average, and mean daily maximum temperatures were above the historical averages from May to August (Table 1.3.a). At MI, total precipitation from June to August was 9.43 cm below thirty-year averages, and mean daily maximum temperatures above historical averages from May to September (Table 1.3.b). Soil volumetric water content (cm^3 H_2O per soil cm^3) at both sites dropped considerably in the month of June as very few rain events occurred (Figures 1.3.a and 1.3.b). At MI, a series of rain events briefly increased VWC, but given the sandy texture of the soil on-site, VWC dropped again quickly. At IL, VWC remained low throughout the month of July except after one rain event towards the middle of the month. As a result of low rainfall and high air temperatures, soil temperatures (C) increased rapidly at both sites during

the month of June to reach a peak above 30 C at the beginning of July, declining thereafter (Figs. 1.4.a and 1.4.b).

1.4.2. Nitrate:

Soil NO_3 values tended to be highest in the 0-5 cm depth and were generally constrained to similar ranges at either site for each sample round, with the exception of Soil Sampling 1 at MI, for which values were much higher than at IL (Table 1.4). But, spatial patterns of distribution varied across sample rounds. Initial analysis of Soil Sampling 1 data from both sites revealed a strong effect of site ($p = 0.02$), so Soil Sampling 1 data was then separated by site and reanalyzed. At IL, there were strong main effects of tillage, cover, position, and depth ($p < 0.05$) for Soil Sampling 1, as well as several higher level interaction effects (Table 1.5). Plots with rye winter cover in both tillage treatments had lower NO_3 levels than corresponding fallow plots (Table 1.4). At the furrow position, average NO_3 across 0-20 cm was 5.4 ± 0.5 mg kg soil^{-1} and 11.0 ± 0.8 mg kg soil^{-1} in the RT-rye and RT-fallow treatments, while corresponding values in the CP treatments were higher (CP-rye: 7.4 ± 3.1; CP-fallow: 17.2 ± 0.4). At the MI site, mean NO_3 from 0-20 cm ranged from 14.9 – 39.6 mg kg soil^{-1} across all treatments and positions, and values were generally higher and more variable than at IL (Fig. 1.3.b, Table 1.4). There were no significant treatment or position effects except for an interaction effect of tillage and depth ($p < 0.05$, Table 1.5).

Patterns of NO_3 distribution began to change at Soil Sampling 2 as position effects emerged at both sites. An initial analysis of Soil Sampling 2 data with data from both sites

combined revealed interaction effect site **x** tillage **x** position, so data were separated by site and reanalyzed. At both sites the highest level interaction effect was tillage **x** position **x** depth ($p < 0.05$, Table 1.7). At the 0-5 cm depth, NO_3 values at the ridge position in RT treatments were 11.8 ± 6.3 and 13.1 ± 0.5 mg kg soil^{-1}, for rye and fallow treatments, respectively (Table 1.6). While in CP treatments values at the ridge position were lower (CP-rye = 5.4 ± 1.8; CP-fallow = 5.9 ± 1.0 mg kg soil^{-1}). At IL, NO_3 at the furrow position was lower in RT treatments than in corresponding CP treatments, while at MI NO_3 was similar across corresponding treatments in the furrow position. Similar to Soil Sampling 2, there was a marginal interaction effect of tillage **x** position ($p=0.06$) for Soil Sampling 3, with NO_3 values being higher in RT treatments than in corresponding CP treatments at all positions (Fig. 1.5 and Table 1.8).

1.4.3. Ammonium:

Treatment effects for soil NH_4 differed by site and sample round. Like soil NO_3, means were generally constrained to the same ranges at either site, but MI had more high, outlying values than IL, particularly at Soil Sampling 1 (Fig. 1.6.b). Data for Soil Sampling 1 were again analyzed separately by site since there was a effect of site in initial analysis ($p < 0.05$). With separate analyses, however, there were still no significant treatment effects at either site for Soil Sampling 1, except for a marginally significant effect of position **x** depth at IL ($p = 0.06$, Table 1.11). Data from Soil Sampling 2 were also analyzed separately by site. There were no treatment effects at IL, except for a marginal interaction effect of cover **x** position ($p = 0.08$, Table 1.13). This effect was likely due to higher levels of NH_4 in the ridge position for rye cover

treatments compared to fallow in both tillage treatments (Fig. 1.7.a, Table 1.12). At MI, the highest level interaction effect was tillage **x** position **x** depth, with lower level interaction effects of tillage **x** depth and tillage **x** position, and a main effect of depth (Table 1.13). Mean NH_4 values from 0-20 cm at the ridge position of RT treatments were 4.1 ± 0.8 and 5.4 ± 1.7 mg kg soil^{-1} for rye and fallow treatments, respectively (Table 1.12), which were higher than corresponding CP treatments (CP-rye = 2.8 ± 0.4 mg kg soil^{-1}; CP-fallow = 4.1 ± 0.4 mg kg soil^{-1}). For Soil Sampling 3, there was a marginal interaction effect of tillage **x** position **x** depth ($p=0.06$). Mean NH_4 values from 0-20 cm in RT treatments decreased from the ridge position outward, while in CP treatments there was no similar pattern (Fig. 1.8).

1.4.4. Potentially Mineralizable Nitrogen:

PMN data from Soil Sampling 1 were analyzed separately by site since an initial combined analysis showed a strong interaction effect of site **x** position ($p < 0.05$). PMN was generally low at both sites for Soil Sampling 1, and in some locations was even negative, indicating an immobilization effect. Distribution of PMN in Soil Sampling 1 was relatively uniform across row positions at both sites with no tillage effects at either site but strong effects of depth (Fig. 1.9, Table 1.16). At IL there was an interaction effect of cover **x** position **x** depth ($p = 0.05$), but there are no apparent patterns to explain this effect (Fig. 1.9.a). At MI, there were no effects other than depth. PMN in Soil Sampling 2 increased at both sites, and patterns of distribution changed, particularly at the 0-5 cm depth (Fig. 1.10 and Table 1.17). Both sites had strong main effects of depth, as well as a strong interaction effects of tillage **x** position (Table 1.18). Additionally, the IL site had an interaction effect of tillage **x** position **x** depth, while

MI had a strong main effect of position and a position **x** depth interaction effect. RT treatments at both sites exhibited the same patterns of PMN distribution, with PMN levels being highest in the ridge, lower at the shoulder, and lowest at the furrow (Fig. 1.10). No spatial pattern was observed for CP treatments at either site, as PMN values summed across 0-20 cm generally remained in the same range across all positions within CP treatments (Table 1.17). At IL, cumulative PMN values across the 0-20 cm depth increment at the ridge position of RT treatments were 5.4 ± 1.1 and 3.5 ± 0.5 mg kg soil^{-1} day^{-1} for rye and fallow treatments, respectively, which were higher than corresponding CP treatments (CP-rye = 2.7 ± 0.9 mg kg soil^{-1} day^{-1}; CP-fallow = 2.5 ± 0.6 mg kg soil^{-1} day^{-1}). At MI, differences between CP and RT treatments in PMN summed across depths in the ridge position were less pronounced, as mean values ranged from only 4.8 – 5.9 mg kg soil^{-1} day^{-1} , and variability was greater (Table 1.17). Patterns of distribution were similar for RT treatments in Soil Sampling 3, though the tillage **x** position effect was lost.

1.4.5. Particulate organic matter:

Results from POM analyses of surface soils from Soil Sampling 2 generally reflected PMN results from Soil Sampling 2. At both sites, there was an interaction effect of tillage **x** position on POM-C and POM-N in both light and coarse fractions, though the effect was only marginal on light fraction POM-N at both sites (IL: p=0.07, MI: p=0.08). In RT treatments POM-C and POM-N were highest in the ridge position and decreased towards the furrow in both coarse and light fractions (Figs. 1.12 and 1.13). Differences between positions were particularly pronounced in RT treatments at MI in the coarse fraction (Fig. 1.12). There were no

pronounced spatial patterns in CP treatments, except in coarse fraction POM-C and POM-N at IL, where values at the shoulder position) were consistently higher than ridge and furrow positions (Fig. 1.12.a and Fig., 1.13.a). Aside from position effects, there was a strong effect of cover on light fraction POM-C and POM-N at IL, where values in plots treated with rye cover were generally higher than those without ($p = 0.02$). As well, there were marginal effects of tillage **x** cover on coarse POM-C and POM-N at IL, with values being higher overall in RT-rye treatments than CP-rye treatments.

1.5. Discussion:

The 2012 growing season was among the hottest and driest on record across the American Midwest. Precipitation at both IL and MI sites was well below the thirty-year average in the latter parts of the season (July, early August), as were average daily maximum temperatures (Table 1.3). Drought conditions also dramatically reduced soil moisture and raised temperatures at both sites, particularly during the months of June and July (Figs. 1.1 and 1.2). The effect of the 2012 drought on soil N pools is hard to surmise from our data as there are no previous zero-fertilizer data to which we can compare. But soil NO_3 was considerably reduced by the latter part of the season with most NO_3 values cumulative across depths below 10 mg kg soil^{-1} by Soil Sampling 3.

Overall, tillage seemed to have little effect on the total size of N pools, as values summed across positions and depths were generally constrained to the same range in both CP and RT treatments, except in one case. This lack of an effect on the size of pools, especially biological pools, is unsurprising as the pace of change in these pools is slow after

implementation of ridge tillage systems (Zibiliske and Bradford 2007, Shi et al. 2012). The only significant main effect of tillage observed was on NO_3 at Soil Sampling 3. This late season effect on NO_3 lends partial support to our hypothesis that RT can improve temporal synchrony by ensuring turnover occurs later in the season. However, since N levels in RT treatments were comparable to CP treatments for Soil Samplings 1 and 2, it appears RT did not reduce early-season turnover relative to CP, meaning higher levels in the later season may not be due to improved synchrony, but instead to overall greater late-season turnover in RT treatments.

The negative effect of cover on soil NO_3 at IL during Soil Sampling 1 is consistent with other findings that rye cover can cause early season immobilization (Hu et al. 1997, Rosecrance et al. 2000), but the loss of a cover effect after Soil Sampling 1 seems to indicate that similar to other studies (McSwiney et al. 2010), this immobilization effect quickly diminished over time. The lack of interaction effects between cover, tillage, and position at IL for Soil Sampling 1 did not support our hypothesis that RT might mitigate early season immobilization effects of rye cover by relocating the site of immobilization to the furrow, away from seedlings. At IL, the significant tillage **x** position effect and lower levels of NO_3 at the furrow position in the RT-fallow treatment for Soil Sampling 1 may lend partial support to this hypothesis. However, the effect was small and RT did not offer any advantage over CP, as NO_3 values in CP treatments were comparable or higher than RT treatments at all positions. The lack of difference between ridge and furrow position for NO_3 in the RT-rye treatment may be related to the location, quality, and quantity of residues that were actually manipulated by RT operations. Several

studies have demonstrated that because of their high C:N ratio, decomposition of roots can lead to greater N immobilization (Jackson et al. 2008, Bauhus 1998). If cover crop roots remained in-row after ridge-slicing and planting, then immobilization would continue to occur there, despite the transfer of vegetative tissues to the furrow; thus diminishing the magnitude of a relocation effect.

Similar to IL, at the MI site there were no significant position or tillage effects on soil NO_3 or NH_4, and mean values were consistent across positions and treatments, except for a few outlying NH_4 values. Outlying NH_4 values are possibly due to sampling error, in which cores were accidentally pulled from fertilized subplots rather than unfertilized, though no such error was recorded. Lack of a cover effect indicates that either immobilization did not occur to a measureable extent or cover inputs were too low to elicit an effect. However, cover crop biomass was similar in all treatments at MI to IL, however (IL = 687.07 ± 179.85 kg ha^{-1}; MI = 726.67 ± 95.71 kg ha^{-1}). Barrett and Burke (2000) found that higher levels of soil C, especially labile C, can increase immobilization. Higher baseline soil C at IL may mean that decomposition and, hence, immobilization were more pronounced at IL. Further evidence to support this notion is found in the fact that the only other effect of cover seen was on light fraction POM-C and POM-N at IL. The lack of a similar effect at MI might suggest differences in the sites' capacities for residue turnover, as increases in POM-C in lighter fractions indicate the incorporation of processed residues into microaggregates (Six et al. 2004).

The most pronounced and consistent effects across sites were tillage **x** position interaction effects on all types of N for Soil Sampling 2 and 3. For the most part, this effect was

defined by higher levels of N in the ridge space of RT treatments than in the furrows, except in the case of NO3, in which the opposite was true. However, CP treatments appeared to exhibit the same pattern. The pattern may be explained by the fact that mineral N uptake is higher near plants, meaning that soils closer to the plant will have lower NO_3 availability. Furthermore, NO_3 in the ridge position was higher in RT treatments than in corresponding CP treatments, corroborating results from the other assays that there is an increase in N in the in-row space relative to CP treatments. These results support our hypothesis that RT is effectively relocating residues and their associated nutrients to the ridge/in-row space after re-ridging and is consistent with results from a handful of other studies on zonal differences in C and N pools in RT systems (Müller et al. 2009 (a) and (b), Clay et al. 1995, Shi et al. 2012). Most importantly, the translocation of these materials did not appear to cause any significant N immobilization in the ridge space as levels of all forms of N remained higher in the ridge of RT treatments than in corresponding CP treatments. Furthermore, the similar effect seen for POM-C in the coarse fraction at both sites indicates that this translocation is primarily of fresh inputs, as that is was the coarse fraction is understood to represent (Six et al. 1998).

This combined evidence that RT is effectively translocating fresh residues that are sufficiently processed so as to increase mineralizable N is strong evidence that RT can improve spatial N synchrony. Whether or not this relocation is advantageous to crops is unclear, especially since PMN values at the ridge were only marginally higher in RT treatments than CP treatments for Soil Sampling 2 (Fig. 1.8). But given previous studies that indicate re-ridging can elicit nodal root growth (Thomas and Kaspar 1995 and 1997) and stimulate microbial activity in

the ridge (Grigera et al. 2007) it is a positive result. Furthermore, since previous studies have found that long-term RT management results in higher C and N in the ridge position (Shi et al. 2012), this effect may become more pronounced with time. Improvements in spatial N synchrony could be especially useful for growers interested in adjusting soil fertility strategies to displace or replace fertilizer N. By concentrating SOM-N in the in-row space, growers may be more able to effectively utilize it both within and across seasons. Furthermore, if soil SOM is being simultaneously protected in the furrow space, RT may be able to strike a sufficient balance between conserving and utilizing SOM pools.

1.6. Conclusions:

1.) RT had little to no effect on early season N immobilization and did not appear to relocate the site of immobilization to the furrow.

2.) Limited evidence that RT improved temporal N synchrony in that NO_3 levels were higher in RT treatments at Soil Sampling 3. However, this effect was not accompanied by the expected reduction in N levels in the early season, indicating that it may have just been the result of greater total turnover in RT treatments.

3.) RT effectively translocated fresh inputs from the furrow to the ridge space, improving spatial N synchrony by increasing PMN in the in-row space.

Tables 1.1.a and 1.1.b: Thirty-year (1981-2010) climate averages for (a) Urbana, IL and (b) Lansing, MI (Source: NOAA National Climatic Data Center).

(a)

Month	**Average precip. (cm)**	**Mean temp. (C)**	**Mean daily min. temp (C)**	**Mean daily max. temp (C)**
May	12.4	16.9	10.9	23.0
June	11.0	22.3	16.6	28.1
July	11.9	23.8	18.3	29.4
August	9.9	23.0	17.3	28.7
September	7.9	19.0	12.3	25.7
October	8.3	12.2	5.9	18.4
SUM	61.4			

(b)

Month	**Average precip. (cm)**	**Mean temp. (C)**	**Mean daily min. temp (C)**	**Mean daily max. temp (C)**
May	8.5	14.3	8.2	20.4
June	8.8	19.8	13.7	25.8
July	7.2	21.9	15.9	28.0
August	8.2	21.0	15.2	26.7
September	8.9	16.6	10.7	22.6
October	6.4	10.2	4.8	15.5
SUM	48.0			

Table 1.2: Management tables for IL and MI sites in the 2012 growing season, including dates of field management and soil sampling events. (* Since spring conditions are generally wet at the IL, these tillage operations are performed the preceding fall before cover crops are planted).

	Date completed	
Event	**IL**	**MI**
Cover crop terminated	April 5	April 27
Chisel plow	September 22, 2011 *	May 11
Ridge slicing	September 22, 2011 *	May 11
Soil finishing	April 5	May 17
Planting	April 12	May 17
Soil Sampling 1	April 27	May 29
Re-ridging	May 30	July 3
Soil Sampling 2	June 1	July 10
Soil Sampling 3	N/A	August 6
Harvest	September 18	October 3

Table 1.3.a and 1.3.b: Weather data for 2012 growing season at (a) IL and (b) MI.

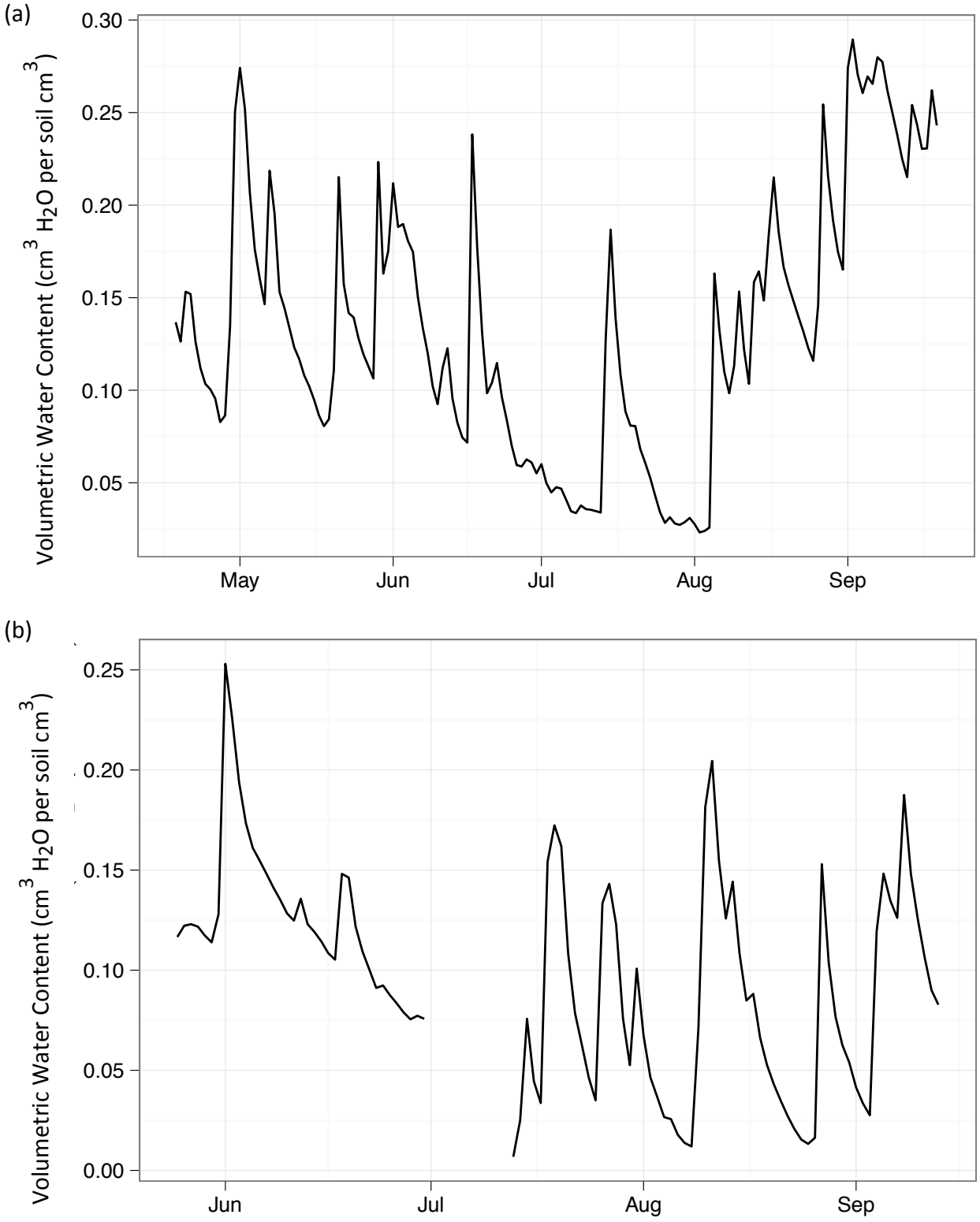
(a)

Month	**Total precip. (cm)**	**Mean temp. (C)**	**Mean daily min. temp (C)**	**Mean daily max. temp (C)**
May	6.7	20.5	13.5	27.4
June	4.6	22.7	15.6	29.6
July	1.5	27.6	20.7	34.9
August	14.2	23.1	16.6	30.5
September	14.3	17.8	12.2	24.6
October	13.8	10.7	5.3	16.4
SUM	54.1			

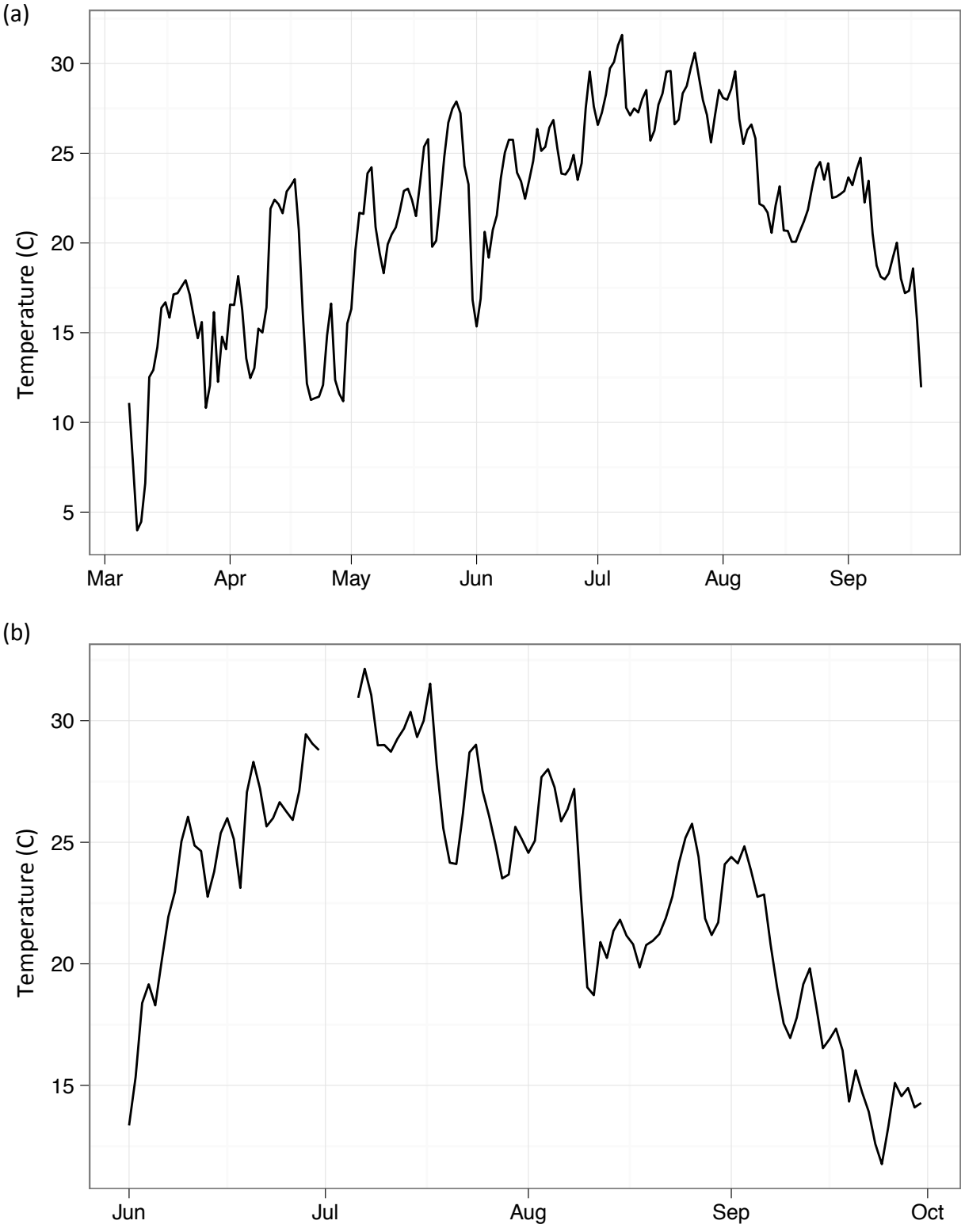
(b)

Month	**Total precip. (cm)**	**Mean temp. (C)**	**Mean daily min. temp (C)**	**Mean daily max. temp (C)**
May	7.3	16.7	9.5	23.4
June	2.8	20.6	12.7	27.2
July	6.4	24.3	16.9	31.2
August	4.9	20.3	13.5	27.3
September	5.9	15.8	9.1	22.9
October	9.6	9.6	4.7	15.3
SUM	36.9			

Figures 1.1.a and 1.1.b: Average daily soil volumetric water content (cm^3 H2O per soil cm^3) at 0-5 cm as measured by HOBO EC-5^R soil moisture loggers at (a) IL and (b) MI continuously throughout the growing season.

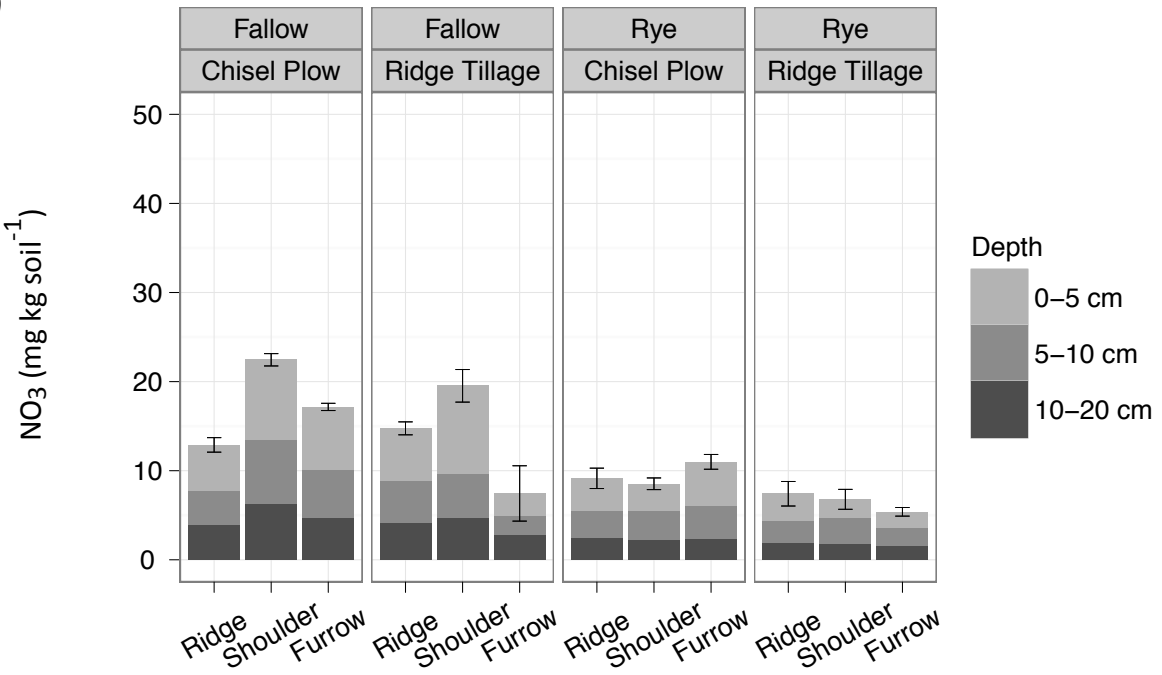


Figures 1.2.a and 1.2.b: Average daily soil temperature (C) at 0-5 cm as measured by HOBO^{R} Onset pendant temperature loggers at (a) IL and (b) MI continuously throughout the growing season.



Figures 1.3.a and 1.3.b: Stacked bar graphs of average soil KCl-extractable NO_3 (mg kg $soil^{-1}$) from Soil Sampling 1 at (a) IL and (b) MI. Colored stacks represent average values of depth increments within each position of each experimental treatment. Error bars represent ± S.E. of NO_3 combined across depths.

(a)



(b)

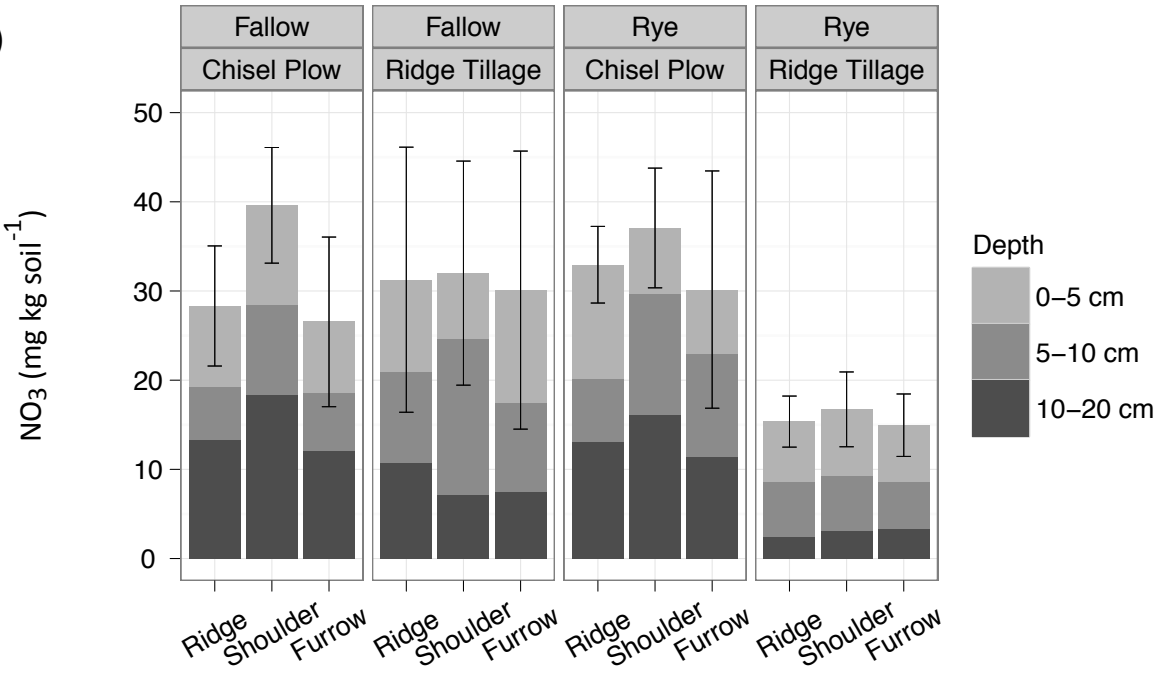


Table 1.4: Average soil KCl-extractable NO_3 (mg kg $soil^{-1}$) ± S.E. combined across depths for Soil Sampling 1.

		CP-fallow	**RT-fallow**	**CP-rye**	**RT-rye**
IL	Ridge	12.9 ± 0.8	14.8 ± 0.7	9.1 ± 1.1	7.4 ± 1.4
	Shoulder	22.5 ± 0.7	19.5 ± 1.8	8.5 ± 0.7	6.8 ± 1.1
	Furrow	17.2 ± 0.4	7.4 ± 3.1	10.9 ± 0.8	5.4 ± 0.5
MI	Ridge	28.3 ± 6.7	31.3 ± 14.9	32.9 ± 4.3	15.4 ± 2.9
	Shoulder	39.6 ± 6.5	32.0 ± 12.6	37.1 ± 6.7	16.7 ± 4.2
	Furrow	26.5 ± 9.5	30.2 ± 15.6	30.2 ± 13.3	15.0 ± 3.5

Table 1.5: Results of mixed-effects ANOVAs run in SAS PROC MIXED for soil KCl-extractable NO_3 (mg kg $soil^{-1}$) data from Soil Sampling 2. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	20.66	0.02	0.76	0.45
Cover	133.25	< 0.0001	1.21	0.31
Tillage **x** Cover	0.18	0.69	1.98	0.21
Position	14.1	< 0.0001	1.15	0.33
Tillage **x** Position	11.81	0.0003	0.58	0.57
Cover **x** Position	18.59	< 0.0001	0.1	0.90
Tillage **x** Cover **x** Position	2.85	0.08	0.13	0.88
Depth	20.17	< 0.0001	0.32	0.73
Tillage **x** Depth	0.39	0.68	6	0.004
Cover **x** Depth	5.71	0.005	0.2	0.82
Tillage **x** Cover **x** Depth	0.97	0.38	0.96	0.39
Position **x** Depth	0.91	0.46	0.86	0.49
Tillage **x** Position **x** Depth	2.53	0.05	0.56	0.69
Cover **x** Position **x** Depth	3.56	0.01	0.33	0.85
Tillage **x** Cover **x** Position **x** Depth	0.8	0.53	0.73	0.58

Figures 1.4.a and 1.4.b: Stacked bar graphs of average soil KCl-extractable NO_3 (mg kg $soil^{-1}$) from Soil Sampling 2 at (a) IL and (b) MI. Colored stacks represent average values of depth increments within each position of each experimental treatment. Error bars represent ± S.E. of NO_3 combined across depths.

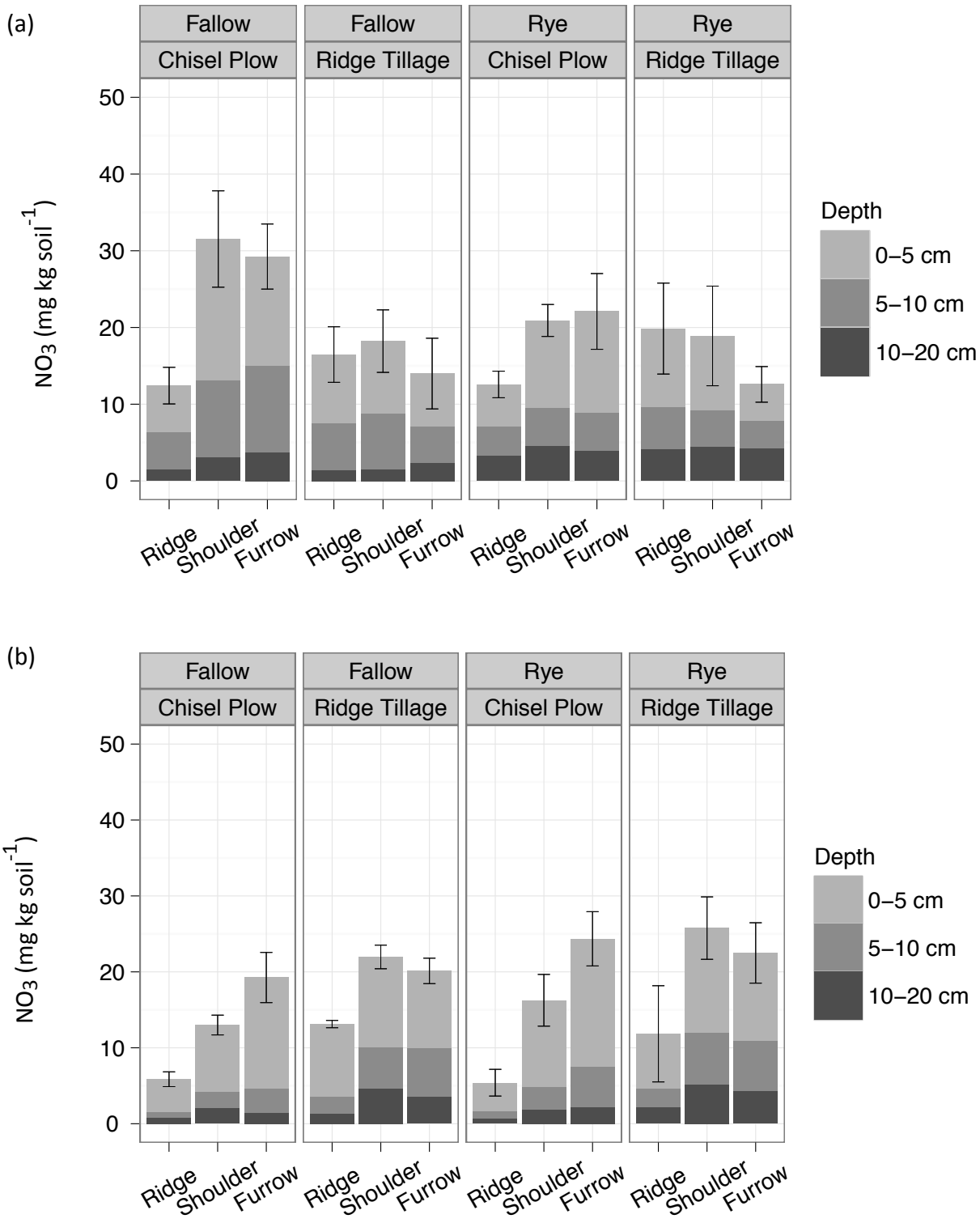


Table 1.6: Average soil KCl-extractable NO_3 (mg kg soil^{-1}) ± S.E. combined across depths for Soil Sampling 2.

		CP-fallow	**RT-fallow**	**CP-rye**	**RT-rye**
IL	Ridge	12.4 ± 2.4	16.5 ± 3.6	12.6 ± 1.7	19.9 ± 5.9
	Shoulder	31.5 ± 6.3	18.2 ± 4.1	20.9 ± 2.1	18.9 ± 6.5
	Furrow	29.2 ± 4.2	14.0 ± 4.6	22.1 ± 4.9	12.6 ± 2.3
MI	Ridge	5.9 ± 1.0	13.1 ± 0.5	5.4 ± 1.8	11.8 ± 6.3
	Shoulder	13.0 ± 1.3	22.0 ± 1.6	16.3 ± 3.4	25.8 ± 4.1
	Furrow	19.3 ± 3.3	20.1 ± 1.7	24.4 ± 3.6	22.5 ± 4.0

Table 1.7: Results of mixed-effects ANOVAs run in SAS PROC MIXED for soil KCl-extractable NO_3 (mg kg soil^{-1}) data from Soil Sampling 2. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	4.18	0.13	3.96	0.14
Cover	1.15	0.33	0.66	0.45
Tillage **x** Cover	2.11	0.20	0.04	0.85
Position	6.11	0.007	37.83	< 0.0001
Tillage **x** Position	10.63	0.0005	5.5	0.01
Cover **x** Position	1.67	0.21	1.45	0.26
Tillage **x** Cover **x** Position	0.52	0.60	0.14	0.87
Depth	62.83	< 0.0001	143.77	< 0.0001
Tillage **x** Depth	2.84	0.07	1.54	0.22
Cover **x** Depth	8.2	0.0006	0.11	0.90
Tillage **x** Cover **x** Depth	0.19	0.83	0.36	0.70
Position **x** Depth	1.88	0.12	5.42	0.0007
Tillage **x** Position **x** Depth	3.87	0.01	6.05	0.0003
Cover **x** Position **x** Depth	0.53	0.72	0.76	0.55
Tillage **x** Cover **x** Position **x** Depth	1.1	0.36	0.13	0.97

Figure 1.5: Stacked bar graphs of average soil KCl-extractable NO_3 (mg kg soil^{-1}) from Soil Sampling 3 at MI. Colored stacks represent average values of depth increments within each position of each experimental treatment. Error bars represent ± S.E. of NO_3 combined across depths.

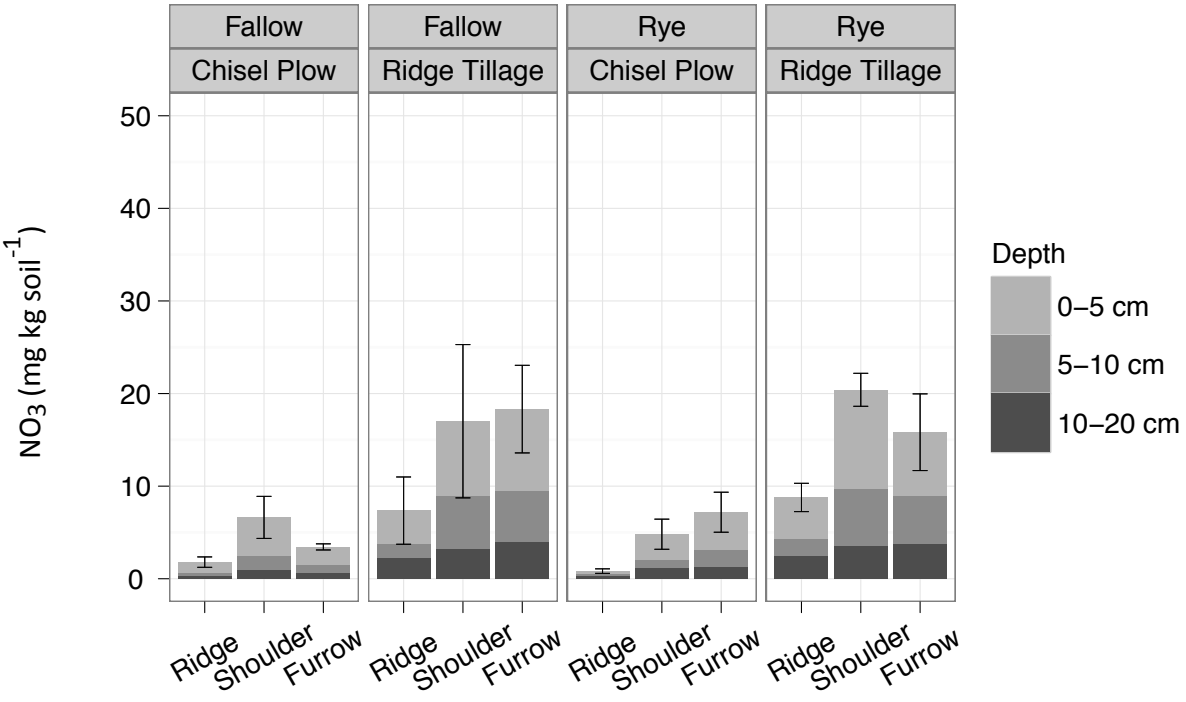


Table 1.8: Average soil KCl-extractable NO_3 (mg kg soil^{-1}) ± S.E. combined across depths for Soil Sampling 3.

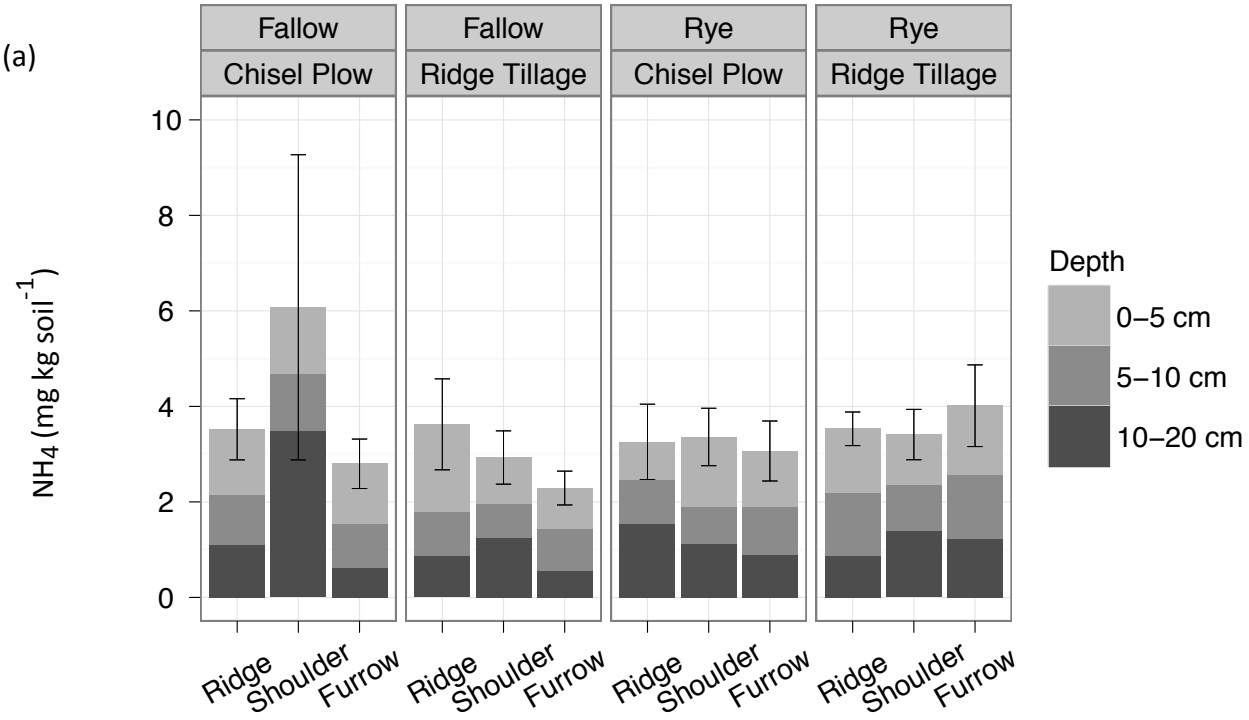
		CP-fallow	**RT-fallow**	**CP-rye**	**RT-rye**
MI	Ridge	1.8 ± 0.6	7.4 ± 3.6	0.8 ± 0.2	8.8 ± 1.5
	Shoulder	6.6 ± 2.3	17.0 ± 8.3	4.8 ± 1.6	20.4 ± 1.8
	Furrow	3.4 ± 0.3	18.3 ± 4.7	7.2 ± 2.2	15.8 ± 4.1

Table 1.9: Results of mixed-effects ANOVA run in SAS PROC MIXED for soil KCl-extractable NO_3 (mg kg $soil^{-1}$) data from Soil Sampling 2. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

	MI	
Effect	F value	p
Tillage	8.6	0.06
Cover	0.08	0.78
Tillage **x** Cover	0.01	0.91
Position	19.07	< 0.0001
Tillage **x** Position	3.12	0.06
Cover **x** Position	0.02	0.98
Tillage **x** Cover **x** Position	2.55	0.10
Depth	39.65	< 0.0001
Tillage **x** Depth	6.3	0.003
Cover **x** Depth	0.02	0.98
Tillage **x** Cover **x** Depth	0.16	0.85
Position **x** Depth	4.17	0.004
Tillage **x** Position **x** Depth	1.28	0.29
Cover **x** Position **x** Depth	0.07	0.99
Tillage **x** Cover **x** Position **x** Depth	1.55	0.20

Figures 1.6.a and 1.6.b: Stacked bar graphs of average soil KCl-extractable NH_4 (mg kg $soil^{-1}$) from Soil Sampling 1 at (a) IL and (b) MI. Colored stacks represent average values of depth increments within each position of each experimental treatment. Error bars represent ± S.E. of NH_4 combined across depths.

(a)



(b)

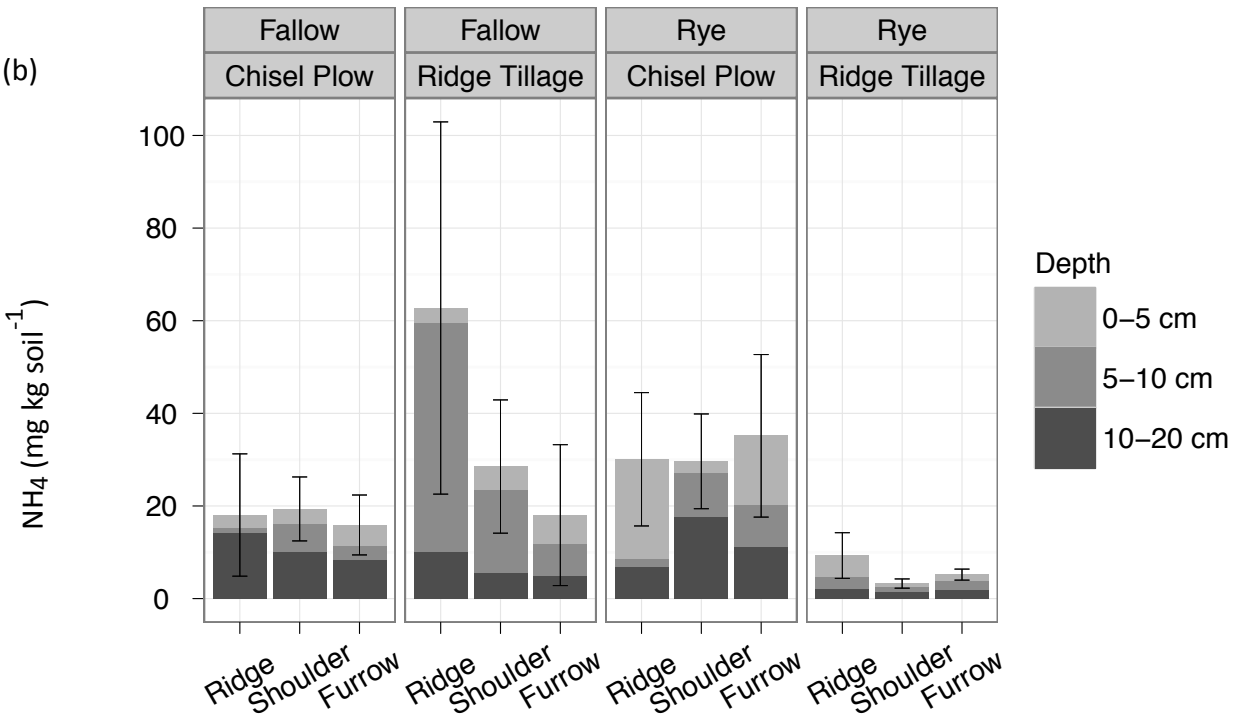


Table 1.10: Average soil KCl-extractable NH_4 (mg kg soil^{-1}) ± S.E. combined across depths for Soil Sampling 1.

		CP-fallow	**RT-fallow**	**CP-rye**	**RT-rye**
IL	Ridge	3.5 ± 0.6	3.6 ± 1.0	3.3 ± 0.8	3.5 ± 0.4
	Shoulder	6.1 ± 3.2	2.9 ± 0.6	3.4 ± 0.6	3.4 ± 0.5
	Furrow	2.8 ± 0.5	2.3 ± 0.4	3.1 ± 0.6	4.0 ± 0.9
MI	Ridge	18.0 ± 13.2	62.7 ± 40.2	30.1 ± 14.4	9.3 ± 4.9
	Shoulder	19.4 ± 6.9	28.5 ± 14.4	29.6 ± 10.2	3.2 ± 1.0
	Furrow	15.9 ± 6.5	18.0 ± 15.2	35.1 ± 17.6	5.2 ± 1.2

Table 1.11: Results of mixed-effects ANOVAs run in SAS PROC MIXED for soil KCl-extractable NH_4 (mg kg soil^{-1}) data from Soil Sampling 1. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	0.27	0.64	0.1	0.77
Cover	0.03	0.87	0.69	0.44
Tillage **x** Cover	1.76	0.23	4.88	0.07
Position	0.74	0.49	0.65	0.53
Tillage **x** Position	0.93	0.41	0.79	0.46
Cover **x** Position	1.02	0.38	0.61	0.55
Tillage **x** Cover **x** Position	0.53	0.60	0.36	0.70
Depth	1.35	0.27	0.43	0.65
Tillage **x** Depth	1.18	0.31	2.58	0.08
Cover **x** Depth	0.29	0.75	1.73	0.18
Tillage **x** Cover **x** Depth	0.33	0.72	1.02	0.37
Position **x** Depth	2.38	0.06	0.36	0.83
Tillage **x** Position **x** Depth	0.62	0.65	1.08	0.37
Cover **x** Position **x** Depth	1.55	0.20	1.07	0.38
Tillage **x** Cover **x** Position **x** Depth	1.27	0.29	0.53	0.71

Figures 1.7.a and 1.7.b: Stacked bar graphs of average soil KCl-extractable NH_4 (mg kg soil^{-1}) from Soil Sampling 2 at (a) IL and (b) MI. Colored stacks represent average values of depth increments within each position of each experimental treatment. Error bars represent ± S.E. of NH_4 combined across depths.

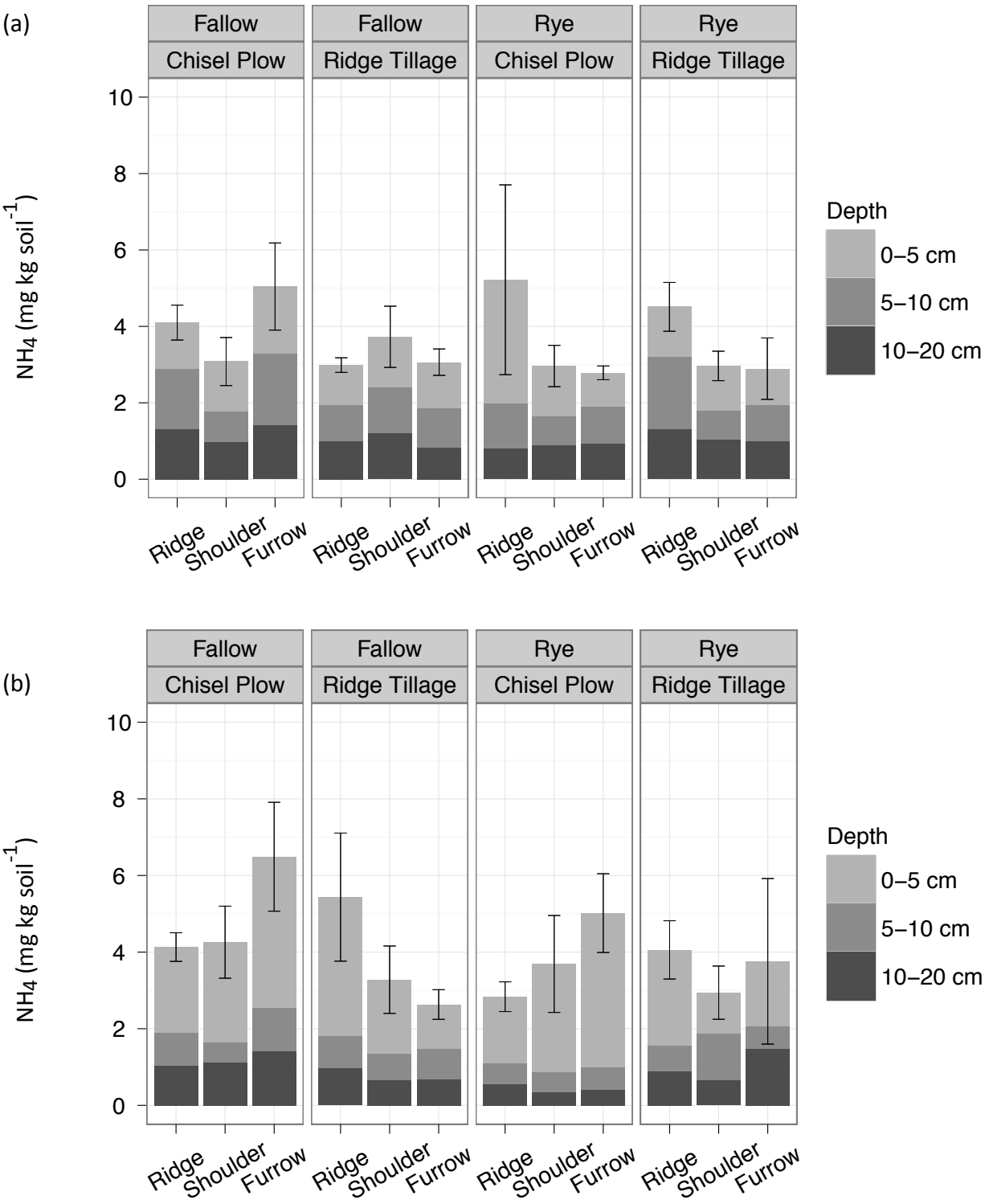


Table 1.12: Average soil KCl-extractable NH_4 (mg kg soil^{-1}) ± S.E. combined across depths for Soil Sampling 2.

		CP-fallow	**RT-fallow**	**CP-rye**	**RT-rye**
IL	Ridge	4.1 ± 0.5	3.0 ± 0.2	5.2 ± 2.5	4.5 ± 0.6
	Shoulder	3.1 ± 0.6	3.7 ± 0.8	3.0 ± 0.5	3.0 ± 0.4
	Furrow	5.0 ± 1.1	3.1 ± 0.3	2.8 ± 0.2	2.9 ± 0.8
MI	Ridge	4.1 ± 0.4	5.4 ± 1.7	2.8 ± 0.4	4.1 ± 0.8
	Shoulder	4.3 ± 0.9	3.3 ± 0.9	3.7 ± 1.3	2.9 ± 0.7
	Furrow	6.5 ± 1.4	2.6 ± 0.4	5.0 ± 1.0	3.8 ± 2.2

Table 1.13: Results of mixed-effects ANOVAs run in SAS PROC MIXED for soil KCl-extractable NH_4 (mg kg soil^{-1}) data from Soil Sampling 2. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	0.61	0.49	1.48	0.31
Cover	0.06	0.82	1.23	0.31
Tillage **x** Cover	0.46	0.52	0.6	0.47
Position	1.8	0.19	0.84	0.44
Tillage **x** Position	0.83	0.45	3.5	0.05
Cover **x** Position	2.71	0.09	0.35	0.72
Tillage **x** Cover **x** Position	0.76	0.48	0.51	0.61
Depth	1.63	0.20	46.1	< 0.0001
Tillage **x** Depth	0.9	0.41	4.28	0.02
Cover **x** Depth	0.48	0.62	0.09	0.92
Tillage **x** Cover **x** Depth	1.09	0.34	1.6	0.21
Position **x** Depth	0.49	0.74	0.36	0.83
Tillage **x** Position **x** Depth	0.65	0.63	4.83	0.002
Cover **x** Position **x** Depth	0.87	0.49	0.72	0.58
Tillage **x** Cover **x** Position **x** Depth	1.12	0.35	0.24	0.91

Figures 1.8: Stacked bar graphs of average soil KCl-extractable NH_4 (mg kg soil^{-1}) from Soil Sampling 3 at MI. Colored stacks represent average values of depth increments within each position of each experimental treatment. Error bars represent ± S.E. of NH_4 combined across depths.

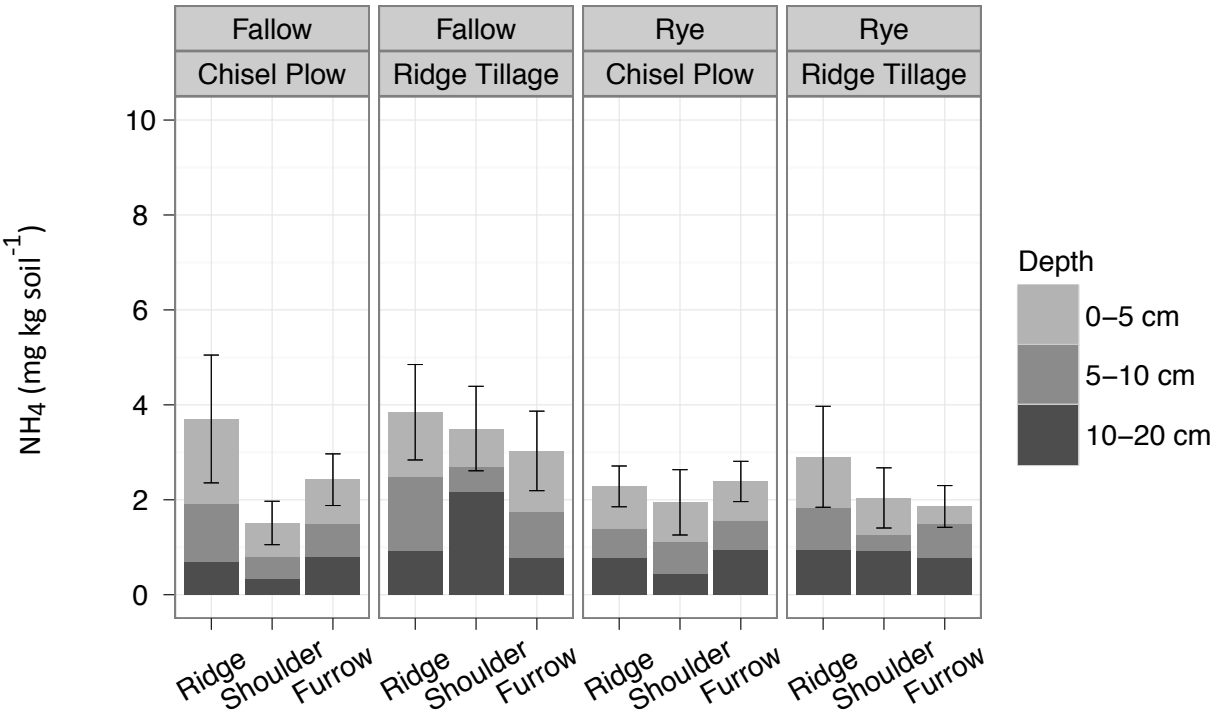


Table 1.14: Average soil KCl-extractable NH_4 (mg kg soil^{-1}) ± S.E. combined across depths for Soil Sampling 3.

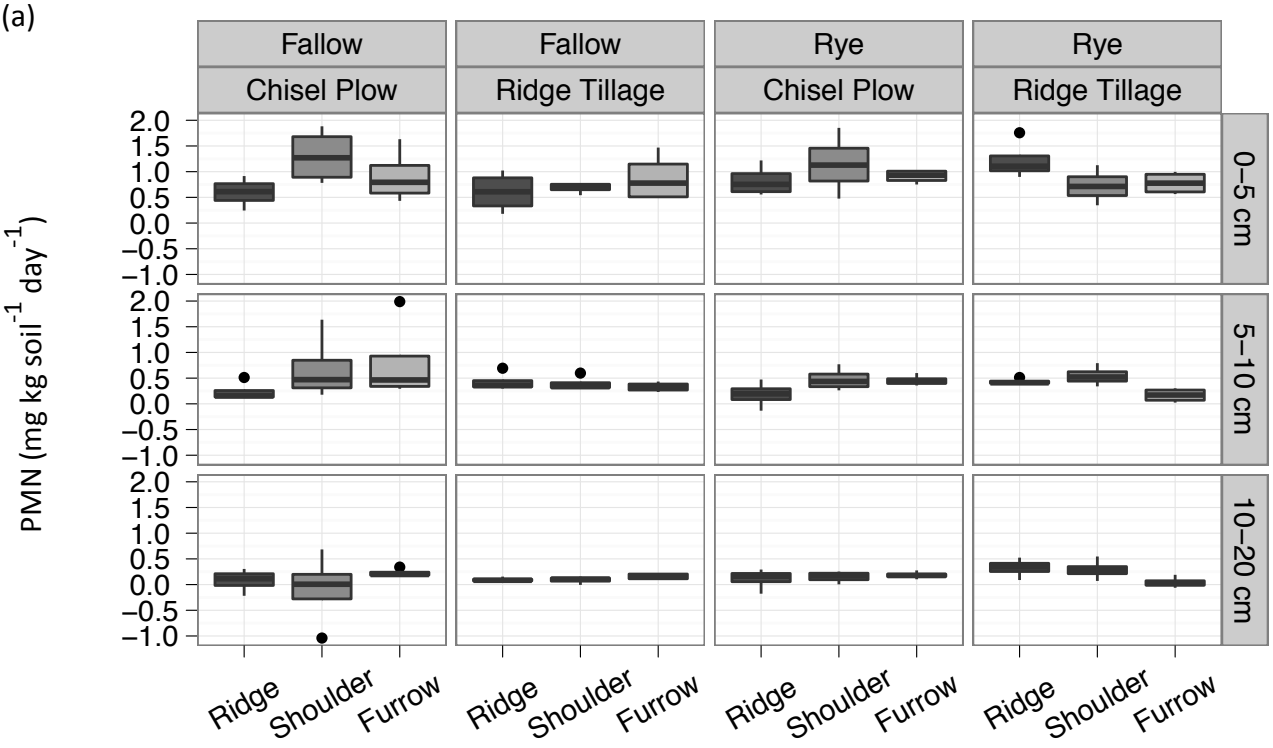
		CP-fallow	**RT-fallow**	**CP-rye**	**RT-rye**
MI	Ridge	3.7 ± 1.3	3.8 ± 1.0	2.3 ± 0.4	2.9 ± 1.1
	Shoulder	1.5 ± 0.5	3.5 ± 0.9	1.9 ± 0.7	2.0 ± 0.6
	Furrow	2.4 ± 0.5	3.0 ± 0.8	2.4 ± 0.4	1.9 ± 0.4

Table 1.15: Results of mixed-effects ANOVAs run in SAS PROC MIXED for soil KCl-extractable NH_4 (mg kg $soil^{-1}$) data from Soil Sampling 3. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

	MI	
Effect	F value	p
Tillage	0.73	0.46
Cover	3.24	0.12
Tillage **x** Cover	1	0.36
Position	1.82	0.18
Tillage **x** Position	0.48	0.63
Cover **x** Position	0.24	0.79
Tillage **x** Cover **x** Position	0.68	0.52
Depth	1.37	0.26
Tillage **x** Depth	2.06	0.13
Cover **x** Depth	0.36	0.70
Tillage **x** Cover **x** Depth	0.39	0.68
Position **x** Depth	1.93	0.11
Tillage **x** Position **x** Depth	2.41	0.06
Cover **x** Position **x** Depth	1.95	0.11
Tillage **x** Cover **x** Position **x** Depth	0.83	0.51

Figures 1.9.a and 1.9.b: Boxplots of soil PMN (mg kg soil^{-1} day^{-1}) from Soil Sampling 1 at (a) IL and (b) MI.

(a)



(b)

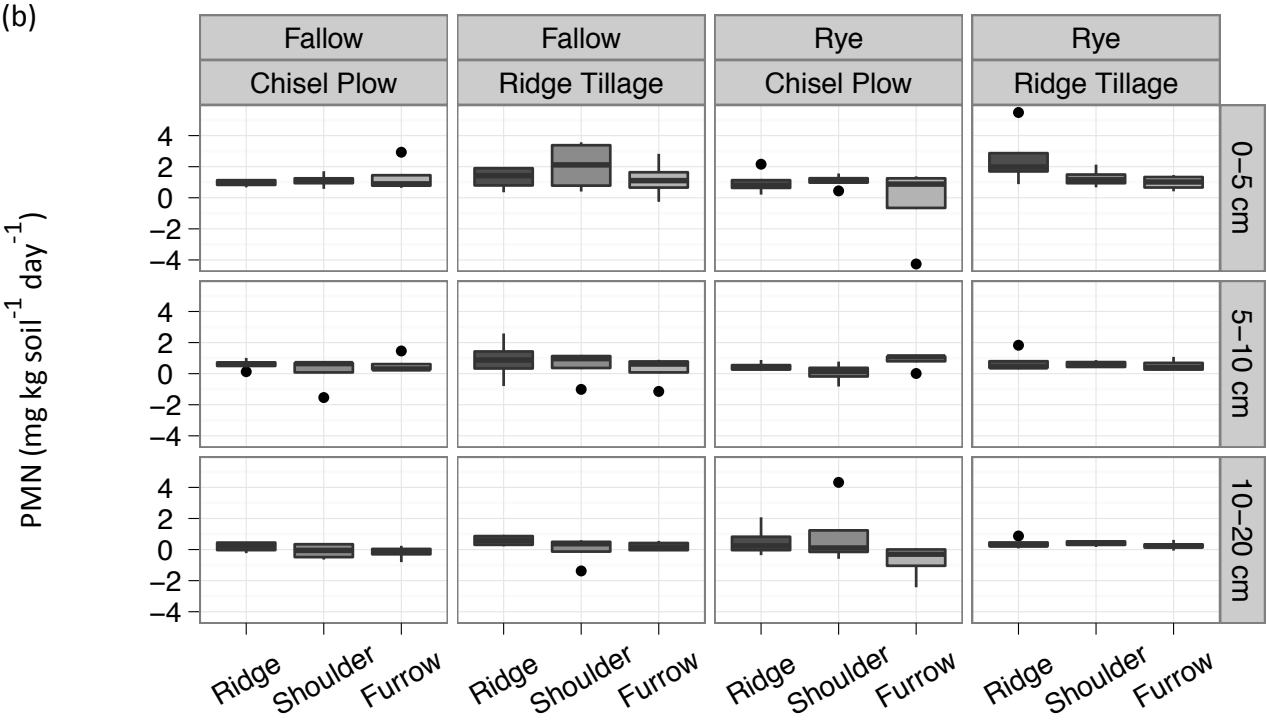
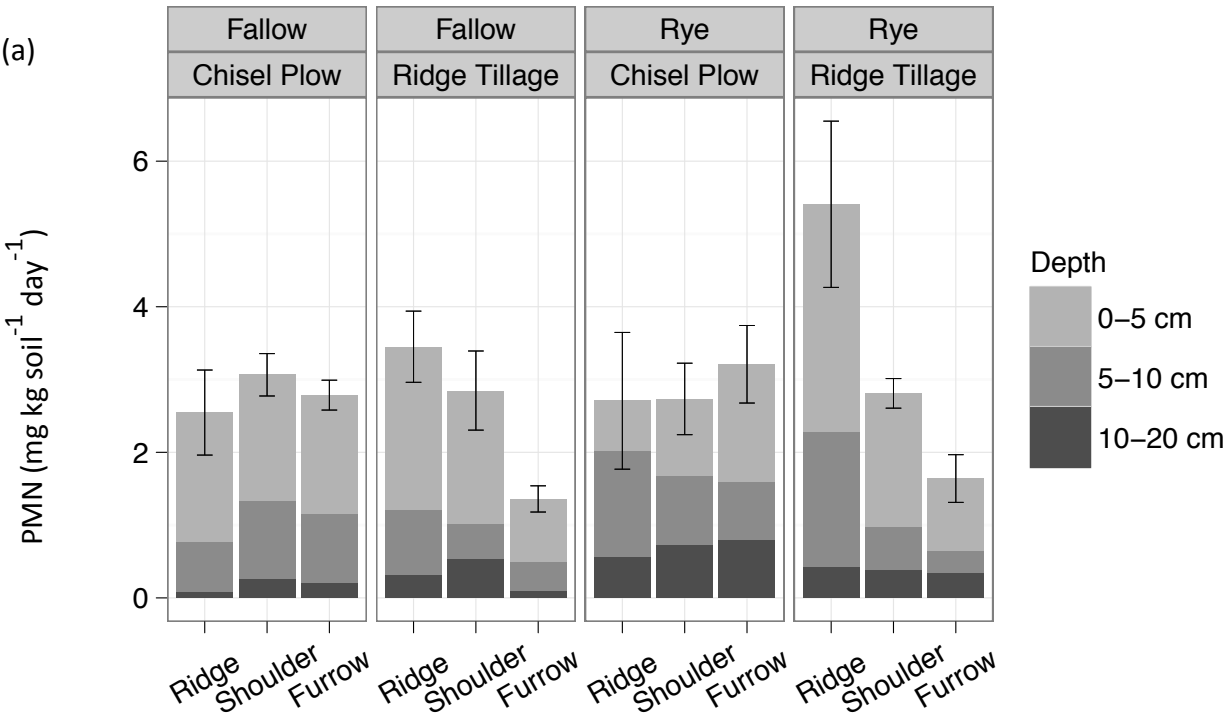


Table 1.16: Results of mixed-effects ANOVAs run in SAS PROC MIXED for PMN (mg kg soil^{-1} day^{-1}) data from Soil Sampling 1. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	0.22	0.67	1.41	0.32
Cover	0.36	0.57	0.84	0.40
Tillage **x** Cover	0.98	0.36	0.83	0.40
Position	0.45	0.65	2.65	0.09
Tillage **x** Position	1.59	0.23	1.06	0.37
Cover **x** Position	2.15	0.14	2.08	0.15
Tillage **x** Cover **x** Position	0.21	0.81	0.31	0.74
Depth	32.89	< 0.0001	12.67	< 0.0001
Tillage **x** Depth	0.93	0.40	1.71	0.19
Cover **x** Depth	1.14	0.33	0.37	0.69
Tillage **x** Cover **x** Depth	1.19	0.31	0.18	0.83
Position **x** Depth	0.68	0.61	1.68	0.16
Tillage **x** Position **x** Depth	2.28	0.07	0.47	0.76
Cover **x** Position **x** Depth	2.51	0.05	1.66	0.17
Tillage **x** Cover **x** Position **x** Depth	0.52	0.72	0.45	0.77

Figures 1.10.a and 1.10.b: Stacked bar graphs of average PMN (mg kg soil^{-1} day^{-1}) from Soil Sampling 2 at (a) IL and (b) MI. Colored stacks represent average values of depth increments within each position of each experimental treatment. Error bars represent ± S.E. of PMN combined across depths.

(a)



(b)

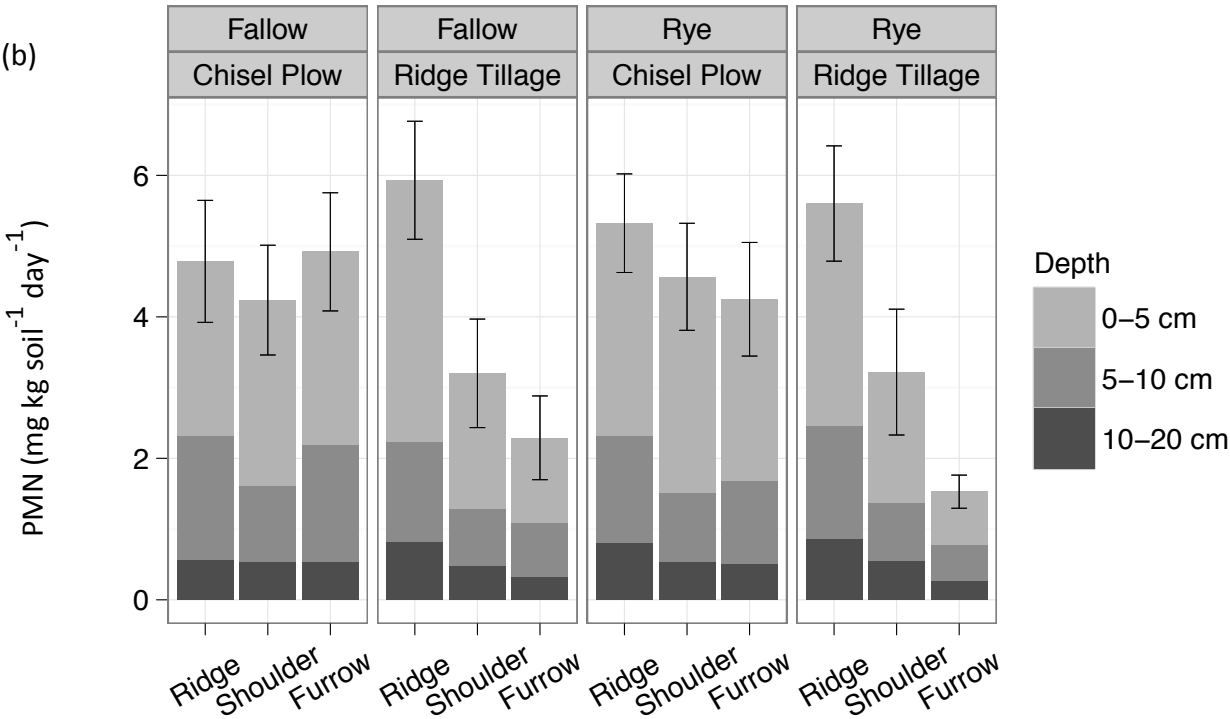


Table 1.17: Average PMN (mg kg soil^{-1} day^{-1}) ± S.E. combined across depths for Soil Sampling 2.

		CP-fallow	**RT-fallow**	**CP-rye**	**RT-rye**
IL	Ridge	2.5 ± 0.6	3.5 ± 0.5	2.7 ± 0.9	5.4 ± 1.1
	Shoulder	3.1 ± 0.3	2.8 ± 0.5	2.7 ± 0.5	2.8 ± 0.2
	Furrow	2.8 ± 0.2	1.4 ± 0.2	3.2 ± 0.5	1.6 ± 0.3
MI	Ridge	4.8 ± 0.9	5.9 ± 0.8	5.3 ± 0.7	5.6 ± 0.8
	Shoulder	4.2 ± 0.8	3.2 ± 0.8	4.6 ± 0.8	3.2 ± 0.9
	Furrow	4.9 ± 0.8	2.3 ± 0.6	4.2 ± 0.8	1.5 ± 0.2

Table 1.18: Results of mixed-effects ANOVAs run in SAS PROC MIXED for PMN (mg kg soil^{-1} day^{-1}) data from Soil Sampling 2. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	0.26	0.65	6	0.09
Cover	0.05	0.83	0.04	0.86
Tillage **x** Cover	0.1	0.77	1.14	0.33
Position	1.91	0.17	19.95	< 0.0001
Tillage **x** Position	4.68	0.02	3.42	0.05
Cover **x** Position	0.35	0.71	0.72	0.50
Tillage **x** Cover **x** Position	0.06	0.94	0.78	0.47
Depth	36.98	< 0.0001	61.71	< 0.0001
Tillage **x** Depth	1.13	0.33	1.27	0.29
Cover **x** Depth	2.43	0.10	0.18	0.84
Tillage **x** Cover **x** Depth	2.28	0.11	1.83	0.17
Position **x** Depth	0.89	0.48	2.55	0.05
Tillage **x** Position **x** Depth	3.1	0.02	0.77	0.55
Cover **x** Position **x** Depth	1.62	0.18	0.05	0.99
Tillage **x** Cover **x** Position **x** Depth	0.46	0.77	1.2	0.32

Figures 1.11: Stacked bar graphs of average PMN (mg kg soil^{-1} day^{-1}) from Soil Sampling 3 at MI. Colored stacks represent average values of depth increments within each position of each experimental treatment. Error bars represent ± S.E. of PMN combined across depths.

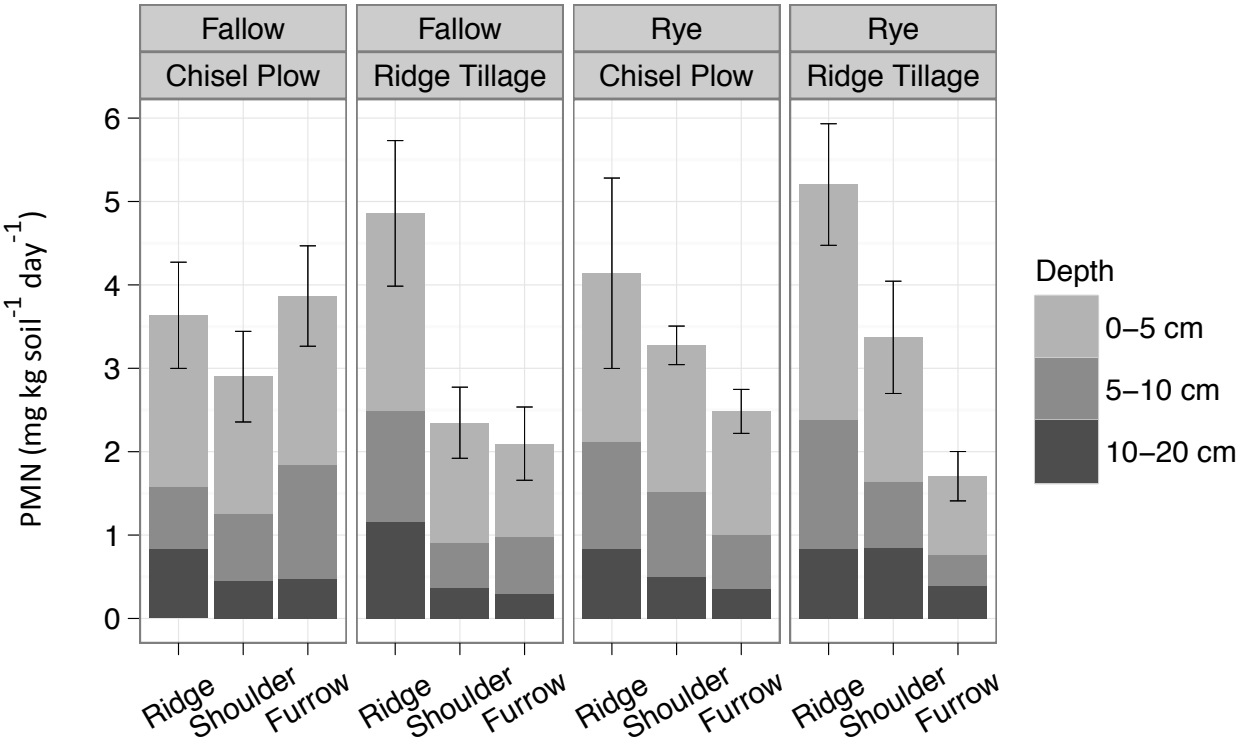


Table 1.19: Average PMN (mg kg soil^{-1} day^{-1}) ± S.E. combined across depths for Soil Sampling 3.

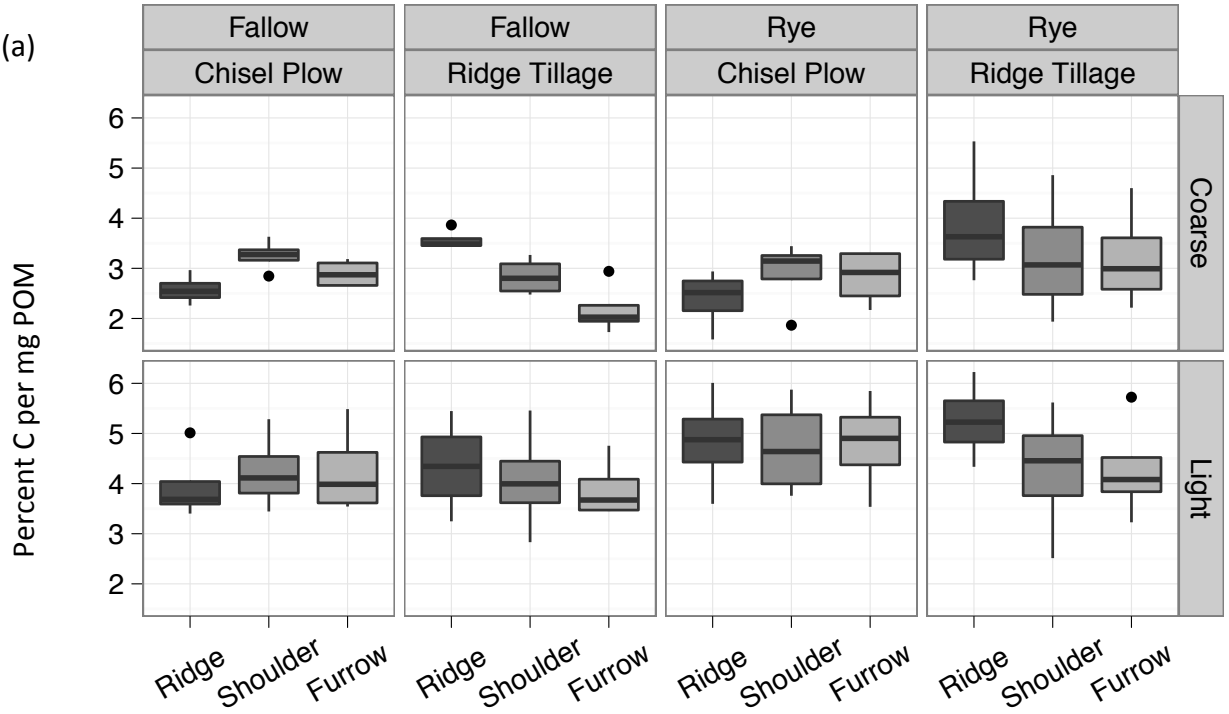
		CP-fallow	**CP-rye**	**RT-fallow**	**RT-rye**
MI	Ridge	3.6 ± 0.6	4.9 ± 0.9	4.1 ± 1.1	5.2 ± 0.7
	Shoulder	2.9 ± 0.5	2.3 ± 0.4	3.3 ± 0.2	3.4 ± 0.7
	Furrow	3.9 ± 0.6	2.1 ± 0.4	2.5 ± 0.3	1.7 ± 0.3

Table 1.20: Results of mixed-effects ANOVA run in SAS PROC MIXED for PMN (mg kg soil^{-1} day^{-1}) data from Soil Sampling 2. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

	MI	
Effect	F value	p
Tillage	0.42	0.57
Cover	0.11	0.75
Tillage **x** Cover	3.17	0.13
Position	5.94	0.01
Tillage **x** Position	1.1	0.35
Cover **x** Position	1.19	0.32
Tillage **x** Cover **x** Position	0.04	0.97
Depth	22.03	< 0.0001
Tillage **x** Depth	0.22	0.80
Cover **x** Depth	0.11	0.90
Tillage **x** Cover **x** Depth	0.36	0.70
Position **x** Depth	0.15	0.96
Tillage **x** Position **x** Depth	0.31	0.87
Cover **x** Position **x** Depth	0.45	0.77
Tillage **x** Cover **x** Position **x** Depth	0.27	0.90

Figures 1.12.a and 1.12.b: Boxplots of percent mg C per mg POM of both light (53-230 µm) and coarse (230-2000 µm) POM from 0-5 cm depth increment of Soil Sampling 2 at (a) IL and (b) MI.

(a)



(b)

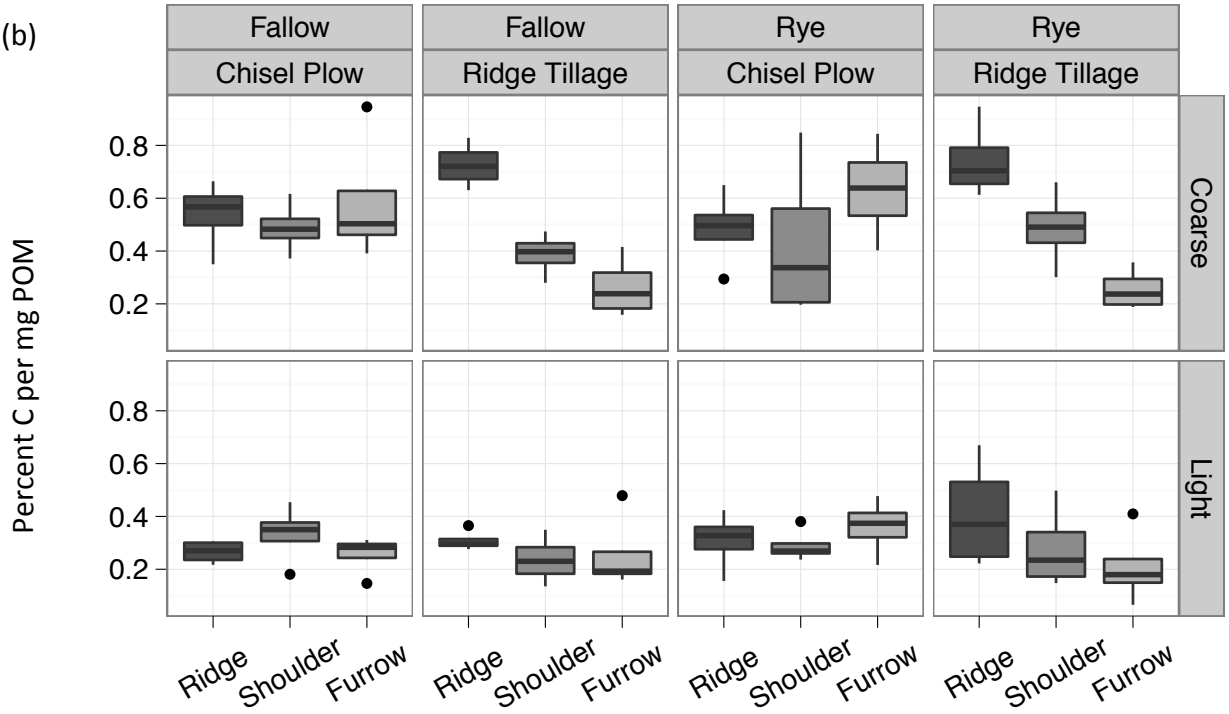


Table 1.21.a and Table 1.21.b: Results of mixed-effects ANOVAs run in SAS PROC MIXED for POM-C (%) data from (a) light (53-230 µm) fraction POM and (b) coarse (230-2000 µm) fraction POM from 0-5 cm depth increment of Soil Sampling 2. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

(a)

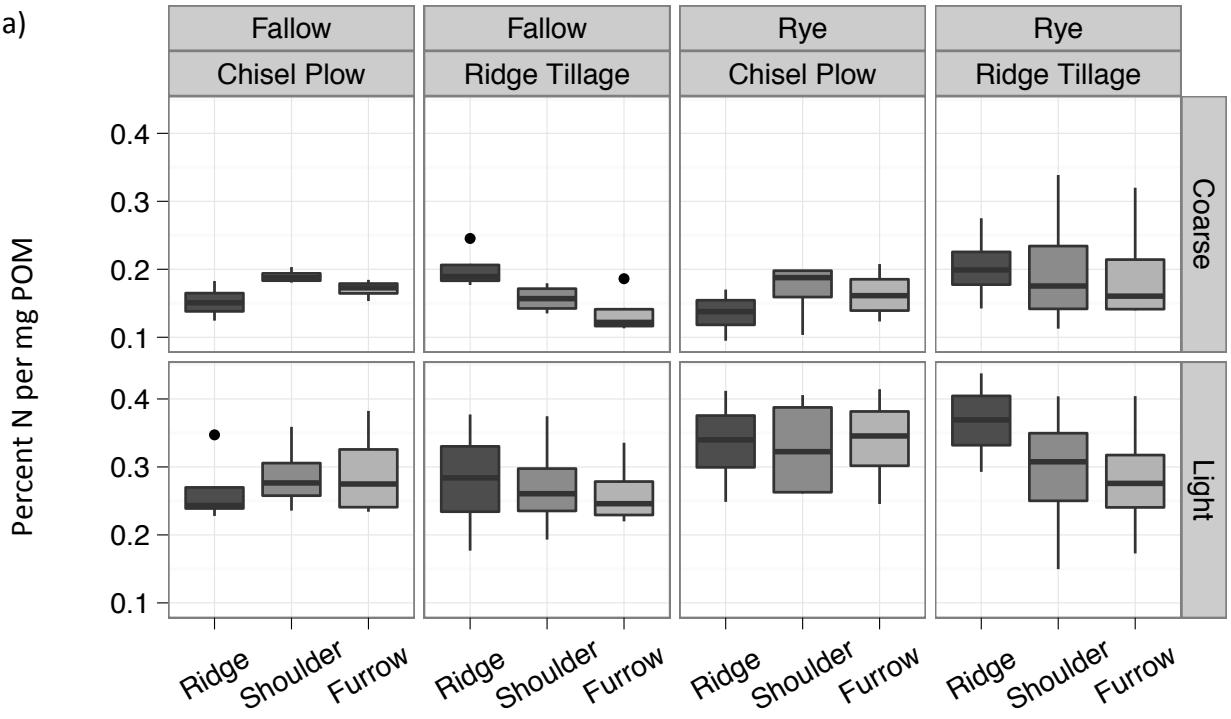
	IL		**MI**	
Effect	F value	p	F value	p
Tillage	0.28	0.63	0.16	0.71
Cover	10.92	0.02	0.68	0.44
Tillage **x** Cover	0.18	0.69	0	0.97
Position	1.81	0.19	1.89	0.17
Tillage **x** Position	3.56	0.04	4.02	0.03
Cover **x** Position	1.46	0.25	0.86	0.43
Tillage **x** Cover **x** Position	0.1	0.90	2.74	0.08

(b)

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	3.27	0.17	0.54	0.52
Cover	0.97	0.36	0.02	0.89
Tillage **x** Cover	4.24	0.09	0.35	0.57
Position	1.81	0.18	9.62	0.0009
Tillage **x** Position	8.76	0.001	18.03	< 0.0001
Cover **x** Position	0.9	0.42	0.1	0.90
Tillage **x** Cover **x** Position	0.3	0.74	0.61	0.55

Figures 1.13.a and 1.13.b: Boxplots of percent mg N per mg POM of both light (53-230 µm) and coarse (230-2000 µm) POM from 0-5 cm depth increment of Soil Sampling 2 at (a) IL and (b) MI.

(a)



(b)

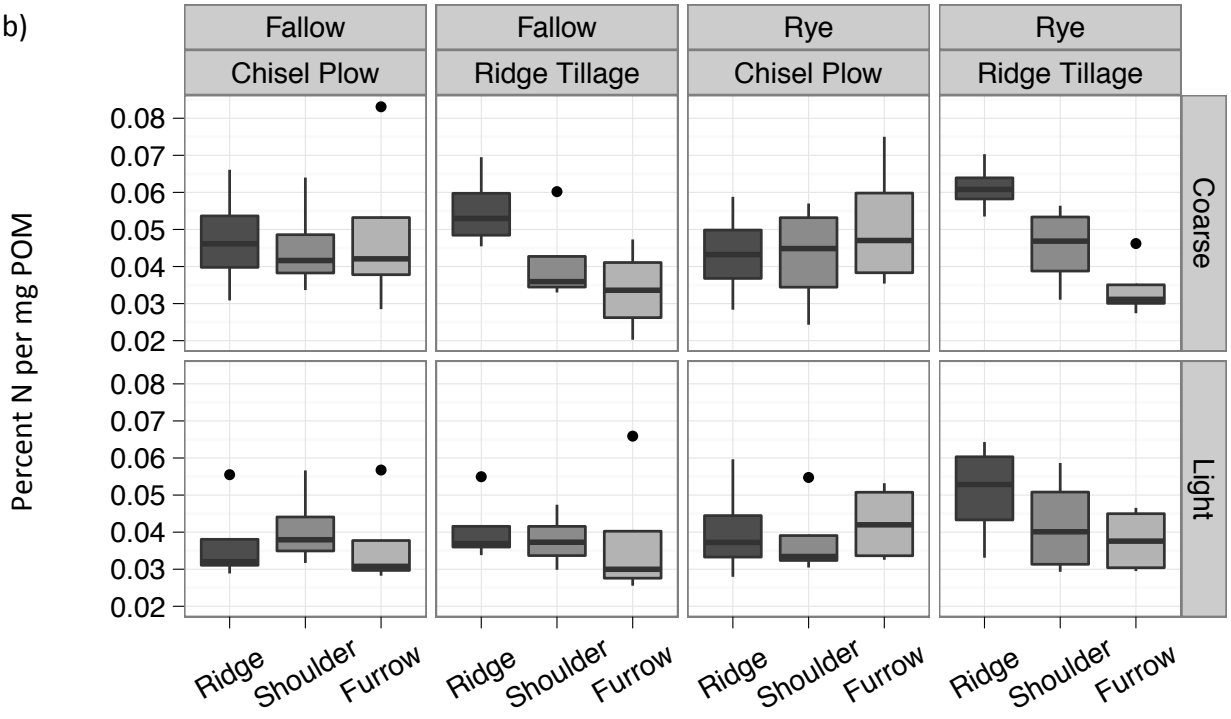


Table 1.22.a and Table 1.22.b: Results of mixed-effects ANOVAs run in SAS PROC MIXED for POM-N (%) data from (a) light (53-230 µm) fraction POM and (b) coarse (230-2000 µm) fraction POM from 0-5 cm depth increment of Soil Sampling 2. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 1.3.7.

(a)

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	0.54	0.52	0.59	0.50
Cover	10.41	0.02	1.94	0.21
Tillage **x** Cover	0.12	0.75	0.3	0.60
Position	1.06	0.36	1.87	0.18
Tillage **x** Position	2.89	0.07	2.79	0.08
Cover **x** Position	1.76	0.19	1.39	0.27
Tillage **x** Cover **x** Position	0.34	0.72	1.89	0.17

(b)

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	1.54	0.30	0.08	0.80
Cover	0.67	0.44	0.16	0.70
Tillage **x** Cover	4.03	0.09	0.89	0.38
Position	0.59	0.56	12.19	0.0002
Tillage **x** Position	4.23	0.03	23.11	< 0.0001
Cover **x** Position	0.96	0.40	0.01	0.99
Tillage **x** Cover **x** Position	0.59	0.56	1.02	0.38

CHAPTER TWO

Spatial and temporal dynamics of nitrogen (N) availability in ridge tillage systems and effects on plant N uptake

Abstract**:**

Management of agricultural soils by ridge tillage (RT) leads to differentiation of ridge and furrow zones in soil physical characteristics (Liebig 1993), while its reduction of soil disturbance leads to increased aggregation (Zhang et al. 2012) and soil water retention capacity (Zibilske and Bradford 2007). In addition, RT's alteration of the three-dimensional structure of soil in the row/inter-row space changes how water infiltrates the soil as water preferentially flows to the furrow space (Chen et al. 2011) and the ridge remains drier and warmer (Stone et al. 1980). This alteration of soil moisture and temperature patterns relative to more conventional tillage systems could have significant implications for spatial N mineralization patterns, as mineralization is a process that is strongly affected by temperature and moisture conditions (Zak et al. 1999).

To test how RT may alter patterns of N mineralization spatially, we used ion exchange membranes to continuously sample soil inorganic N in situ throughout the 2012 growing season in a tillage study at Mason, Michigan (MI) that included chisel plow (CP) and ridge tillage treatments both with and without rye winter cover crops and planted to corn (Zea mays). To better characterize spatial differences across the row/inter-row space, we used a sampling design with a fine spatial resolution. In addition, to monitor how tillage treatments may affect plant N uptake and performance we sampled plants at both the MI site and a fully replicated site in Urbana, IL to quantify yield and %N on a variety of plant tissue fractions. Higher

cumulative adsorption of NO_3 was seen in RT treatments in the ion strip experiment at MI, as well as higher rates of NO_3 adsorption across the row/inter-row space following re-ridging. Similarly, soil gravimetric water content was found to be higher in the shoulder and furrow positions of RT treatments relative to CP treatments during the latter part of the growing season. Plant tissue and yield assessments were consistent with these results as both total tissue %N and grain %N were higher in RT treatments at both sites, as well as per plant yield. Overall, results indicated that spatial patterns of N mineralization are distinct in RT from CP systems and that these distinctions may improve plant performance.

2.1. Introduction:

While Chapter 1 illustrates that RT systems have the potential to improve fertility within the row/ridge space by increasing PMN and POM-N, soil sampling methods do not necessarily provide an accurate account of how much N is available to plants in the field. Processing of samples can destroy soil aggregates, exposing physically protected SOM, stimulating microbial metabolism, and inflating estimates of soil N. Additionally, the method we employed to evaluate PMN is one that estimates the entire pool through a saturated, high temperature incubation – conditions highly amenable to N turnover that are unlikely to be met in the field. In other words, though soil sampling and laboratory extractions/incubations are insightful, they do not necessarily reflect processes that make N available to plants in the field.

Nitrogen availability and subsequent plant uptake are strongly influenced by soil physical conditions that can dictate both the rate of turnover and the capacity of roots to absorb N. Zak et al. (1999) and Cassman and Munns (1980) found that simple first order kinetics

explain rates of N mineralization in soils as mineralization rates are positively correlated with increasing temperatures. Earlier work by Miller and Johnson (1964) and Stanford and Epstein (1974) showed similar correlations with soil moisture content. Conversely, dry conditions can limit the activity of nitrifying bacteria by reducing substrate uptake (Stark and Firestone 1995), and under extremely dry conditions, cell death can occur (Griffin 1981). Even if N is available in soil, plant uptake is not necessarily occurring. Soil physical conditions such as compaction and the location of soil water can constrain or redirect root growth, limiting where roots are able to scavenge for N (Krishna 2013). As soil physical conditions change throughout the season, effective in situ N availability changes and may differ greatly from estimates of the size of different N pools made in vitro from soil samples. Since RT strongly modifies the soil physical environment, possible effects on soil N turnover and plant uptake are particularly interesting.

Zibilske and Bradford (2007) found that the water holding capacity of RT soils overall was significantly greater than that of soils under conventional tillage. This result is likely due to the increased aggregation and bulk density in the inter-row space of RT systems (Liebig 1993 and 1995). Beyond higher water holding capacity, RT has unique impacts on soil moisture and temperature gradients given how it changes the three-dimensional structure of the row/inter-row space, increasing the surface area to volume ratio of soil in the crop row. In a container study, Chen et al. (2011) demonstrated that in RT systems water flows primarily to the furrow space, where it drains slowly through the profile while capillary action draws moisture up from the furrow into the ridge. Similar patterns were observed by Jaynes and Swan (1999) and Müller et al. (2009). This unique effect on soil moisture movement makes the furrow into a soil

moisture reservoir, while the ridge remains drier and warmer. In fact this was one of the most touted benefits of RT when it was more widely used in the 1980's (Stone et al. 1990).

Given this evidence, it's possible that patterns of N availability and turnover will differ greatly between RT and more conventional systems if measured in situ. So, to complement soil sampling methods and gain a more accurate sense of nitrogen availability at different spatial locations over the course of the entire season, we used the ion exchange resin method described in Qian and Schoneau (1995 and 2002). Ion exchange resins are an in situ sampling method in which strips of an organic polymer are buried in soil for days to months to adsorb ions from soil solution. This process of adsorption simulates the action of roots, meaning the ion strips arguably sample only the N that is available to plants over the period of their deployment. In addition to ion strips, we took a number of plant measurements to understand plant responses to treatments, as well as soil moisture measurements to understand how RT modifies soil physical characteristics as compared to CP.

We hypothesized that turnover in RT systems would be higher at the ridge/row position since residues were being concentrated there, and that the disturbance caused by re-ridging would result in higher N turnover rates. We additionally hypothesized that in response to higher N turnover, plant measures of N would increase, especially following re-ridging. Finally, based on previous literature that has demonstrated similar results, we hypothesized that RT would create dynamic gradients in soil moisture across the row/inter-row space.

2.2. Objectives:

1.) Measure N turnover at several depth-positions via resin strips continuously throughout the growing season.

2.) Quantify plant response to N availability in soil.

3.) Measure soil moisture and temperature at several depth-positions via resin strips continuously throughout the growing season.

2.3. Methods:

2.3.1. Ion exchange resins:

Ion exchange resins are a sampling method in which strips of an organic polymer are buried in soil for days to months to absorb ions from soil solution. We utilized 2.5 x 5 cm strips cut from sheets of anion-absorbing and cation-abosorbing resins. Ion exchange resin strips were buried in the same three horizontal positions as soil samples, ridge, shoulder, and furrow, but only in two depth increments: 0-5 and 5-10 cm. Ziadi et al. (2011) demonstrated that concentrations of inorganic nitrogen can vary greatly across small spatial scales. To account for this variation, we deployed three sets of strips in each plot. Each set consisted of one anion strip and one cation strip at each position (ridge, shoulder, furrow) for both depth increments. Sets were randomly located within the plot and were never placed in the exact same location as the prior set in order to avoid artificially high inorganic N concentrations due to soil disturbance.

Sets were buried for three week periods beginning May 24 2012, seven days after planting, and ending September 24 2012, seven days before harvest (Table 2.2). At the end of each three week period, all sets were removed from the soil and replaced with recently charged resin strips. At each removal date, anion and cation strips from each depth-position of all three sets in a plot were combined in a 100 mL Nalgene tube with distilled water to remove any adhering soil. Strips were then transferred into a clean 100 mL tube with 100 mL 2M KCl

and shaken on a reciprocating shaker at 120 RPM for 1 h to extract the absorbed NH_4 and NO_3. About 15 mL of extractant of each sample was then transferred into a scintillation vial, labeled, frozen, and stored at 0 C until analysis. NH_4 and NO_3 concentrations were determined using the same 96 well plate method as soil samples. By dividing the total amount adsorbed throughout deployment by the period of time deployed, an adsorption rate is estimated that could be considered a proxy for N turnover. If strips are deployed continuously throughout the season, total accumulated N can be calculated and used as a proxy for whole-season N turnover.

2.3.2. SPAD:

To quantify plant N uptake throughout the season, we measured chlorophyll content of corn plants in 0N subplots at stages V6, V12, VT, and R2 using a SPAD meter. Although SPAD units cannot be directly converted into units of N uptake, SPAD is often used as a cheap, non-destructive proxy for plant health and N uptake (Schepers et al. 1992). At each measurement point, a SPAD reading was taken on the most recently emerged leaf of 40 different plants in the 0N subplot of each plot. At MI, all values were recorded on the meter's computer then averaged by the meter's computer, while at IL all values were recorded by hand directly from the meter and averaged later. For consistency, only the plot-wide average of all 40 measurements and standard errors across treatments are reported here. Since plant emergence times and rate of development were variable across treatments and plots, plant growth stage is an approximation of all plants in the plot. At MI, early season differences in plant growth stage between RT and CP treatments were pronounced enough that we chose to

take the V6 measurements of RT and CP plots on separate dates to ensure measurements were taken at a similar point in phenology.

2.3.3. Biomass, yield, and tissue C:N :

To quantify whole season plant N uptake and partitioning, we measured C and N content of different plant fractions on corn plants harvested at reproductive stage R6 in zero fertilizer plots. In each plot 6 plants were randomly selected, harvested, and separated into three fractions: grain, reproductive tissues (cob, silks, husk), and vegetative tissues (stem, leaves, tassel, spike). Fractions from all 6 plants were then combined, processed (i.e. vegetative tissue run through plant shredder, etc.), and weighed. Each of these samples was then dried in a forced air oven at 60 C for 7 days. Once dried, each sample was reweighed to quantify the biomass of each fraction and further processed to pass through a 1 mm sieve. Tissue C and N concentrations were then determined by dry combustion of the samples, using a Carlo-Erba NA 1500 CNS (Carlo-Erba, Milan, Italy). Yield was quantified by calculating mass (g) grain per plant and multiplying that number by plant population estimates (# plants/ha) for each plot. In zero feritlizer plots, grain (g) per plant was calculated by dividing the mass (g) of the grain fraction collected for R6 C:N analysis by the number of plants collected.

2.3.4. Gravimetric water content:

Gravimetric Water Content (GWC) was determined on all soil samples taken as described in section 1.3.3 by weighing 20 g ± 1 g soil into tins, drying the samples in a forced air oven at 60 C for several days, and reweighing dry samples. Dry mass of samples (g) was then subtracted from the wet mass (g) to determine the mass of water in samples, which was then divided by the dry mass to calculate a percent value.

2.3.5. Data analysis:

For analysis, data were again treated as having one main plot factor, tillage, and three split plot factors, cover, position, and depth. Although position and depth cannot be considered as treatments, we chose to analyze them as fixed, split-plot factors since we were specifically interested in their possible effects on data, particularly the effects of position.

Ion resin strips produced two types of data for analysis, cumulative N adsorption and N adsorption rates for each sampling period. Cumulative adsorption data were analyzed using a mixed effects, split-plot model ANOVA in SAS PROC MIXED that included tillage, cover, position, and depth as fixed factors. Adsorption rate data were analyzed using a similar model in a repeated measures ANOVA in which sampling period was the repeated factor.

Since plant N response data were taken over two sites, an analysis procedure similar to that of Chapter 1 was employed. In an initial analysis, data from both sites were combined and analyzed in a mixed effects model ANOVA with site as a fixed factor, as well as tillage and cover, to determine if site had a significant effect ($\alpha = 0.05$) on results. If site had a significant effect, or a significant interaction with a treatment effect of interest, data from either site was separated and re-analyzed with just tillage and cover as fixed effects. If site did not have a significant effect or interaction with a treatment effect of interest, it was changed to a random factor while tillage and cover remained fixed. Finally, soil GWC data were analyzed separately by site with tillage, cover, position, and depth as fixed factors.

2.4. Results:

2.4.1. 2012 weather:

As detailed in Ch. 1, 2012 was an exceptionally hot and dry year at both the IL and MI site. Unusually high temperatures combined with little precipitation (Table 1.3) led to drought conditions that left soils at both sites dry and warm through the months of June and July (Figs. 1.1 and 1.2). Periodic rains recharged soil water at MI, but given the site's sandy soils, effects of those rains were short-lived. At IL, only two rain events occurred from mid-June through July, but the effect of these rain events was more prolonged given the site's high clay and organic matter content.

2.4.2. Ion resin strips nitrate:

Analysis revealed an effect of tillage ($p = 0.01$) and a marginally significant interaction effect of tillage **x** position ($p = 0.07$, Table 2.4) on end-of-season accumulated NO_3. Total accumulated NO_3 was highest in the RT-fallow treatment at 1034 ± 57.2 μg cm^{-2} soil, followed by RT-rye (979.7 ± 17.37), then CP-fallow (693.2 ± 57.2), and then CP-rye (594.2 ± 45.4). Mean cumulative NO_3 was also higher in RT treatments than in corresponding CP treatments at all three positions at both depths (Table 2.3, Fig. 2.1). Rates of NO_3 adsorption increased gradually over the beginning of the growing season and were highest at all positions in all treatments during Sampling 3 (July 5 – July 23), the sampling period immediately following re-ridging (Fig. 2.2). During Sampling 3, adsorption rates were higher at all depth-positions in RT treatments than in corresponding CP treatments, particularly at the ridge position. After Sampling 3, adsorption declined gradually for the rest of the season in all treatments, but declines were slower in RT treatments than in CP treatments (Fig. 2.2). Repeated measures ANOVA indicated

there was an interaction effect of tillage and position on nitrate adsorption rates ($p = 0.03$, Table 2.5).

2.4.3. Ion resin strips ammonium:

Cumulative NH_4 adsorption summed across all six depth-positions was highest in the CP-fallow treatment at 29.4 ± 8.1 μg cm^{-2} soil, followed by CP-rye (27.6 ± 10.2), then RT-fallow (26.1 ± 2.3), and then RT-rye (23.6 ± 1.4). Differences were small, and statistical analysis revealed there were no effects of tillage or interaction effects with tillage on cumulative NH_4 adsorption (Table 2.7). Repeated measures ANOVA indicated a significant interaction effect of tillage and position on NH_4 adsorption rates ($p = 0.04$, Table 2.8), but unlike NO_3 adsorption rates, they did not exhibit a clear pattern of increase or decrease and varied greatly with sampling (Table 2.4).

2.4.4. SPAD:

Patterns in SPAD readings were site-specific. At IL, the directionality of changes in SPAD between growth stages was similar for all four treatments, as average readings peaked at V12 between 46 – 50 SPAD units, but declined by R2 to a range of 30.6 – 35.5 (Table 2.9, Fig. 2.5). Repeated measures ANOVA indicated an interaction effect of tillage **x** cover ($p = 0.05$) and a strong main effect of cover ($p < 0.0001$, Table 2.10). At MI, there were main effects of tillage ($p = 0.004$) and cover ($p = 0.01$) on SPAD (Table 2.10). SPAD averages of both CP treatments dropped between V6 and V12, stabilizing between 36.8 – 38.9 SPAD units for the remainder of the season. RT treatment averages started out lower than CP treatments at V6, but increased during the season to stabilize between 39.7 – 42.3 SPAD units (Fig. 2.5, Table 2.9). Additionally,

at MI, fallow treatments generally had higher SPAD readings than rye treatments for both types of tillage (Table 2.9).

2.4.5. Yield and biomass:

A combined analysis of both sites indicated that there were no significant treatment effects on no-fertilizer yields measured on an areal basis (Table 2.12). Average RT yields at IL were higher than CP treatments, but high variability negated an effect, while yields at MI were relatively consistent (Fig. 2.6, Table 2.11). However, the same analysis when applied to yield on a per plant basis (g grain plant^{-1}) indicated marginally significant effect of tillage ($p = 0.07$, Table 2.14). RT-rye had the highest per plant yield, with 86.8 ± 12.4 and 78.7 ± 10.7 g grain plant^{-1} at IL and MI, respectively. At IL, CP-fallow was the lowest at 67.2 ± 11.8 g grain plant^{-1}, and at MI, CP-rye was the lowest at 68.2 ± 7.0 g grain plant^{-1}. Patterns for total plant biomass in the zero fertilizer subplots differed by site, so analyses were separated. Biomass data were similar to yield per hectare for IL with mean total plant biomass being higher in RT treatments than in corresponding CP treatments (Fig. 2.8, Table 2.15), but no significant treatment effects were found (Table 2.16). At MI, CP-fallow had the highest total plant biomass at 109.6 ± 8.7 g plant^{-1}, RT-rye had the lowest at 68.7 ± 9.0 g plant^{-1}, and CP-rye and RT-fallow were similar at 86.7 ± 7.3 and 86.3 ± 5.8 g plant^{-1}, respectively. Analysis indicated that at MI there was an effect of cover ($p=0.04$) on plant biomass and a marginal effect of tillage ($p=0.08$).

2.4.6. Tissue N:

There were no treatment effects on either stover or cob tissue %N at either site, but a combined analysis of data from both sites found there was a marginally significant effect of tillage on total tissue %N ($p = 0.09$, Table 2.18) and a strong effect of tillage on grain %N ($p = 0.02$, Table 2.20). At IL, RT plants (RT-fallow = 0.7 ± 0.05 %; RT-rye = 0.8 ± 0.02 %) had higher total tissue N concentrations than CP plants in corresponding treatments (CP-fallow = 0.8 ± 0.03 %; CP-rye = 0.7 ± 0.04 %). At MI, concentrations were higher in both RT treatments than in CP treatments with the highest concentration in RT-rye plants (1.0 ± 0.09 %) and the lowest in CP-fallow treatments (0.9 ± 0.03 %, Fig. 2.8, Table 2.16). For grain tissue %N, both RT treatments were higher than either CP treatment at both IL and MI (Fig. 2.9, Table 2.18).

2.4.7. Gravimetric water content:

Across all samplings and treatments, Gravimetric water content (GWC) was higher at IL than MI, generally falling between 0.2 to 0.3 g H_2O g soil^{-1}, while at MI the highest GWC recorded was 0.14 g H_2O g soil^{-1} and the lowest was just 0.01 g H_2O g soil^{-1}. GWC values measured at Soil Sampling 1 were consistent across tillage and cover treatments within both sites (Fig. 2.11). Both sites, however, exhibited significant tillage **x** position interaction effects for Soil Sampling 1 (Table 2.21). At IL, this effect is likely due to higher GWC values in the furrow than in ridge and shoulder positions in the RT-rye treatment (Fig. 2.11a), while at MI it is likely explained by higher values in the shoulder position than in other positions of the CP-fallow treatment. By Soil Sampling 2, GWC had dropped significantly at MI in all treatments (Fig. 2.12b), especially at surface depths where all values were below 0.08 g H_2O g soil^{-1}, while at IL GWC remained in the same range as Soil Sampling 1 (Fig. 2.12a). Separate analyses indicated

tillage **x** position effects at both sites (Table 2.22), but these effects were characterized differently at either site. At IL, the effect seems primarily due to higher GWC at the ridge position than shoulder and furrow positions within CP treatments, whereas in MI the pattern is explained by higher GWC in the furrow and shoulder positions than in the ridge position within RT treatments (Fig. 2.11). GWC values remained in the same range at Soil Sampling 3 as in Soil Sampling 2 (Fig. 2.13), as did patterns of distribution and statistical effects (2.23).

2.5. Discussion:

The 2012 growing season was unusually hot and dry during the months of June and July, leading to extremely low soil moisture levels at both sites (Fig. 1.1). Given these field conditions and the strong positive correlation between temperature, moisture, and N mineralization rates (Zak et al. 1999), spatial and temporal patterns of N turnover examined here were likely affected by differences in the distribution of soil moisture and retention capacity of different tillage treatments.

Overall this study highlighted the dynamic and spatially structured nature of soil inorganic N distribution across the row/inter-row space in field corn, particularly in RT systems. NO_3 adsorption by ion resin strips was generally lower at the ridge position than shoulder or furrow positions for all treatments at both depths. This trend is likely explained by greater competition by plant roots for soluble N, meaning a smaller inorganic N pool, that was reflected by lower NO_3 adsorption by resin strips. The increase in NO_3 adsorption in all treatments from Sampling 2 to Sampling 3 is likely explained by an increase in soil growing degree days as temperatures rose, resulting in a release of immobilized N from residues. However, adsorption

was higher in RT treatments at all sample positions of both depths for Sampling 3, and there was a strong statistical effect of tillage. The increase at the ridge position also corresponds to the higher levels of PMN and POM-N at the ridge position highlighted in Chapter 1, indicating that relocation of residues resulted in higher nitrate turnover there. While continued turnover of relocated residues and higher levels of PMN may explain higher levels of NO_3 adsorption at the ridge position, it is interesting that despite lower levels of PMN than in CP treatments, as noted in Chapter 1, the shoulder and furrow positions still had higher NO_3 adsorption in RT treatments.

NH_4 adsorption by ion strips followed a few of the same important patterns as NO_3 strips. In particular, adsorption increased between Samplings 2 and 3 at all positions as soil growing degree days increased and residues began to be mineralized. Otherwise, patterns of NH_4 adsorption by ion strips were more erratic and had much higher error than NO_3 strips. Statistical results indicate an interaction effect of tillage and position, with adsorption at the ridge position in CP being higher at a few points throughout the season, particularly at the 5-10 cm depth in CP treatments at Sampling 4, and at the 0-5 cm depth in CP treatments at Sampling 5. Interestingly, these peaks in NH_4 adsorption also correspond with lower levels of NO_3 adsorption. A high ratio of NH_4 to NO_3 could be indicative of poor conditions for nitrification as N accumulates in the form of NH_4 because it is too dry for nitrifying bacteria to function. The large differences in cumulative adsorption between NO_3 and NH_4 strips are not unsurprising as

NO_3 is generally the larger, more available pool. Treatment effects are then more visible in the NO_3 data, suggesting that N was overall more available in RT treatments. Alternatively, higher N adsorption may also suggest that ion strips in RT treatments had to compete less with plant roots for available N, implying that N uptake was lower in RT plants. However, that explanation is contradicted by results from the various plant measures, which are consistent with higher N uptake in RT plants compared to CP plants.

Corn nitrogen uptake was higher in RT than in CP at both sites, as indicated by both higher SPAD readings and plant tissue N concentration at MI and higher tissue N concentrations at IL. At MI, the significant effect of tillage on SPAD and higher readings in RT treatments following re-ridging may be due to a crop response to higher N concentrations. Chlorophyll content is closely related to N concentration in leaves (Schepers et al. 1992, Alberte et al. 1977). By increasing NO_3 turnover, RT may have been able to increase photosynthetic activity at the MI site. At the IL site, tillage had no effect on SPAD readings despite RT being associated with altered N pools as discussed in Ch. 1. However, higher total tissue N and grain N concentrations in RT plants than CP plants of corresponding cover treatments at IL, as well as MI, indicated higher N uptake in RT plants as compared to CP plants. Higher cumulative NO_3 levels in the ion strip study suggest that this result could be primarily explained by greater availability of N to plants in RT treatments at least at the MI site where ion strips were deployed.

Although tillage did not have a significant effect on yield measured on an areal basis (Mg ha^{-1}), if yield is evaluated on a per plant basis (g $plant^{-1}$), RT elicited a yield advantage that may

be explained by higher levels of N uptake. Maintaining the correct plant density is crucial to achieving yield goals in agronomic crops like corn, and even minor differences in population numbers can result in significantly reduced yields. End-of-season plant populations were higher in CP treatments at MI, while at IL there were no differences between treatments. Lower populations likely explain the yield gap in zero fertilizer plots at MI. However, developing a sufficient number of ovules and ensuring they develop into kernels is also important in achieving yields. The number of kernels developed per ear depends strongly on having sufficient soil moisture and nutrients in stages V12 to R2 (Otegui and Slafer 2000). By maintaining higher soil moisture levels and sustaining NO_3 turnover until late in the season, RT may have contributed to greater kernel development and grain-filling, and therefore higher per plant yields.

Overall, results are consistent with increased soil N availability in RT especially late in the growing season, which supplied N for plant uptake. This is shown clearly at the MI site, and there is some evidence for it at the IL site. This supports the hypothesis that RT can improve temporal N synchrony, although not early in the growing season as hypothesized. Higher N availability in the ridge position is consistent with the increase in POM-N and PMN at Samplings 2 and 3 observed in Chapter 1, suggesting an improvement in spatial N synchrony by concentrating high-N residues around the root ball. However, higher N availability in the shoulder and furrow positions as measured by ion strip adsorption contradicts the high levels of PMN and POM-N measured at those positions in Ch. 1. Differences in these measurements suggest that field conditions somehow limited N turnover or availability in CP treatments relative to RT.

One explanation for patterns in NO_3 and NH4 adsorption results may lie in patterns of soil moisture and temperature. The 2012 growing season was exceptionally hot and dry across the American Midwest. At MI, total precipitation from June to August was 9.4 cm below thirty-year averages, and mean daily maximum temperatures above historical averages from May to September. Lack of rainfall and high temperatures led to drought conditions at the MI field site, especially during crop establishment and the earlier stages of exponential growth. However, under drought conditions in Soil Sampling 2 and Soil Sampling 3 there was a significant effect of tillage on soil moisture with RT having higher moisture levels than CP, particularly at the furrow and shoulder positions. These patterns are consistent with studies that have demonstrated that by reducing disturbance, RT systems tend to be moisture conservative, creating moisture sinks in the furrow space (Chen et al. 2011, Zibilske and Bradford 2007). By protecting soil moisture in the shoulder and furrow spaces, RT systems may have ensured that nitrogen cycling continued to occur in those positions in periods of drought, whereas it was inhibited in CP systems with the uniform loss of moisture in surface soils. This argument implies that results are specific to the 2012 growing season, but even so they are informative since they may imply better N performance of RT systems in drought years.

Additionally the re-ridging process, which was conducted just before ion strip Sampling 3, destroys aggregates, exposing protected soil organic matter (SOM) for turnover (Kristensen et al. 2000). Since no such cultivation occurs in CP systems, a similar release of physically protected SOM-N would not have occurred. However, sieving soils in the lab may simulate this process, inflating estimates of what may truly be available in the field. In other words, despite

the fact that the PMN may have been higher in those positions in CP treatments, that PMN remained protected in the field in CP treatments, while in RT treatments it was exposed.

Improvements in N availability in RT systems compared to CP systems may be specific to the 2012 season, since RT conferred a soil moisture advantage in what was a very hot and dry year. More long-term research across seasons could reveal if similar improvements in N availability occur in years with more normal weather. Nonetheless, these results are still interesting given that they indicate the possibility that RT might mitigate problems of reduced SOM turnover and N mineralization in exceptionally dry years. Additionally, the concentration of available N to the in-row space, which appeared to improve plant N status and uptake, supports the hypothesis that improvements in spatial N synchrony and the creation of zones can impact plant performance. These results could be important to growers interested in displacing or replacing fertilizer N in operations on more marginal soils that are perhaps dryer or lack the baseline SOM resources to provide ample quantities of mineralizable N to crops.

2.6. Conclusions:

1.) RT improved overall N availability and plant N uptake, especially in the late season following re-ridging. This pattern was marked at the MI site where soil organic matter levels were low.

2.) High levels of NO_3 adsorption in the shoulder and furrow positions was not consistent with the PMN data described in Ch. 1. This contradiction is most likely explained by high moisture levels in the shoulder and furrow positions in what was a droughty year, as well as high levels of disturbance in the field from the re-ridging operation.

Table 2.1: Management tables for IL and MI sites in the 2012 growing season, including dates of field management and soil sampling events. (* Since spring conditions are generally wet at the IL, these tillage operations are performed the preceding fall before cover crops are planted).

	Date completed	
Event	**IL**	**MI**
Cover crop terminated	April 5	April 27
Chisel plow	September 22, 2011 *	May 11
Ridge slicing	September 22, 2011 *	May 11
Soil finishing	April 5	May 17
Planting	April 12	May 17
Soil Sampling 1	April 27	May 29
Re-ridging	May 30	July 3
Soil Sampling 2	June 1	July 10
Soil Sampling 3	N/A	August 6
Harvest	September 18	October 3

Table 2.2: Dates of ion strip sampling periods. Ion strips were deployed in the MI field site for periods of about 21 days throughout the growing season. Refer to Table 2.1 for corresponding field management events.

Sampling period #	**Dates**
1	May 24 – June 13
2	June 13 – July 2
3	July 5 – July 23
4	July 23 – August 13
5	August 14 – September 5
6	September 5 – September 24

Fig. 2.1: Mean NO_3 (µg cm^{-2}) accumulated on ion strips throughout the season at MI. Values across sampling periods are additive, and error bars at each sampling point represent ± S.E. Line type represents position in the row/inter-row space.

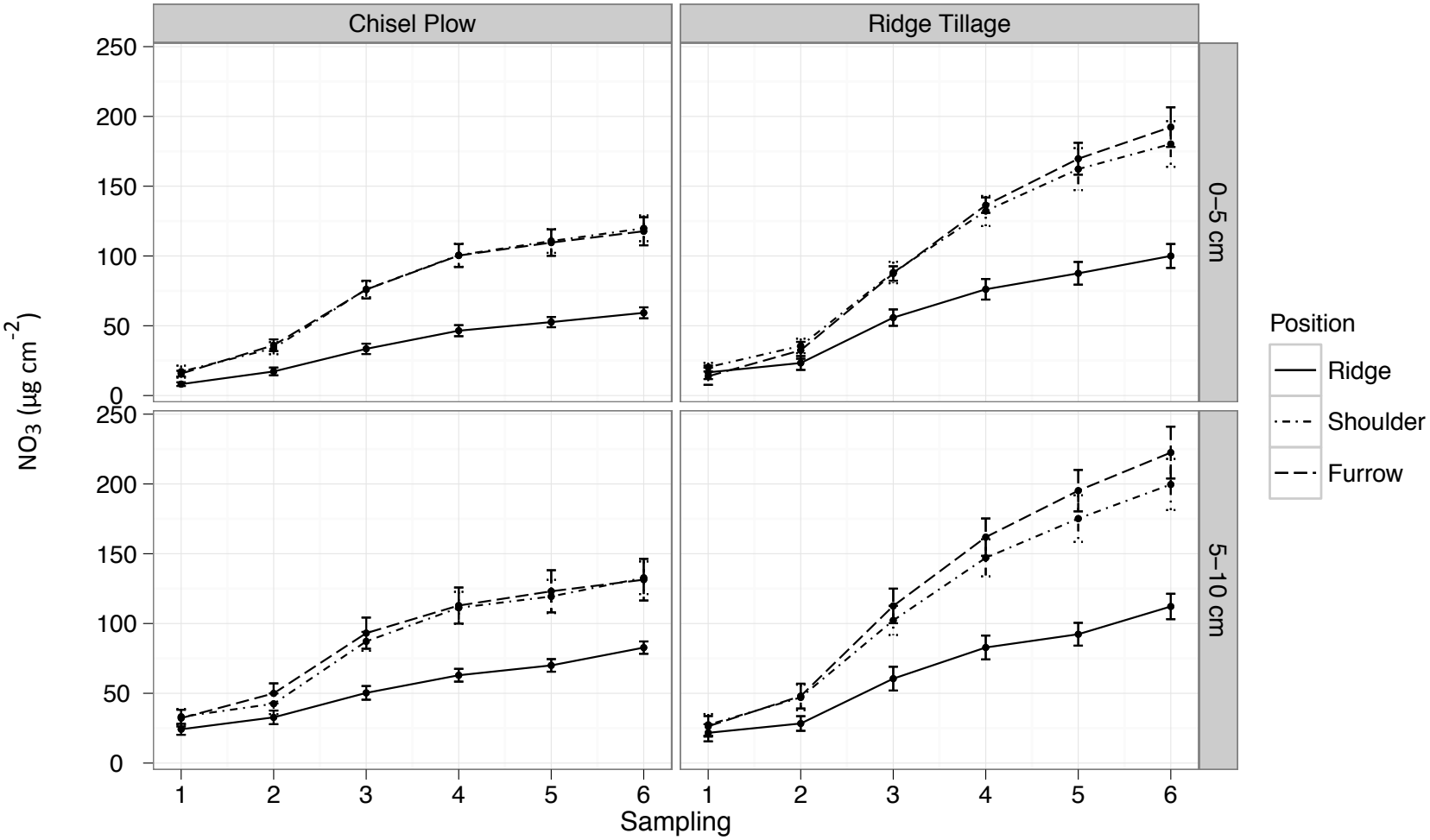


Table 2.3: End-of-season cumulative NO_3 (µg cm^{-2} soil) from ion strips at MI. Values represent the total amount of NO_3 accumulated ± S.E.

		CP-fallow	**CP-rye**	**RT-fallow**	**RT-rye**
0-5 cm	Ridge	63.8 ± 6.4	54.7 ± 4.2	101.1 ± 17.4	98.9 ± 6.1
	Shoulder	138.7 ± 8.1	100.9 ± 9.4	176.1 ± 34.1	184.4 ± 8.8
	Furrow	117.9 ± 14.5	117.5 ± 16.2	204.1 ± 23.8	180.6 ± 16.8
5-10 cm	Ridge	87.8 ± 4.6	77.7 ± 7.3	128.5 ± 5.8	95.9 ± 13.3
	Shoulder	145.7 ± 16.4	119.9 ± 15.9	189.5 ± 38.2	209.7 ± 6.1
	Furrow	139.2 ± 27.9	123.6 ± 14.8	234.8 ± 37.2	210.1 ± 11.3
Total		693.2 ± 57.2	594.2 ± 45.4	1034.0 ± 57.2	979.7 ± 17.3

Table 2.4: Results of a mixed-effects ANOVA run in SAS PROC MIXED for end-of-season cumulative NO_3 (µg cm^{-2}). Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

Effect	**F value**	**p**
Tillage	29.7	0.01
Cover	1.3	0.29
Position	0.1	0.75
Depth	37	< 0.0001
Tillage **x** Cover	2.9	0.07
Tillage **x** Position	0.1	0.93
Cover **x** Position	1.5	0.25
Tillage **x** Depth	16.2	0.0003
Cover **x** Depth	0.2	0.68
Position **x** Depth	0.2	0.67
Tillage **x** Cover **x** Position	0.1	0.78
Tillage **x** Cover **x** Depth	0.1	0.87
Tillage **x** Position **x** Depth	0.8	0.47
Cover **x** Position **x** Depth	0.8	0.46
Tillage **x** Cover **x** Position **x** Depth	0.5	0.62

Fig. 2.2: Mean NO_3 adsorption rates (µg cm^{-2} soil day^{-1}) across the growing season in MI. Values were calculated by dividing the total amount extracted from ion strips and dividing by the number of days ion strips were deployed during the corresponding sampling period. Error bars represent ± S.E., and line type represents sampling position.

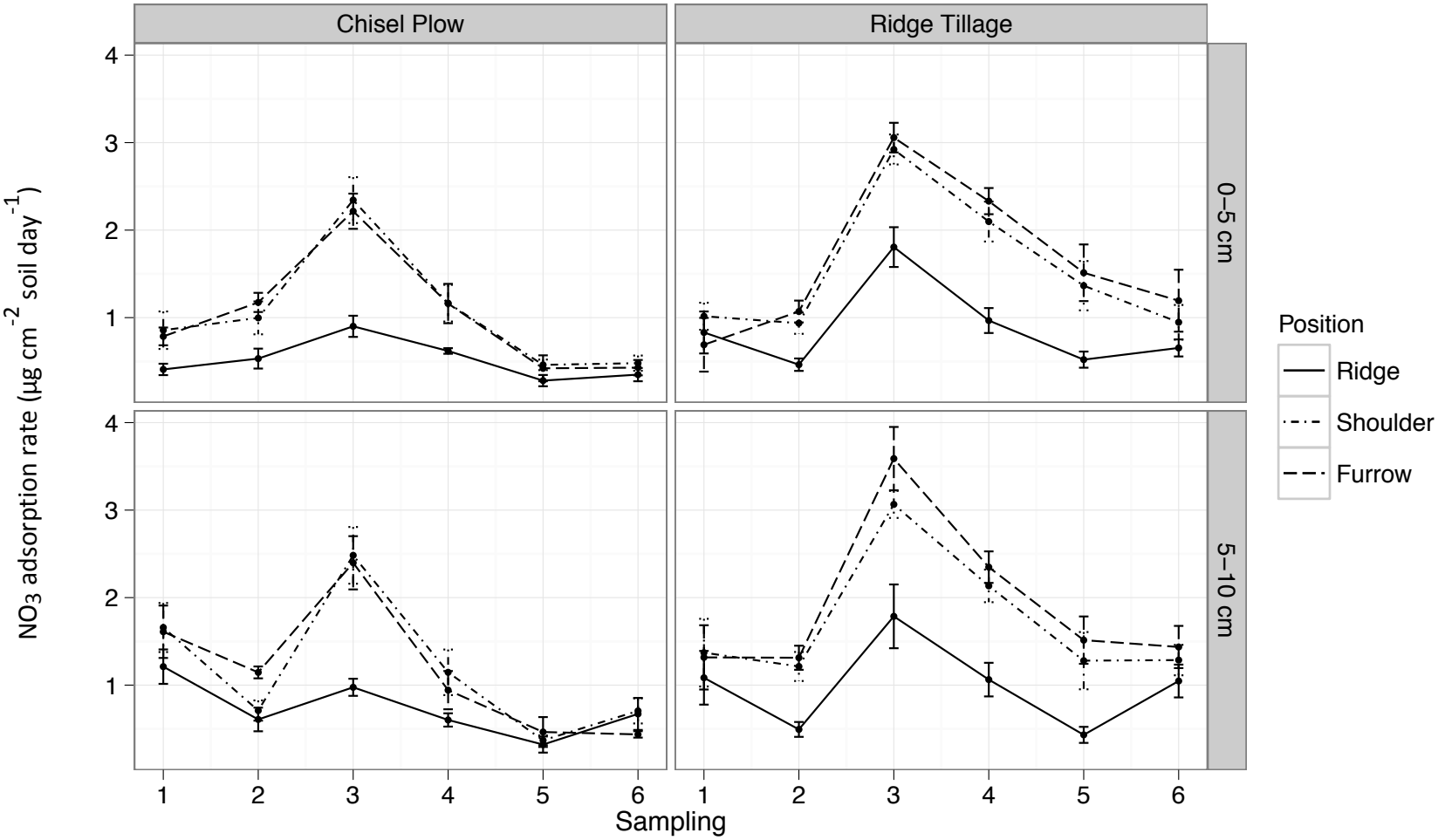


Table 2.5: Results of a mixed-effects, repeated measures ANOVA run in SAS PROC MIXED for NO_3 adsorption rates (µg cm^{-2} day^{-1}). Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

Effect	**F value**	**p**
Tillage	22.0	0.02
Cover	1.6	0.25
Position	28.6	< 0.0001
Depth	7.2	0.01
Tillage **x** Cover	0.2	0.69
Tillage **x** Position	4.0	0.03
Cover **x** Position	0.2	0.81
Tillage **x** Depth	1.0	0.31
Cover **x** Depth	0.70	0.40
Position **x** Depth	0.08	0.92
Tillage **x** Cover **x** Position	0.58	0.57
Tillage **x** Cover **x** Depth	0.02	0.90
Tillage **x** Position **x** Depth	0.69	0.50
Cover **x** Position **x** Depth	0.28	0.76
Tillage **x** Cover **x** Position **x** Depth	0.66	0.52

Fig. 2.3: NH_4 (µg cm^{-2}) accumulated on ion strips throughout the season at MI. Values across sampling periods are additive, and error bars at each sampling point represent ± S.E. Line type represents position in the row/inter-row space.

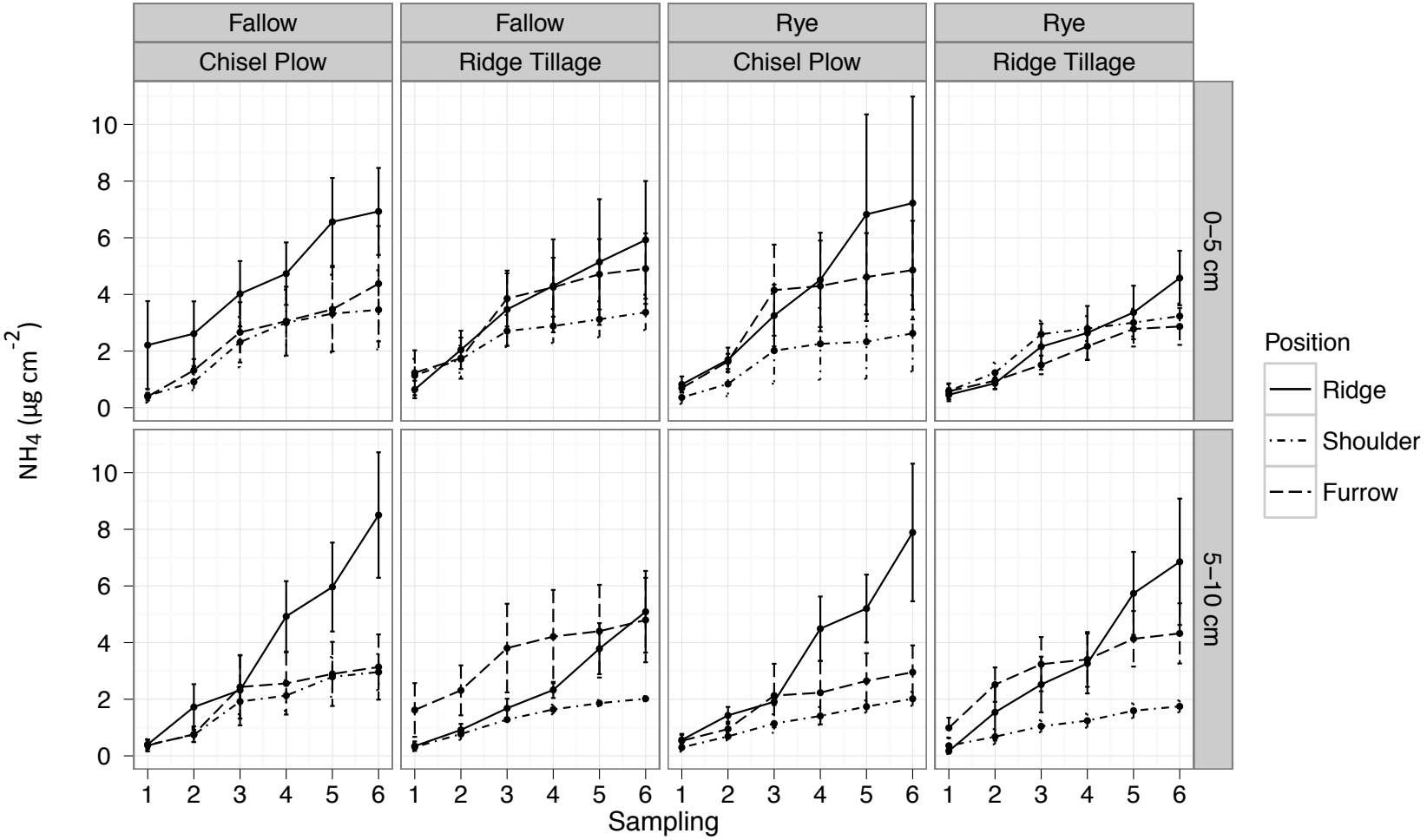


Table 2.6: End-of-season cumulative NH_4 (μg cm^{-2} soil) from ion strips in MI. Values represent the total amount of NH_4 accumulated ± S.E. and correspond with values at Sampling 6 in Fig. 2.3.

		CP-fallow	**CP-rye**	**RT-fallow**	**RT-rye**
0-5 cm	Ridge	6.9 ± 1.5	7.2 ± 3.8	5.9 ± 2.1	4.6 ± 1.0
	Shoulder	3.5 ± 1.4	2.2 ± 1.3	3.4 ± 0.6	3.2 ± 0.4
	Furrow	4.4 ± 2.0	4.9 ± 1.7	4.9 ± 1.2	2.9 ± 0.6
5-10 cm	Ridge	8.5 ± 2.2	7.9 ± 2.4	5.1 ± 1.4	6.9 ± 2.2
	Shoulder	3.0 ± 0.6	2.0 ± 0.2	2.0 ± 0.1	1.7 ± 0.2
	Furrow	3.1 ± 1.12	3.0 ± 0.9	4.8 ± 1.5	4.3 ± 1.1
Total		29.4 ± 8.1	27.6 ± 10.2	26.1 ± 2.3	23.6 ± 1.4

Table 2.7: Results of a mixed-effects ANOVA run in SAS PROC MIXED for end-of-season cumulative NH_4 (μg cm^{-2}). Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

Effect	**F value**	**p**
Tillage	0.2	0.71
Cover	0.5	0.49
Position	0.01	0.91
Depth	22.1	< 0.0001
Tillage **x** Cover	2.2	0.13
Tillage **x** Position	0.15	0.86
Cover **x** Position	0.44	0.65
Tillage **x** Depth	0.12	0.73
Cover **x** Depth	0.11	0.74
Position **x** Depth	0.23	0.63
Tillage **x** Cover **x** Position	1.11	0.30
Tillage **x** Cover **x** Depth	1.33	0.28
Tillage **x** Position **x** Depth	0.97	0.39
Cover **x** Position **x** Depth	0.13	0.88
Tillage **x** Cover **x** Position **x** Depth	0.35	0.71

Fig. 2.4: NH_4 adsorption rates (µg cm^{-2} soil day^{-1}) across the growing season in MI. Values were calculated by dividing the total amount extracted from ion strips and dividing by the number of days ion strips were deployed during the corresponding sampling period. Error bars represent ± S.E., and line type represents sampling position.

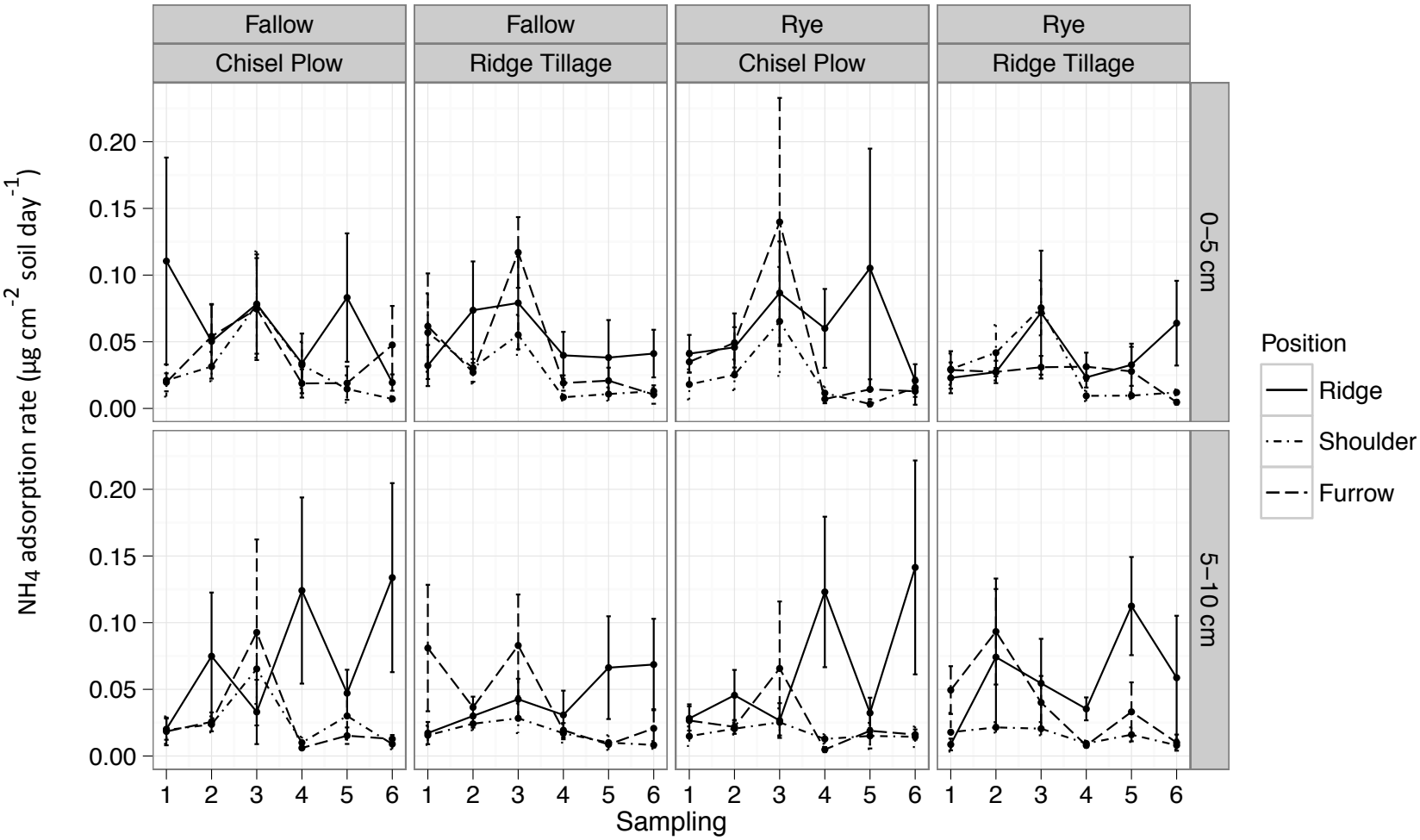


Table 2.8: Results of a mixed-effects, repeated measures ANOVA run in SAS PROC MIXED for NO_3 adsorption rates (μg cm^{-2} day^{-1}). Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

Effect	**F value**	**p**
Tillage	0.21	0.68
Cover	0.67	0.44
Position	24.5	< 0.0001
Depth	0.03	0.87
Tillage **x** Cover	0.53	0.50
Tillage **x** Position	3.66	0.04
Cover **x** Position	0.03	0.97
Tillage **x** Depth	0.12	0.73
Cover **x** Depth	0.73	0.39
Position **x** Depth	1.78	0.17
Tillage **x** Cover **x** Position	0.14	0.87
Tillage **x** Cover **x** Depth	1.08	0.30
Tillage **x** Position **x** Depth	1.64	0.19
Cover **x** Position **x** Depth	0.17	0.85
Tillage **x** Cover **x** Position **x** Depth	0.61	0.55

Fig. 2.5: Chlorophyll content (SPAD units) at growth stages V6, V12, VT, and R2 at both sites. Rye and fallow columns represent cover treatments, IL and MI labels represent site, and line type represents tillage treatment. Error bars represent ± S.E. at the corresponding sampling point.

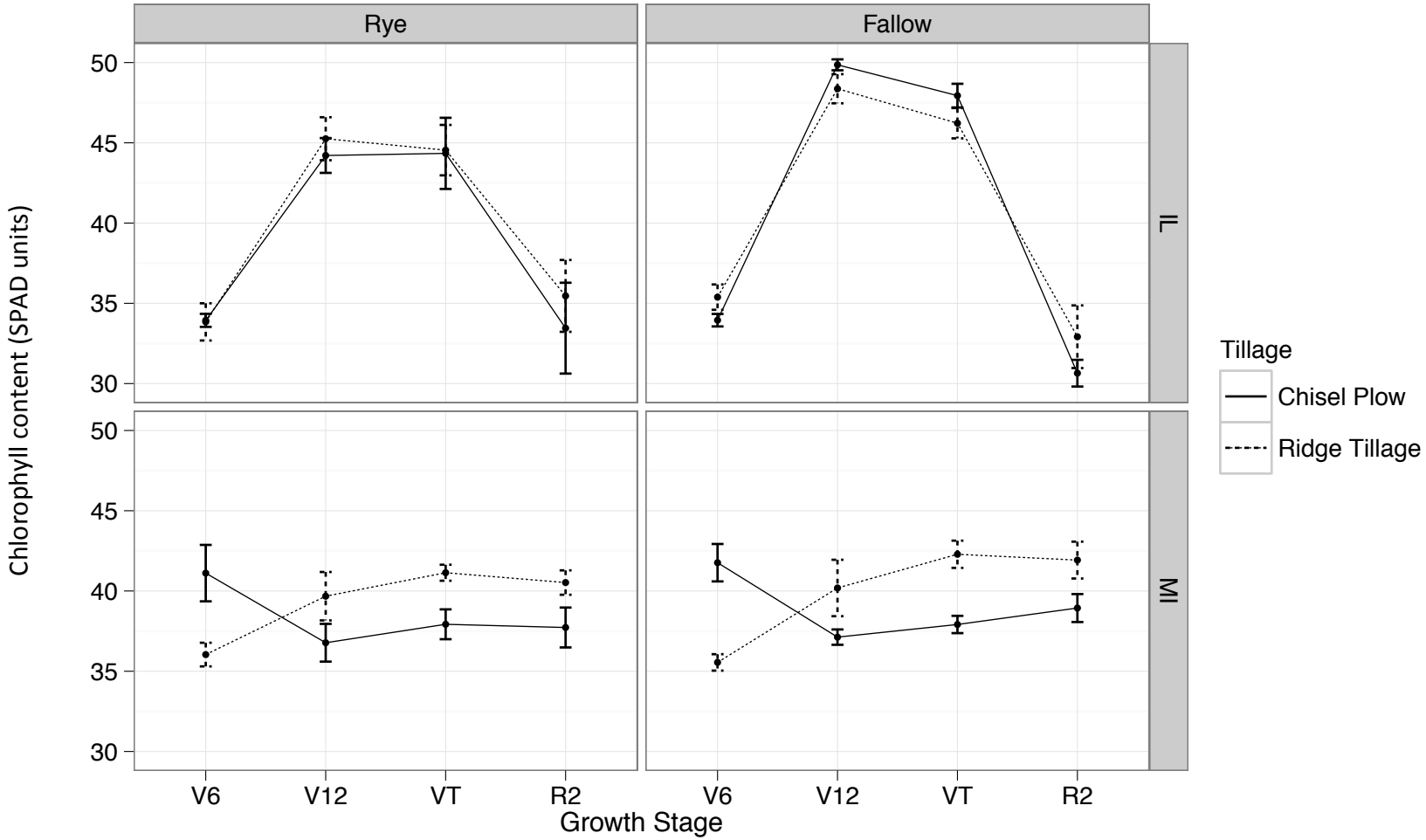


Table 2.9: Chlorophyll content (SPAD units) ± S.E. at growth stages V6, V12, VT, and R2 at both sites.

	Treatment	**V6**	**V12**	**VT**	**R2**
IL	**CP-fallow**	34.0 ± 0.4	49.9 ± 0.3	47.9 ± 0.7	30.6 ± 0.8
	CP-rye	33.9 ± 0.4	44.2 ± 1.1	44.3 ± 2.2	33.5 ± 2.8
	RT-fallow	35.4 ± 0.8	48.4 ± 0.9	46.2 ± 0.9	32.9 ± 2.0
	RT-rye	33.8 ± 1.2	45.3 ± 1.3	44.5 ± 1.6	35.5 ± 2.2
MI	**CP-fallow**	41.8 ± 1.2	37.1 ± 0.5	37.9 ± 0.5	38.9 ± 0.9
	CP-rye	41.1 ± 1.8	36.8 ± 1.2	37.9 ± 0.9	37.7 ± 1.2
	RT-fallow	35.6 ± 0.5	40.2 ± 1.8	42.3 ± 0.8	41.9 ± 1.1
	RT-rye	36.0 ± 0.7	39.7 ± 1.5	41.1 ± 0.5	40.5 ± 0.8

Table 2.10: Results of a mixed-effects, repeated measures ANOVA run in SAS PROC MIXED for chlorophyll content (SPAD units). Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	0.07	0.81	61.12	0.004
Cover	44.80	<0.05	7.40	0.009
Tillage **x** Cover	4.08	0.05	0.59	0.45

Fig. 2.6: Boxplots of yield on an areal basis (Mg/ha) of zero fertilizer plots at both sites. Panels correspond to sites and cover treatments. Different color boxplots within panels represent tillage treatments.

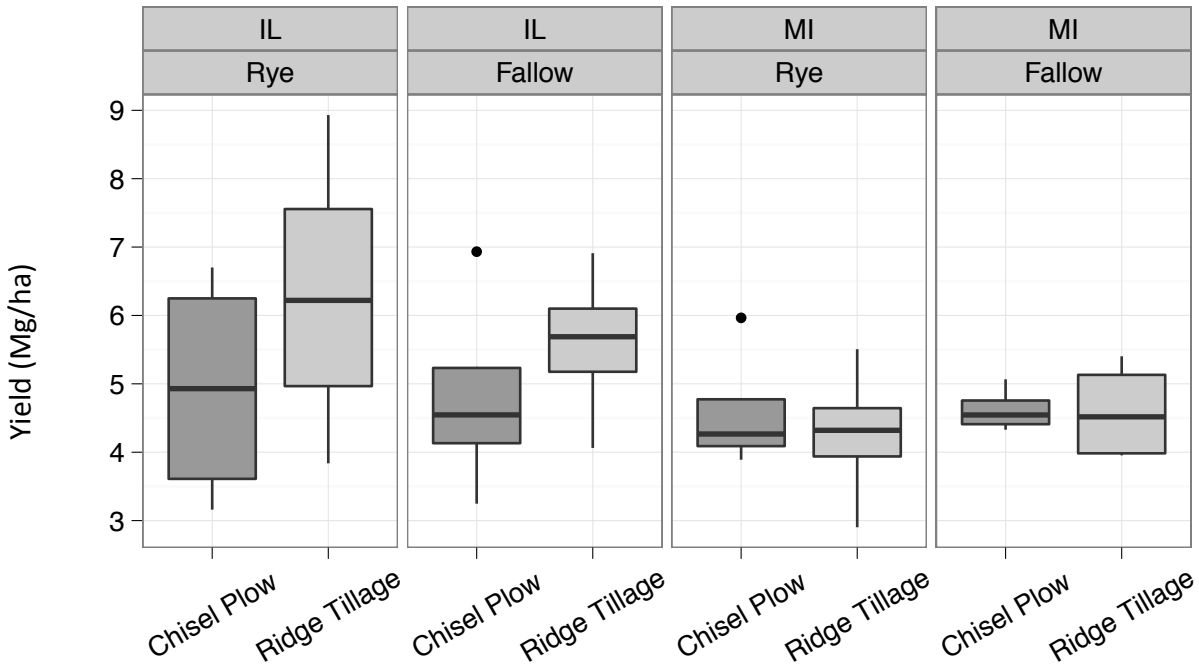


Table 2.11: Yield on an areal basis (Mg/ha) of zero fertilizer plots at both sites ± S.E.

	CP-fallow	**CP-rye**	**RT-fallow**	**RT-rye**
IL	4.8 ± 0.8	4.9 ± 0.9	5.6 ± 0.6	6.3 ± 1.1
MI	4.6 ± 0.2	4.6 ± 0.5	4.6 ± 0.4	4.3 ± 0.5

Table 2.12: Results of a mixed-effects, repeated measures ANOVA run in SAS PROC MIXED for areal yield (Mg/ha) data combined from both sites. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

Effect	F value	p
Tillage	1.32	0.29
Cover	0.09	0.78
Tillage **x** Cover	0.04	0.85

Fig. 2.7: Boxplots of per plant yield (g grain per plant) of zero fertilizer plots at both sites. Panels correspond to sites and cover treatments. Different color boxplots within panels represent tillage treatments.

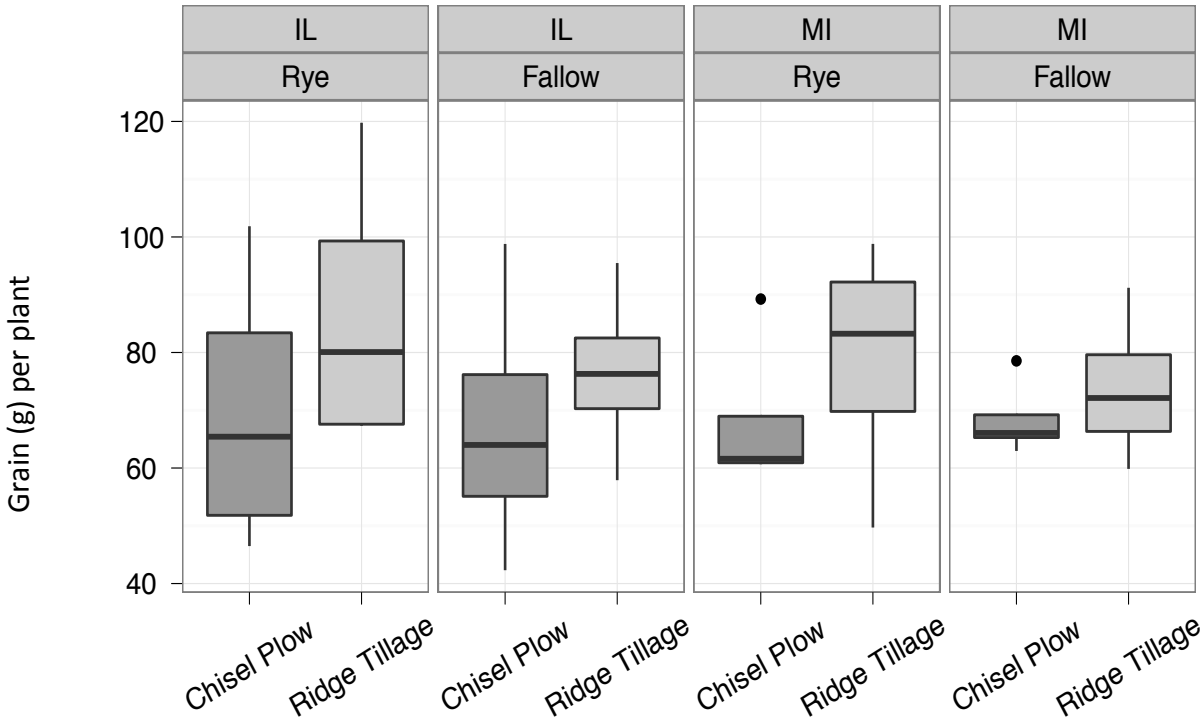


Table 2.13: Per plant yield (g grain per plant) of zero fertilizer plots at both sites ± S.E.

	CP-fallow	**CP-rye**	**RT-fallow**	**RT-rye**
IL	67.2 ± 11.8	69.7 ± 12.5	76.4 ± 7.7	86.8 ± 12.4
MI	68.4 ± 3.5	68.2 ± 7.0	73.8 ± 6.6	78.7 ± 10.7

Table 2.14: Results of a mixed-effects ANOVA run in SAS PROC MIXED for per plant yield (g grain per plant) data combined from both sites. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5..

Effect	F value	p
Tillage	4.68	0.07
Cover	0.82	0.38
Tillage **x** Cover	0.44	0.52

Fig. 2.8: Boxplots of per plant biomass (g plant^{-1}) of zero fertilizer plots at both sites. Panels correspond to sites and cover treatments. Different color boxplots within panels represent tillage treatments.

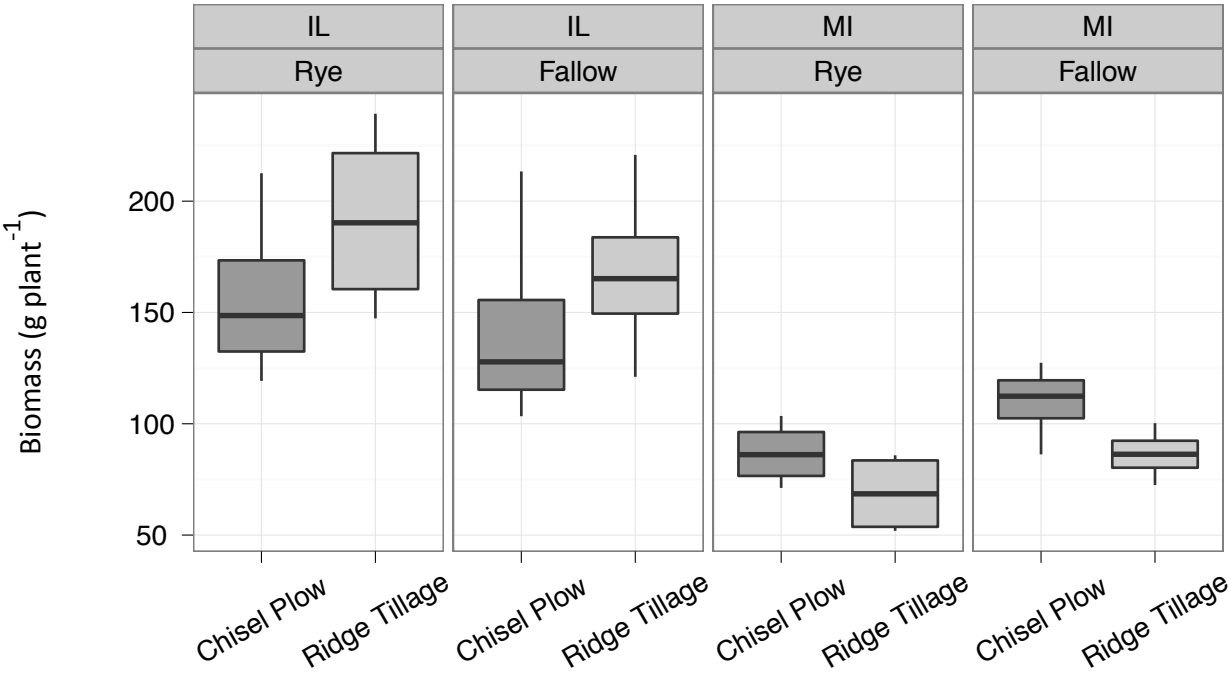


Table 2.15: Per plant biomass (g plant^{-1}) of zero fertilizer plots at both sites ± S.E.

	CP-fallow	**CP-rye**	**RT-fallow**	**RT-rye**
IL	143.1 ± 24.4	157.3 ± 20.3	168.1 ± 20.6	191.8 ± 21.5
MI	109.6 ± 8.7	86.7 ± 7.3	86.3 ± 5.8	68.7 ± 9.0

Table 2.16: Results of a mixed-effects ANOVA run in SAS PROC MIXED for per plant biomass (g plant^{-1}) data combined from both sites. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	3.51	0.16	6.93	0.08
Cover	1.43	0.28	6.66	0.04
Tillage **x** Cover	0.09	0.77	0.11	0.75

Fig. 2.9: Boxplots of total tissue N (% per g tissue) of plants in zero fertilizer plots at both sites. Panels correspond to sites and cover treatments. Different color boxplots within panels represent tillage treatments.

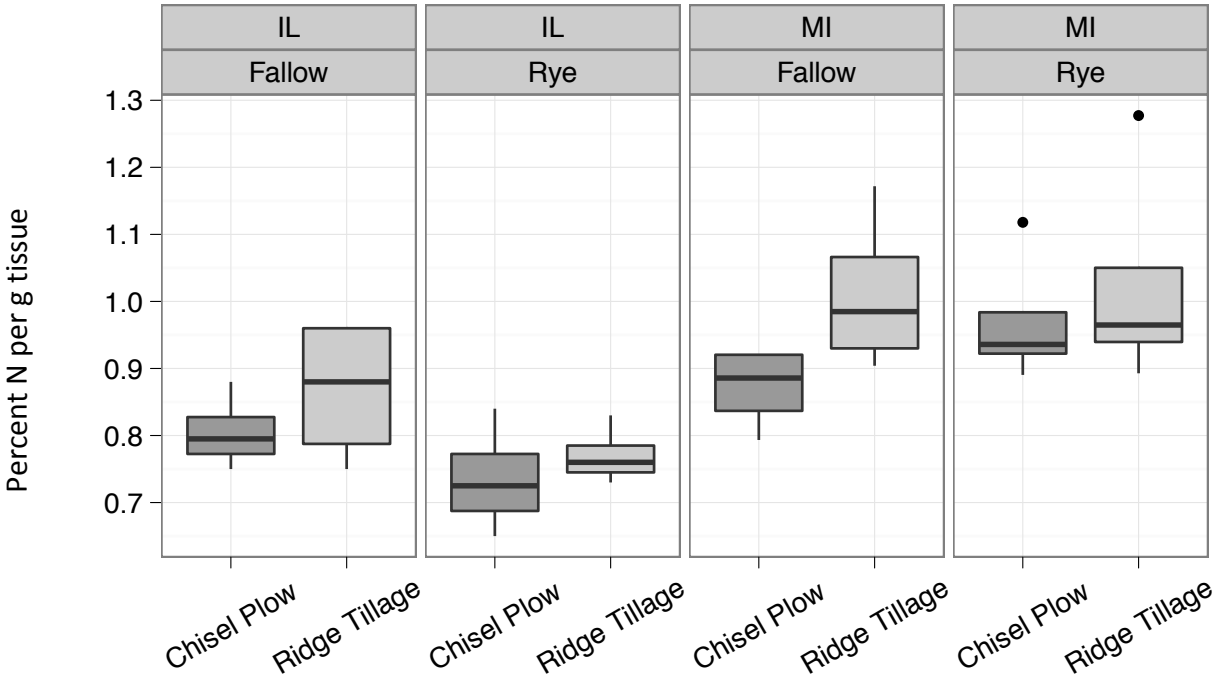


Table 2.17: Total tissue N (% N per g tissue) ± S.E. of plants in zero fertilizer plots at both sites.

	CP-fallow	**CP-rye**	**RT-fallow**	**RT-rye**
IL	0.8 ± 0.03	0.7 ± 0.04	0.9 ± 0.05	0.8 ± 0.02
MI	0.9 ± 0.03	1.0 ± 0.05	1.0 ± 0.06	1.0 ± 0.09

Table 2.18: Results of a mixed-effects ANOVA run in SAS PROC MIXED for total tissue N (% N per g tissue) data combined from both sites. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

Effect	**F value**	**p**
Tillage	3.99	0.09
Cover	0.14	0.71
Tillage **x** Cover	0.59	0.45

Fig. 2.10: Boxplots of grain tissue N (% N per g grain) of plants in zero fertilizer plots at both sites. Panels correspond to sites and cover treatments. Different color boxplots within panels represent tillage treatments.

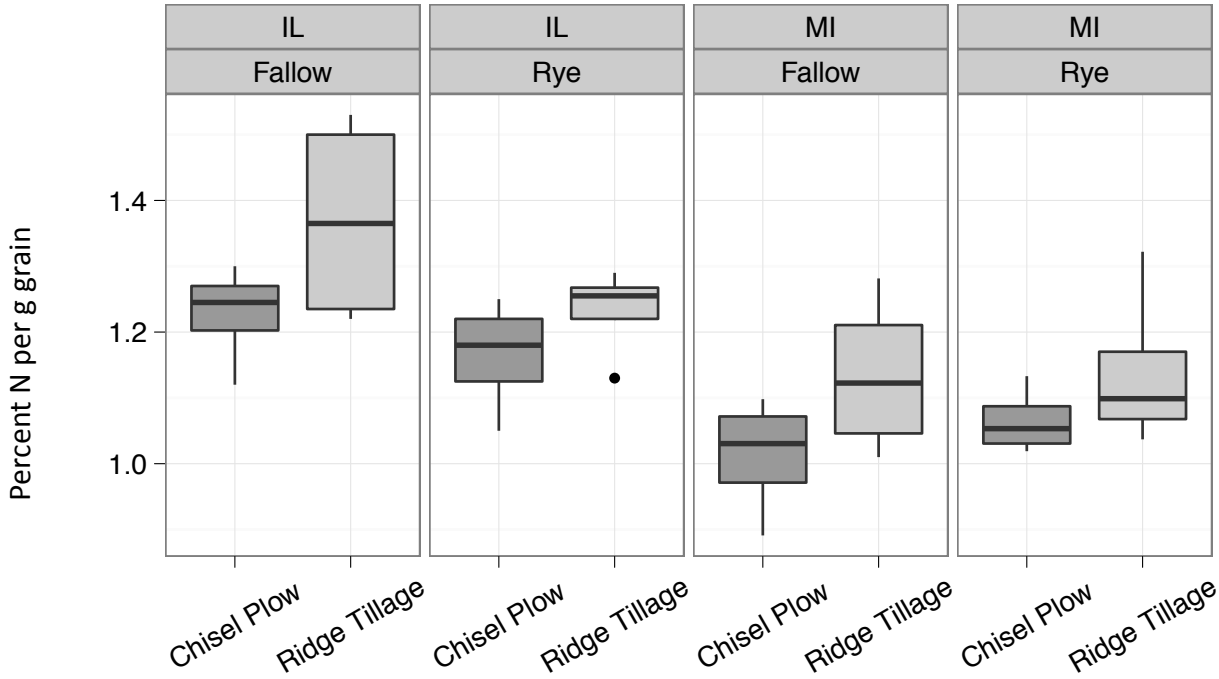


Table 2.19: Grain tissue N (% N per g grain) ± S.E. of plants in zero fertilizer plots at both sites.

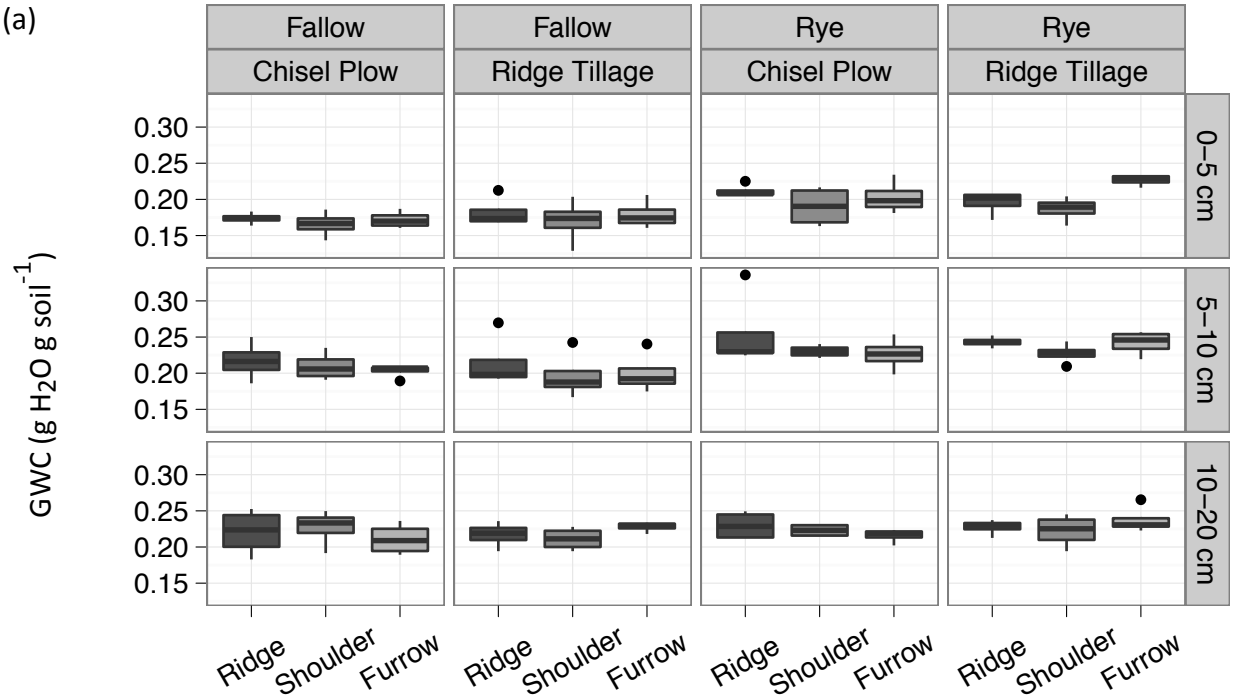
	CP-fallow	**CP-rye**	**RT-fallow**	**RT-rye**
IL	1.2 ± 0.04	1.2 ± 0.04	1.4 ± 0.08	1.2 ± 0.04
MI	1.0 ± 0.05	1.1 ± 0.03	1.1 ± 0.06	1.1 ± 0.06

Table 2.20: Results of a mixed-effects ANOVA run in SAS PROC MIXED for grain tissue N (% N per g grain) data combined from both sites. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

Effect	**F value**	**p**
Tillage	9.17	0.02
Cover	1.14	0.30
Tillage **x** Cover	0.83	0.38

Figure 2.11.a and 2.11.b: Boxplots of GWC (g H_2O g $soil^{-1}$) at Soil Sampling 1 from 0-20 cm in all experimental treatments and positions at (a) IL and (b) MI.

(a)



(b)

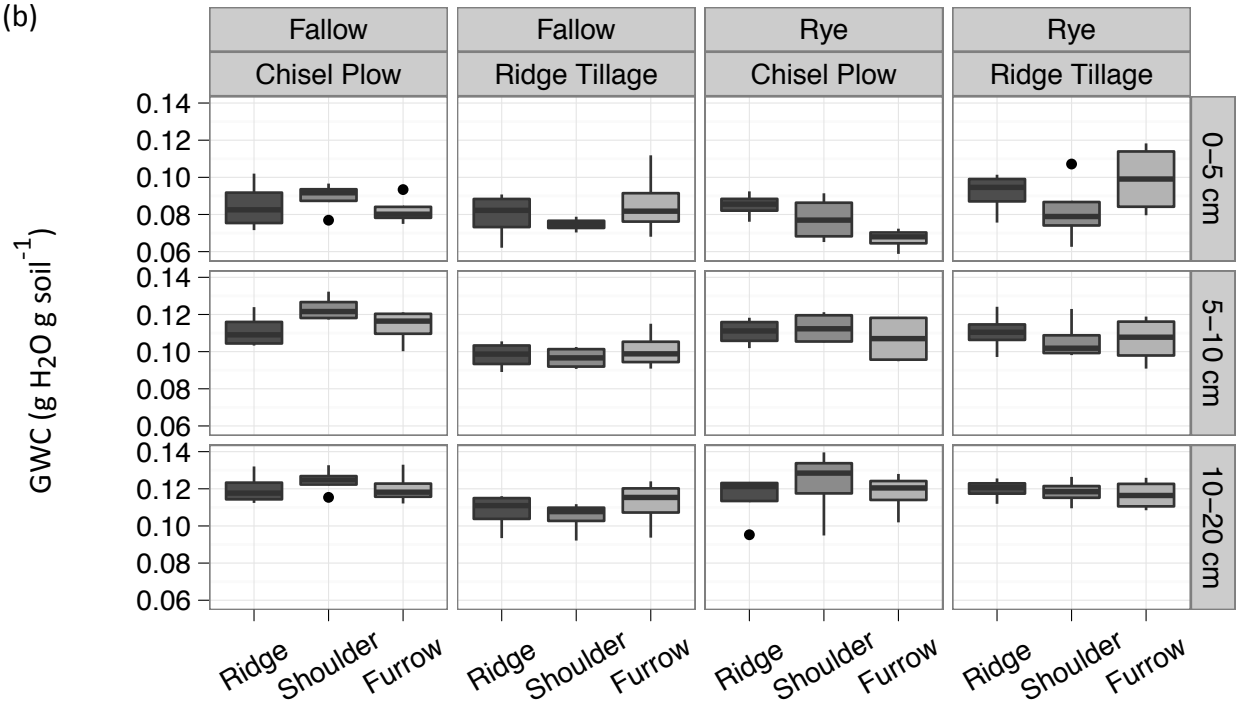
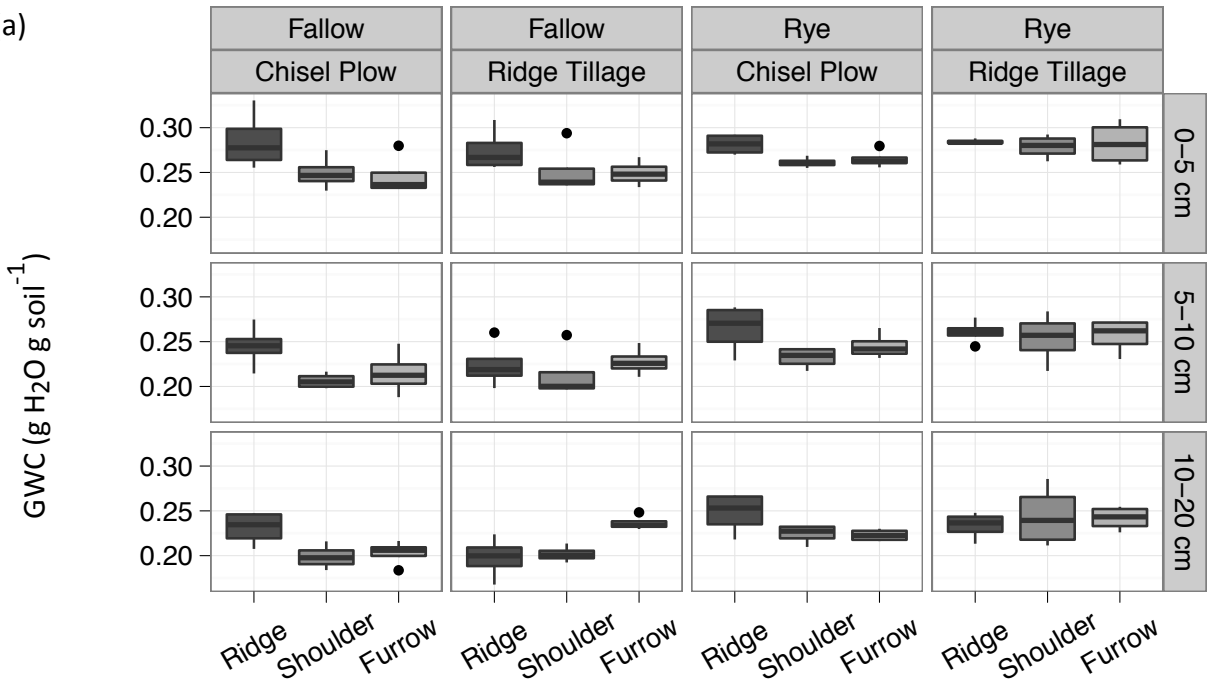


Table 2.21: Results of mixed-effects ANOVAs run in SAS PROC MIXED for soil GWC (g H_2O g soil^{-1})from Soil Sampling 1. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	0.05	0.84	1.26	0.34
Cover	14.06	0.01	0.31	0.60
Tillage **x** Cover	0.06	0.82	4.75	0.07
Position	5.27	0.01	0.03	0.97
Tillage **x** Position	5.15	0.01	6.02	0.01
Cover **x** Position	1.08	0.36	1.07	0.36
Tillage **x** Cover **x** Position	1.68	0.21	0.13	0.88
Depth	69.79	< 0.0001	209.32	< 0.0001
Tillage **x** Depth	0.61	0.54	9.97	0.0002
Cover **x** Depth	7.66	0.001	0.3	0.74
Tillage **x** Cover **x** Depth	0.52	0.60	0.53	0.59
Position **x** Depth	2.2	0.08	0.85	0.50
Tillage **x** Position **x** Depth	0.24	0.91	1.71	0.16
Cover **x** Position **x** Depth	0.36	0.83	0.47	0.76
Tillage **x** Cover **x** Position **x** Depth	0.43	0.79	0.71	0.59

Figure 2.12.a and 2.12.b: Boxplots of GWC (g H_2O g $soil^{-1}$) at Soil Sampling 2 from 0-20 cm in all experimental treatments and positions at (a) IL and (b) MI.

(a)



(b)

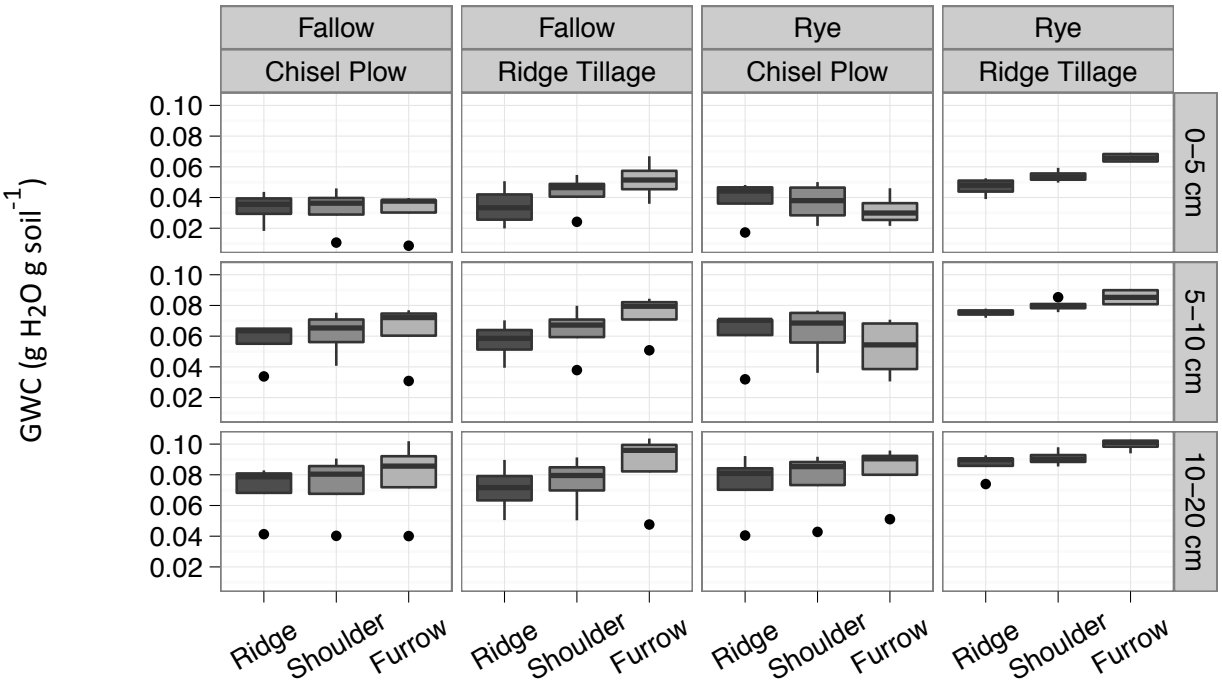


Table 2.22: Results of mixed-effects ANOVAs run in SAS PROC MIXED for soil GWC (g H_2O g soil$^{-1)}$ from Soil Sampling 2. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

	IL		**MI**	
Effect	F value	p	F value	p
Tillage	1.6	0.30	7.07	0.08
Cover	36.07	0.001	4.02	0.09
Tillage **x** Cover	1.8	0.23	2.47	0.18
Position	12.7	0.0002	10.88	0.0004
Tillage **x** Position	9.92	0.0007	9.07	0.001
Cover **x** Position	0.9	0.42	0.79	0.47
Tillage **x** Cover **x** Position	0.86	0.44	0.22	0.80
Depth	112.87	< 0.0001	435.72	< 0.0001
Tillage **x** Depth	0.01	0.99	2.64	0.08
Cover **x** Depth	2.84	0.07	0.36	0.70
Tillage **x** Cover **x** Depth	0.2	0.82	1.31	0.28
Position **x** Depth	2	0.10	1.01	0.41
Tillage **x** Position **x** Depth	1.67	0.17	1.81	0.14
Cover **x** Position **x** Depth	1.81	0.14	0.86	0.49
Tillage **x** Cover **x** Position **x** Depth	0.42	0.79	0.24	0.91

Figure 2.13: Boxplots of GWC (g H_2O g $soil^{-1}$) at Soil Sampling 3 from 0-20 cm in all experimental treatments and positions at (a) IL and (b) MI.

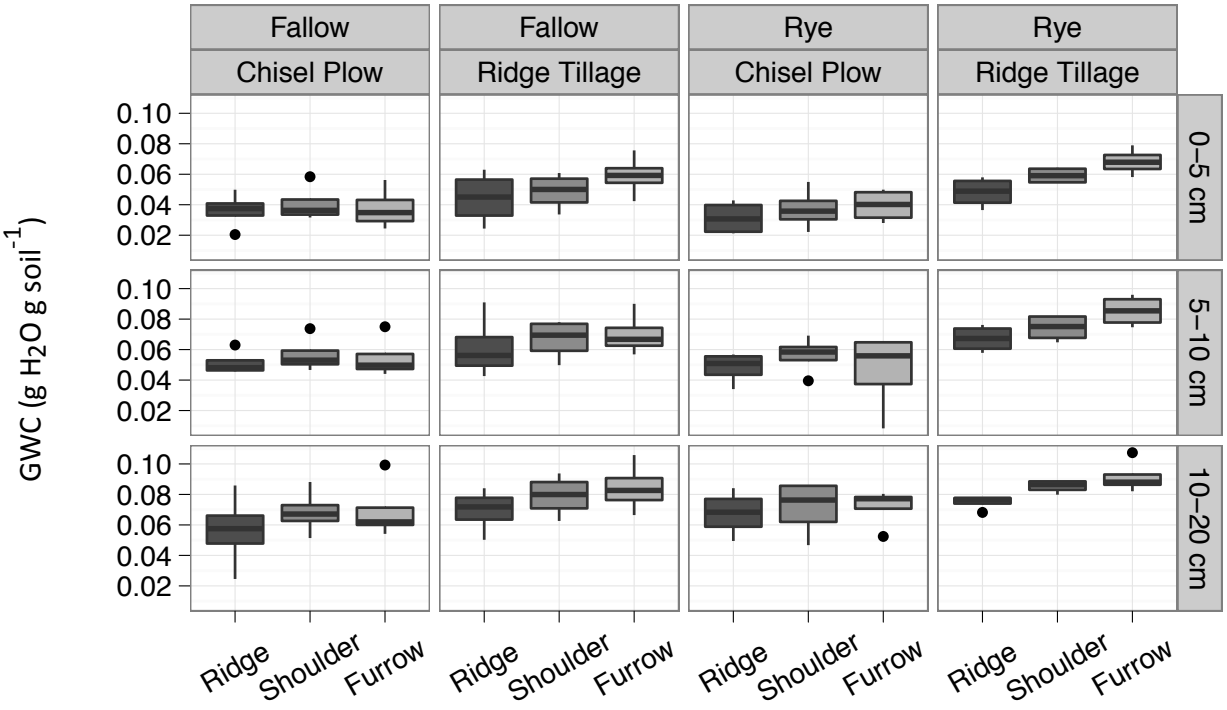


Table 2.23: Results of mixed-effects ANOVAs run in SAS PROC MIXED for soil GWC (g H_2O g soil^{-1}) from Soil Sampling 3. Effect identifies the treatment effect or interaction effect being tested, F value corresponds to the F statistic calculated, and p the probability of rejecting the null hypothesis. For further detail on the structure of the model used refer to section 2.3.5.

Effect	F value	p
Tillage	14.88	0.03
Cover	0.81	0.40
Tillage **x** Cover	0.88	0.38
Position	23.29	< 0.0001
Tillage **x** Position	7.46	0.003
Cover **x** Position	0.13	0.88
Tillage **x** Cover **x** Position	0.85	0.44
Depth	180.02	< 0.0001
Tillage **x** Depth	1.78	0.18
Cover **x** Depth	0.69	0.51
Tillage **x** Cover **x** Depth	2.42	0.10
Position **x** Depth	0.68	0.61
Tillage **x** Position **x** Depth	0.39	0.82
Cover **x** Position **x** Depth	0.53	0.71
Tillage **x** Cover **x** Position **x** Depth	0.72	0.58

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