Ridge tillage (RT) can promote increases in soil C and aggregation at greater rates than conventional tillage, but few studies have investigated how RT may affect soil N distributions across the row/inter-row space. Using a spatially intensive sampling design, we monitored soil potentially mineralizable N (PMN), inorganic N, and plant tissue N in a field study comparing RT and chisel plow (CP) systems. Experiments were fully replicated at two sites in Urbana, IL and Mason, MI during the 2012 growing season. At both sites, a strong interaction effect of tillage \times row position was observed for PMN (Illinois, $p = 0.005$; Michigan, $p = 0.02$) with higher levels of PMN in the in-row (IR) position than off-row (OR) and between-row (BR) positions of RT treatments following re-ridging. Plant tissue analyses indicated a significant RT advantage at both sites (Illinois, $p = 0.04$; Michigan, $p = 0.02$), and a structural equation modeling (SEM) analysis indicated that PMN at the 0- to 5-cm depth in the IR position following re-ridging had a significant effect on inorganic N at the same position and, in turn, a strong influence on plant tissue N (comparative fit index = 0.86, standardized root mean square residual = 0.11, Akaike wt. = 1). Overall, our results suggest that RT can establish soil functional zones (SFZ) with distinct N profiles and that the relocation of PMN in-row may increase the spatial efficiency of N provisioning relative to conventional tillage.

**Abbreviations:** BR, between-row; CEC, cation exchange capacity; CP, chisel plow; IR, in-row; OR, off-row; PMN, potentially mineralizable N; REML, restricted maximum likelihood; RT, ridge tillage; SFZ, soil functional zones; SOM, soil organic matter.
repeated relocation of soil and plant residues associated with the ridge building process generates a pattern of differential soil disturbance and organic matter deposition that could lead to spatially distinct zones with differing concentrations of soil organic matter (SOM) and associated nutrients. Better understanding the potential of such systems to simultaneously support soil building and nutrient provisioning processes will require data on how distinct and durable these soil functional zones are, as well as their significance to plant performance.

Long-term studies comparing RT to other tillage systems have found that increases in soil C and N pools in RT systems are greater relative to tillage methods imposing more intensive and spatially homogeneous soil disturbances, such as chisel plowing and moldboard plow, but RT may not achieve the same gains seen in no-till systems (Zibilske et al., 2002; Varvel and Wilhelm, 2010; Shi et al., 2012). Gains in C and associated N are likely due to increases in soil aggregation and microbial activity–biomass related to reduced disturbance in RT systems (Zhang et al., 2012, 2013). To the extent that RT is associated with soil C aggradation, RT provides some of the same soil physical and microbial benefits as no-till and other conservation tillage systems. For instance, it has been demonstrated that RT can increase water-holding capacity of soils (Kovar et al., 1992), enhance fungal colonization of roots (McConigle et al., 1999), and increase spring invertebrate populations relative to conventional tillage (Neave and Fox, 1998).

Unlike other conservation tillage schemes, there are indications that RT can create distinct spatial zones in soil C and N pools through the repeated relocation of residues and organic matter, with higher levels of C and N on the ridge than in the furrow (Shi et al., 2012). The creation of these zones and their reestablishment every year may have important implications for both spatial and temporal N synchrony with plant N demand. As such, it is important to understand the distribution of organic N pools of varying turnover rates across the row and within the furrow. Aerating and concentrating residues to the ridge, after a period of decomposition in the furrow, may make nutrients more available to plants, especially since the soil–residue mixing entailed by the re-ridging process has been shown to increase microbial activity (Grigera et al., 2007) and nodal root growth (Thomas and Kaspar, 1995, 1997) in the ridge. Additionally, since re-riding is typically done when corn is at the V6 growth stage, just as plants are entering the exponential growth phase, increases in N mineralization due to the re-riding process could improve temporal N synchrony and plant N uptake.

Despite evidence that RT creates distinct SFZ over the long-term, little research has been done on how these zones might affect the distribution and supply of plant-available N within the growing season. Liebreg et al. (1993, 1995) demonstrated differences in a variety of soil physical measurements between ridge and furrow spaces and that greater porosity in the ridge led to higher rates of CO2 respiration. Müller et al. (2009a, 2009b) found that microbial biomass and respiration was higher in the ridge at multiple points in the growing season. These studies demonstrate differences in microbial activity that suggest the ridge zone is characterized by higher levels of SOM turnover. Given this evidence, we sought to quantify differences in inorganic and labile N pools across the row–inter-row space at multiple time points throughout the growing season for plots using RT or CP.

Using a spatially comprehensive sampling design, we conducted soil monitoring during the 2012 growing season at multiple positions across the row–inter-row space at field sites in Illinois and Michigan participating in a multiyear tillage study on RT. Soil cores were taken at several points throughout the growing season that correlated with the timing of high N uptake in plants and key management events. Soil samples were analyzed for inorganic N (NO3–N + NH4–N) and PMN. Additionally, we used ion exchange resin strips to continuously sample available NO3–N throughout the growing season. We also sampled several plant tissue fractions to determine N concentration and total N uptake. We hypothesized that these indicators of labile C and N pools would be higher in the IR space than in the BR space in the RT system but would be the same in the CP system. Furthermore, we hypothesized that the concentration of these pools in the IR space would lead to higher levels of plant N uptake in the RT system compared to the CP system.

**METHODS**

**Site Description**

The study was conducted at two sites participating in a long-term, multi-university tillage experiment (USDA NIFA AFRI Project 2011-6703-30343), one in Mason, MI implemented by Michigan State University and the other in Champaign, IL implemented by the University of Illinois Champaign-Urbana. The Illinois site (40.048766° N lat, −88.236268° W long) is dominated by Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll) with 3 to 3.5% SOM, a pH of 6.4, and a cation exchange capacity (CEC) of 16.6 cmol kg⁻¹. The Michigan site (42.628551° N lat, −84.434808° W long) is dominated by Marlette sandy loam soils (fine-loamy, mixed, semiaactive, mesic Oxyaquic Glossudalfs) with 1 to 2% SOM, a pH of 6.2, and a CEC of 6.6 cmol kg⁻¹. Both sites had previously been planted to corn–soybean rotations using conventional tillage implements, such as CP. The 30-year average growing season (May–October) precipitation in Illinois is 61.59 cm, while in Michigan it is 48.02 cm (NOAA-NCDC, 2014). Summer daytime temperatures have historically ranged from 20°C to 25°C at both sites with periodic highs near 30°C.

**Experimental Design**

The study was conducted in 2012 at both sites for a total of two site-years. The experimental setup is a corn–soybean rotation with sampling conducted only in plots during the corn phase of the rotation. The experimental design is a randomized complete block factorial design with four blocks. Treatments included a whole plot factor of tillage at two levels, CP and RT, and a second whole plot factor of cover crop treatment with two
levels, winter rye (Secale cereale L.) and winter fallow. Zero fertilizer subplots were established within each treatment combination to allow for monitoring of plant N uptake in the absence of fertilization. We chose to conduct this component study in these zero fertilizer subplots because they allow us to examine N turnover exclusively from organic matter.

**Soil Sampling**

We collected soil samples at two time points that coincided with important crop growth stages and field operations. Soil sampling at both sites was conducted during May and June 2012, 10 to 14 d after planting, just as plants were emerging, to document early season conditions. The second soil sampling was conducted at both sites approximately 10 d after re-riding operations were completed 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 N demand is highest.

To gain a better understanding of the spatial distribution of N and the spatial differences in turnover in each system, we used a sampling approach with a high degree of spatial resolution. Soil cores were taken at three positions in the row–inter-row space: IR, 19.05 cm (7.5 in) from the row (OR), and 38.1 cm (15 in) from the row (BR). Five 2.5-cm cores were taken at each position to a depth of 20 cm and divided into three depth increments: 0 to 5, 5 to 10, and 10 to 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.

**Inorganic Nitrogen and Potentially Mineralizable Nitrogen**

Soil inorganic N was extracted from soil samples using a 1 M KCl solution. Although a 2 M KCl solution is generally deemed standard, Bremner and Keeney (1966) demonstrated that using a lower ratio of KCl to soil while also shaking samples on a mechanical shaker for 1 h generally produces very comparable results to 2 M KCl methods in which samples are not shaken. For each subsample, 10 ± 0.1 g of fresh soil was weighed into a 50-mL centrifuge tube, mixed with 40 mL 1 M KCl, and shaken at 240 rpm on an orbital shaker for 1 h. After samples had settled, 15 mL of KCl extractant was then filtered from each sample into scintillation vials through Whatman 42 qualitative filter paper. Extracts were then analyzed for NO$_3$–N and NH$_4$–N concentrations on a Thermo Multiskan 96-well plate reader using the procedures described in Doane and Horwath (2003). Total inorganic N was calculated as the sum of NO$_3$–N and NH$_4$–N for each sample.

At the same time inorganic N extractions were performed, a duplicate set of 50-mL centrifuge tubes containing 10 ± 0.1 g soil from each sample was prepared for a PMN assay as described in Waring and Bremner (1964) and Drinkwater et al. (1996). These samples were mixed with 10 mL of water and allowed to incubate for 7 d at 30°C. After incubation, NH$_4$ was extracted from samples by adding 30 mL of 1.33 M KCl to each sample, effectively bringing the molarity of the sample solution to 1 M KCl. Extracts were then analyzed for NH$_4$ only since the anaerobic condition created during the incubation inhibits nitrification. The initial NH$_4$ concentration of each sample was then subtracted from the concentration of the corresponding incubated sample to determine the amount mineralized during incubation.

**Ion Exchange Resins**

Ion exchange resins are a sampling method in which strips of an organic polymer are buried in soil to adsorb ions from soil solution for a period of days to months. We utilized 2.5- by 5-cm strips cut from sheets of anion-absorbing resins. Ion exchange resin strips were buried in the same three horizontal positions as soil samples, IR, OR, and BR, but only in two depth increments: 0 to 5 and 5 to 10 cm. Nyiraneza et al. (2011) demonstrated that concentrations of inorganic N 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 (IR, OR, BR) for both depth increments. Sets were randomly located within the plot and were deployed beginning 24 May 2012 (7 d after planting) and ending 24 Sept. 2012 (7 d before harvest) for a total of six sampling periods ranging from 18 to 22 d. At the end of each sampling period, all sets were removed from the soil and replaced with recently charged resin strips. At each removal date, 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 of 2 M KCl and shaken on a reciprocating shaker at 120 rpm for 1 h to extract the adsorbed 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. Concentrations of NO$_3$–N and NH$_4$–N were determined using the same 96 well plate method as soil samples. These concentrations were then divided first by the combined area of all the strips deployed per experimental unit and then by the number of days the strips were deployed to standardize results across different sampling periods. Final units for both NO$_3$–N and NH$_4$–N were then combined to calculate total inorganic N adsorbed per day for each experimental unit.

**Tissue Nitrogen**

To quantify whole season plant N uptake and partitioning, we measured N content of different plant fractions on corn plants harvested at reproductive stage R6 in zero fertilizer plots. In each plot, six plants were randomly selected, harvested, and separated into three fractions: grain, reproductive tissues (cob, silks, husk, tassel), and vegetative tissues (stem, leaves). Fractions from all six plants were then combined, processed, and weighed. Each sample was dried in a forced air oven at 60°C for 7 d. Once dried, samples were reweighed to quantify the biomass of each fraction and ground to pass through a 1-mm sieve. Tissue N concentrations were determined by dry combustion of the samples using a Costech ECS 4010 (Costech Analytical Technologies, Inc.,
Valencia, CA). Dry biomass numbers were then multiplied by the determined N concentrations and divided by the number of plants in each sample to calculate their average per-plant mass N within each plant fraction. The mass N of all three fractions were then summed to determine the total per-plant mass N for each sample.

Statistics

The experiment was modeled as a randomized complete block factorial design with two main plot factors of tillage and cover crop, a subplot factor of sample position (IR, OR, and BR), and a second subplot factor of depth (0–5, 5–10, and 10–20 cm). Data were pooled across cover crop treatments following an initial analysis that revealed no effects of cover crop treatments on response variables. Data from each soil assay (PMN and soil inorganic N) were separated by sampling round and site and were then fit to a mixed effects general linear model, specifying block as a random effect and tillage, position, and depth as fixed effects. We used a restricted maximum likelihood (REML) method to test for treatment effects in the SAS PROC MIXED procedure (SAS Version 9.3, SAS Inst., Cary, NC). Mean comparisons were then performed using orthogonal contrasts. Data from ion strip extracts were analyzed using the same model, but data from all sampling periods were combined and a repeated measures approach with sampling period as the repeated factor while fitting the model. Following an initial repeated measures analysis, data were then analyzed separately by sampling period to determine how treatment effects were expressed at different points in the growing season. Total per plant mass N data from either site were also analyzed using a REML approach with only a main effect of tillage.

To analyze the relative influence of PMN on inorganic N at the second soil sampling and end-of-season tissue N in either tillage treatment, data from both sites were combined then separated by tillage treatment. These datasets were then analyzed separately using a backward elimination structural equation modeling approach to produce the most parsimonious models for either tillage treatment utilizing model fitting criteria recommended in Grace (2006). Beginning with the model described in Fig. 1a, wherein PMN at each position was hypothesized to independently influence inorganic N at that same position and all positions together then combine to influence tissue N, individual pathways with low-significance of standardized regression coefficients (i.e., the highest p-values) were iteratively eliminated until the most parsimonious model fit for either data set was achieved. Model fit was assessed using Akaike information criterion (AIC), Akaike weights, and comparative fit index (CFI) values, and all analyses were conducted using the LAVAAN (version 0.5-15) package in R (version 3.1.0).

RESULTS

2012 Weather

The 2012 growing season was exceptionally hot and dry across the Midwest. At the Illinois site, total precipitation in the months of May, June, and July was 22.63 cm below the 30-yr average, and mean daily maximum air temperatures were 3.8°C above the historical average from May to July (NOAA-NCDC, 2014). In Michigan, total precipitation from June to August was 9.43 cm below 30-yr averages, and mean daily maximum temperatures were 2.5°C above historical averages from May to July (NOAA-NCDC, 2014). As a result of low rainfall and high air temperatures, soil temperatures increased rapidly at both sites during the month of June and the beginning of July.

Potentially Mineralizable Nitrogen

Potentially mineralizable N was similar across positions in both CP and RT treatments for the first soil sampling at both sites. There were no treatment effects at the Michigan site but interaction effects of tillage × position × depth and tillage × position were seen at the Illinois site (Table 1). These effects are most likely explained by the difference in OR PMN at 0 to 5 cm between tillage treatments (p = 0.003). By the second soil sampling, interaction effects of tillage × position for PMN were seen at both sites, as well as a strong tillage × position × depth effect at the Michigan site (Table 1). Potentially mineralizable N response to these interaction effects at the second soil sampling was consistent across sites (Fig. 2 and 3). Mean comparisons indicated that PMN was higher at the IR position than in the OR and BR positions of RT treatments (Illinois, p = 0.0007; Michigan, p = 0.0002), while in CP treatments no such differences emerged (Illinois, p = 0.58; Michigan, p = 0.37).

Soil Inorganic Nitrogen and Plant Uptake

Soil inorganic N at the first soil sampling was overall much higher in Michigan than in Illinois, and treatment effects dif-
fected by site. In Michigan there were no main or interaction effects on soil N, while in Illinois there was a main effect of position (Table 1). Mean comparisons indicated that this effect is likely due to the fact that inorganic N for the first soil sampling at the OR is significantly greater than the other positions for both tillage treatments ($p = 0.05$). Similar to PMN, there was an interaction effect of tillage position on soil inorganic N at Soil Sampling 2 at both sites and a strong interaction effect of tillage position depth at the Michigan site (Table 1) with distinct patterns of distribution occurring by tillage treatment. However, patterns at either site were somewhat different. At the Illinois site, inorganic N was lowest at the IR position in CP but equivalent in the OR and BR positions, while in RT treatments all three positions were equivalent but there was a trend of lower inorganic N at the BR position (Fig. 4). At the Michigan site, inorganic N was highest in the BR position in CP, lower in the OR position, and lowest in IR. Whereas in RT treatments at the Michigan site, BR and OR positions were equivalent, and in-row inorganic N was lowest (Fig. 4). Furthermore, inorganic N at the in-row position of the 0- to 5-cm depth was higher in RT treatments than CP treatments at the Michigan site ($p = 0.003$).

Similar patterns of N availability were reflected in the ion strip inorganic N adsorption rates at the Michigan site. An initial analysis using a repeated measures approach indicated a trend toward an interaction effect of tillage and position throughout the season ($p = 0.07$). Separating analyses by sampling period showed that this interaction effect began at Sampling Period 3 (July 5 to July 23), and continued through the rest of the season (Table 2). Finally, a clear main tillage effect was observed on total per plant N mass at both sites (Illinois, $p = 0.04$; Michigan, $p = 0.02$). Total plant N mass was higher in RT treatments than CP. This was observed at both sites and was particularly pronounced 0.02). Total plant N mass was higher in RT treatments than CP.

### Structural Equation Modeling

An initial regression analysis revealed that inorganic N values at 10 to 20 cm had no effect on end-of-season tissue N content, so those data were not utilized in structural equation modeling analyses. Backward elimination reduced models such that the final model for either tillage treatment included only one pathway (Fig. 1b). But the final model for either tillage treatment was different. The most parsimonious model for RT only included a pathway in which in-row PMN at 0 to 5 cm influenced inorganic N at the same position (PMN OR, 0–5 cm $\rightarrow$ Inorganic N, OR 0–5 cm), and the pathway's relationship with plant tissue N was negative (Table 3). **DISCUSSION**

Unger (1995) found short-term increases in SOM at the in-row position following re-ridging, and several studies have demonstrated short-term increases in functional signals of microbial activity, such as CO$_2$ respiration and microbial biomass, in the plant row (Liebig et al., 1995; Müller et al., 2009a, 2009b). Our results indicate that the rapid changes in SOM and microbial activity observed by others may also be accompanied by increases in PMN in the crop row of RT systems due to the relocation of recent plant residues. Functionally, PMN represents a labile organic matter pool that could readily supply nutrients to plants (Drinkwater et al., 1996). Changes in patterns of distribution and tillage effects between the first and second soil samplings (Table 1; Fig. 2 and 3) imply that these increases at the in-row position may be the effect of RT.

**Table 1. F values from mixed-effects ANOVA on various soil assays from the first and second soil sampling periods ($n = 8$).**

<table>
<thead>
<tr>
<th>Effect#</th>
<th>N df§</th>
<th>D df</th>
<th>Soil sample 1</th>
<th>Soil sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
<td>1</td>
<td>3</td>
<td>0.04 5.75</td>
<td>7.65 2.54</td>
</tr>
<tr>
<td>Position</td>
<td>2</td>
<td>12</td>
<td>1.06 2.7</td>
<td>6.14 0.46</td>
</tr>
<tr>
<td>Depth</td>
<td>2</td>
<td>108</td>
<td>71.1 14.83**</td>
<td>5.69 0.38</td>
</tr>
<tr>
<td>Till $\times$ pos</td>
<td>2</td>
<td>12</td>
<td>3.85* 0.13</td>
<td>3.39 0.6</td>
</tr>
<tr>
<td>Till $\times$ dep</td>
<td>2</td>
<td>108</td>
<td>1.23 1.28 0</td>
<td>3.44* 2.92*</td>
</tr>
<tr>
<td>Pos $\times$ dep</td>
<td>4</td>
<td>108</td>
<td>0.74 0.87</td>
<td>0.17 0.32</td>
</tr>
<tr>
<td>Till $\times$ pos $\times$ dep</td>
<td>4</td>
<td>108</td>
<td>2.5 0.97 0.97</td>
<td>0.94 2.15*</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† PMN, potentially mineralizable N.
‡ Till, Tillage; pos, position; dep, depth.
§ N df, numerator degrees of freedom; D df, denominator degrees of freedom.
¶ Significant at the 0.10 probability level.

**Fig. 2. Potentially mineralizable N (PMN) (mg N kg soil$^{-1}$ d$^{-1}$) at different depths and sample positions (IR, in-row; OR, off-row; BR, between-row) in Illinois and Michigan at the second soil sampling event (Illinois, 1 June 2012; Michigan, 10 July 2012). Error bars represent ±SE of the mean total PMN at each position ($n = 8$).**
Increases of PMN in the ridge could create a zone of higher fertility in the in-row space, potentially making inorganic N more available for plant uptake. However, results from soil inorganic N extractions did not fully reflect results from the PMN assay, and results differed across sites. At the Illinois site, there were no differences in inorganic N at the second soil sampling between positions in RT treatments (Fig. 4), and although inorganic N was greater in the IR position of RT treatments than in the IR position of CP treatments, the difference was not significant. At the Michigan site, inorganic N at the IR position was lower than in the OR and BR positions in both tillage treatments (Fig. 5), but inorganic N in the IR position was higher in RT treatments than in CP treatments. Ion strip results from Michigan exhibited a similar trend from Sampling Periods 3 to 5, which encompassed a roughly 2-mo period following re-ridging (Fig. 6). There is little research examining the differences in labile N, such as PMN, or inorganic N between positions both before and after ridging in RT soils planted to corn, limiting comparisons to previous research. Clay et al. (1995), one of the few studies other than ours to examine labile N in these systems, found that despite higher rates of C mineralization in-row, N mineralization was similar across sample positions.

Differences between PMN assays and inorganic N extractions could have several explanations. They may be an artifact of laboratory methods as we chose to incubate PMN samples under saturated conditions. Saturating PMN samples may allow for a more complete assessment of N mineralization potential, but this method may not reflect conditions in the field. Both sites received very little precipitation during the months of July and August, and lack of moisture can markedly reduce N mineralization rates (Stanford and Epstein, 1974; Cassman and Munns, 1980) by reducing microbial uptake of substrates (Stark and Firestone, 1995) and by causing cell death in extreme cases (Griffin, D.M., 1981). Low N mineralization rates in situ would be reflected in both ion strip and soil inorganic N extractions but not necessarily in PMN incubations.

Lower concentrations of inorganic N at sample positions closer to the in-row space and the plant may also be explained simply by higher root density and therefore higher N uptake in the in-row space. Increased levels of inorganic N in the upper portion of the soil (0–5 cm) within the IR space in RT treatments relative to CP treatments, however, may be reflective of the concentration of labile N materials to the in-row space demonstrated by PMN. Disentangling the effects of tillage from plant uptake and environmental conditions in this case is difficult, but end-of-season plant N concentrations help to confirm the effects of tillage on N availability and subsequent uptake.

Results from plant tissue N analyses indicate higher N uptake overall in RT plants than in CP plants at both sites, particularly in the grain fraction (Fig. 5). Higher grain N concentrations additionally indicate that N uptake was greater in RT plants during reproductive stages (Lemcoff and Loomis, 1986; Below and Gentry, 1992), which is
consistent with results from ion strip extractions that show higher overall inorganic N availability in the months of July and August. Higher concentrations of particulate organic matter (POM)-N and PMN in the IR position of RT treatments, as well as higher IR inorganic N in RT treatments relative to CP treatments, may also explain higher plant tissue N concentrations in RT plants. Results from path analyses further support this hypothesis, as they indicated that IR PMN at the soil surface had an outsize effect on tissue N content by increasing plant-available inorganic N. Although we did not measure the spatial distribution of root density to confirm where root density was highest and where N uptake may be greatest, Hilfiker and Lowery (1988) demonstrated that root density in RT systems is highest in-row and at the soil surface, while Thomas and Kaspar (1997) found that ridging stimulated nodal root growth in corn plants.

Conversely, the reduced path analysis model for CP data included only PMN → Inorganic N at 0 to 5 cm at the OR position as a model parameter, and the relationship to tissue N was negative (Table 3). While it is not likely that PMN → Inorganic N could reduce plant tissue N, this negative relationship perhaps indicates underutilization of inorganic N by plants from that position or that increases in PMN may also be related to increases in soil C leading to inorganic N immobilization. Furthermore, the lack of any positive regression results in the CP path analysis arguably implies that given the more even distribution of PMN throughout the soil profile found in the CP results from the second soil sampling, PMN at no one position had an outsize impact on tissue N.

Overall, our results suggest that RT can quickly establish soil functional zones characterized by different N pools and turnover rates, consistent with an improvement in the proximity of soil N provisioning and plant N uptake in RT systems relative to CP systems. By concentrating labile N-rich residues within the in-row space near plants, RT may improve the availability of inorganic N particularly in the latter part of the season during grain fill. Our results also are consistent with stimulation of microbially-mediated turnover processes by re-ridging, based on inorganic N dynamics and the overall increase in ion strip inorganic N at all positions following re-ridging. These results corroborate previous research on RT that indicates increased microbial activity in the ridge space (Liebig et al., 1995; Müller et al., 2009a, 2009b). It should be noted, however, that weather patterns in 2012 may have also affected results. Elevated soil temperatures could have increased soil nutrient turnover rates, while at other times reduced soil moisture could have led to microbial dormancy and reduced turnover rates. Similar research across a variety of soil types and more normal weather patterns could help to confirm the patterns we observed were the result of abnormal weather in 2012.

Given previous long-term research on RT that clearly demonstrates improvements in C sequestration over several seasons (Zibilske et al., 2002; Varvel and Wilhelm, 2010; Shi et al., 2012), the additional possibility that RT could improve spatial efficiency of soil N provisioning by relocating labile organic-N to the in-row space thereby improving efficiency of plant uptake means it could be a tillage system capable of balancing production and soil con-

Table 3. Parameter values and model performance indicators for fully reduced path analysis models. Dependent variable for both models is total plant N (n = 16).

<table>
<thead>
<tr>
<th>Model</th>
<th>Independent variables</th>
<th>Parameter values</th>
<th>Model performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variable 1</td>
<td>Variable 2</td>
<td>$b_1$</td>
</tr>
<tr>
<td>RT PMN IR, 0–5 cm</td>
<td>Inorg. N IR, 0–5 cm</td>
<td>2.53*</td>
<td>0.13§</td>
</tr>
<tr>
<td>CP PMN OR, 0–5 cm</td>
<td>Inorg. N OR, 0–5 cm</td>
<td>-1.08</td>
<td>-0.11§</td>
</tr>
<tr>
<td></td>
<td>$*$ Significant at the 0.05 probability level.</td>
<td>$§$ Significant at the 0.10 probability level.</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Total per-plant mass N (g) of plants in each tillage treatment (RT, ridge tillage; CP, chisel plow) at the Illinois and Michigan sites and separated by each fraction analyzed. Error bars represent ±SE of the mean of the total mass N (n = 8).

Fig. 6. Total inorganic N (mg N cm⁻² d⁻¹) adsorption by ion exchange resin strips at all depths and sample positions at the Michigan site at multiple points throughout the growing season. Error bars at each point represent ±SE of the mean. Gray dotted lines represent times at which re-ridging occurred (n = 8).
servation services. Further research on how RT zones may be characterized by different microbial communities and C pools after several seasons would shed light on how these zones mature and how organic matter is differentially cycled over time.

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