Agriculture, Ecosystems and Environment 231 (2016) 291–295

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Precision control of soil nitrogen cycling via soil functional zone management

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

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

ARTICLE INFO

Article history:
Received 17 June 2016
Received in revised form 14 July 2016
Accepted 18 July 2016
Available online 25 July 2016

Keywords:
Agriculture
Agroecology
Ecological intensification
Microbial processes
Tillage
Zonal management

ABSTRACT

Managing the soil nitrogen (N) cycle is a major component of agricultural sustainability. Soil functional zone management (zonal management) is a novel agroecological strategy for managing row-crop agroecosystems. It may improve the efficiency of soil N cycling compared with conventional and no-tillage approaches, by managing the timing and location (crop row vs inter-row) of key soil N cycling processes. We compared N mineralization and availability during the period of maize peak N demand in crop rows and inter-rows in zonal management and conventional chisel plow tillage systems at four sites across the US Corn Belt over three growing seasons. Under zonal management, potential N mineralization and N availability during crop peak N demand were significantly greater in crop rows, where the majority of crop roots are found, compared with inter-rows. Averaged across all site-years, plant-available N in zonal management crop rows was 46 mg kg^{-1} compared with 21 mg kg^{-1} in inter-rows. In contrast, in conventional tillage, potential N mineralization and N availability were greater in inter-rows compared with crop rows; averaged across all site-years, plant-available N in conventional tillage crop rows was 24 mg kg^{-1} compared with 51 mg kg^{-1} in inter-rows. The results demonstrate that the active management of crop residues under zonal management can enhance the spatiotemporal efficiency of soil N cycling processes, by concentrating N mineralization and availability close to crop roots in synchrony with crop developmental needs. Zonal management therefore has potential to increase crop N-use efficiency compared with conventional tillage, and thereby reduce the impacts of row-crop agricultural production on water resources and greenhouse gas emissions that result from N leaching and denitrification.

1. Introduction

The soil nitrogen (N) cycle plays a critical role within agricultural systems. Microbially-mediated soil processes act upon stocks of organic and inorganic N, affecting crop uptake, N leaching, microbial immobilization of N, and denitrification (Robertson and Vitousek, 2009). Therefore, management of the soil N cycle within agricultural systems is a key global issue, relating to emissions of greenhouse gases, N pollution of terrestrial ecosystems, water resources and the genesis of coastal hypoxic zones (Robertson and Vitousek, 2009). Improvements to N-use efficiency are needed to support high crop yields while reducing N losses from agroecosystems. Soil functional zone management (henceforth, zonal management) may offer a novel, agroecological approach for improving N-use efficiency. Zonal management is a row-crop production strategy that manipulates the timing and location of soil disturbance with the goal of enhancing a range of soil ecosystem services (Williams et al., 2016). In particular, zonal

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

http://dx.doi.org/10.1016/j.agee.2016.07.010
0167-8809/

management aims to actively manage agroecological processes related to N-use efficiency, thereby furthering ecological intensification of row-crop production (Bommarco et al., 2013; Foley et al., 2011).

Under zonal management, crop rows and inter-rows are managed as spatially-distinct functional zones. Soil disturbance is concentrated in crop rows, to enhance nutrient provisioning processes in the vicinity of crop roots; inter-rows are left relatively undisturbed, to promote soil building processes such as soil organic carbon accumulation and nutrient immobilization (Williams et al., 2016). Examples of zonal management include ridge and strip tillage, both of which are widely practiced around the world for a range of crops, including major row-crops (e.g. maize and soybean), small grain cereals and horticultural crops (Williams et al., 2016). Zonal management contrasts with conventional (i.e. intensive tillage systems such as chisel plowing) and no-tillage systems, which both manage crop rows and inter-rows uniformly. We hypothesize that under uniform management, the location and timing of soil N cycling processes are not ideally matched to crop developmental needs. In conventional tillage systems, these mismatches contribute to inefficiencies in resource-use and soil degradation (Kane et al., 2015; Robertson and Vitousek, 2009; Varvel and Wilhelm, 2011); while in immature no-tillage systems, nutrient immobilization that inhibits crop development can result (Martens, 2001).

In contrast, zonal management can improve the match between crop needs and soil N cycling relative to conventional tillage systems, by actively managing soil processes to promote greater N mineralization and availability in crop rows compared with inter-rows (Johnstone et al., 2009; Kane et al., 2015; Müller et al., 2009). For example, ridge tillage systems were recently found to increase plant-available N within crop rows compared with inter-rows, which enhanced maize (*Zea mays* L.) tissue N (Kane et al., 2015). Increases in crop row plant-available N were attributed to the re-ridging process that occurs within ridge tillage, in which labile organic matter is redistributed from inter-rows to rows, causing increases in microbial activity (Grigera et al., 2007; Hatfield et al., 1998). These results suggest that zonal management can promote greater spatiotemporal control of soil N availability to coincide with crop peak N demand, and thus improve crop N-use efficiency and reduce N loss. This would represent a major advance in a critical topic relating to agricultural sustainability (Robertson and Vitousek, 2009). However, previous studies have been limited in terms of site-years (e.g. conducted in a single growing season, or across one or two locations). As such, it is unclear whether these results are consistent over multiple growing seasons or are applicable across a wider range of climates and soils.

In this study we compared conventional uniform tillage and zonal management systems at four sites across the US Corn Belt over three growing seasons. We examined spatial distributions of N mineralization and availability across crop rows and inter-rows. We conducted our analysis during the period of maize peak N demand. During this period, crop roots are concentrated within crop rows (Kaspar et al., 1991) and adequate soil N supply is critical to ensure healthy crop development (Karlen et al., 1987; Martens, 2001). We hypothesized that the active management of soil N cycling processes under zonal management (i.e. movement of labile crop residues from inter-rows to crop rows) would enhance N mineralization and availability in crop rows relative to inter-rows. In contrast, N mineralization and availability would show no such spatial configuration in conventional tillage, due to uniform management of crop residues across crop rows and inter-rows.

2. Methods

2.1. Site descriptions and experimental design

The study was conducted at four sites spanning the US Corn Belt: Illinois, Michigan, Minnesota and Pennsylvania, providing wide variation in soil types and climate. Baseline soil properties (taken in 2011) and climate data are provided in Table 1. At each site the experiment was established as a randomized complete block design with four blocks. Each block had eight plots: four under conventional tillage and four under zonal management. Two of the four plots for each tillage system were planted with maize and the other two with soybean (*Glycine max* (L.) Merr.); crops were rotated annually. For each crop, one plot was planted with a winter rye (*Secale cereale* L.) cover crop following maize/soybean harvest; the other plot was left fallow over winter. Each site therefore had a total of $4 \times 8 = 32$ plots. Chisel plow was chosen as a model conventional tillage system; ridge tillage as a model zonal management system. The ridge tillage system is characterized by ridges (crop rows) and furrows (inter-rows) that are formed by row cultivation. In spring, prior to planting, crop rows are cleared for seed planting, and crop residues are concentrated onto the surface of inter-rows and gradually decompose. Once the crop is established, the decomposing crop residues (labile organic matter) in inter-rows are redistributed to crop rows; this typically around the six leaf stage (V6) for maize (see Hatfield et al. (1998) for a more complete description of ridge tillage). Tillage treatments were initiated in 2012. Table S1 (Supplementary material) provides detailed plot management information.

2.2. Soil sampling and N analysis

Soil samples were taken from maize plots over the 2012–2014 growing seasons, giving a total of twelve site-years. Within each growing season, soil samples were collected shortly after maize V6, which occurred approximately seven days after RT re-ridging and coincided with the onset of maize peak N demand (Karlen et al., 1987). In each plot and within each row position (crop row and inter-row) thirty 2.5 cm diameter soil cores were taken to 5 cm depth and bulked to form a composite sample. Samples were kept refrigerated at 4 °C. Plant-available N was calculated as the sum of ammonium (NH_4^+) and nitrate (NO_3^-), determined from 2 M KCl extraction on 5 g field moist soil samples (Keeney and Nelson, 1982). Potentially mineralizable N was calculated as the difference in plant-available N before and after anaerobic incubation of field

Table 1
Baseline soil properties (0–10 cm depth) of the four sites in 2011 and coordinates of their locations. Precipitation and temperature figures are the 30-year means for the growing season (April–October in Illinois; May–October for Michigan, Minnesota and Pennsylvania).

Location	Soil series	Soil type	SOM ($g\,kg^{-1}$)	Bulk density ($g\,cm^{-3}$)	pH	Precip. (cm)	Temp. (°C)	Location
Illinois	Drummer	Silty clay loam	47.9	1.1	6.0	61.6	18.3	40° 3', −88° 15'
Michigan	Marlette	Sandy loam	19.0	1.1	6.2	48.0	17.3	42° 24', −85° 24'
Minnesota	Waukegan	Silty clay loam	42.5	1.3	6.4	69.0	16.9	44° 44', −93° 7'
Pennsylvania	Hagerstown	Coarse silt loam	33.8	1.1	6.3	55.0	17.9	40° 47', −77° 51'

moist soil samples at 37 °C for seven days (Drinkwater et al., 1996). Results were normalized to soil dry weights for statistical analysis and presentation.

2.3. Maize yields

Maize was harvested at full physiological grain maturity, designated by the development of a black abscission layer at the base of kernels. Within two 3 m long rows in each plot, all maize ears were hand harvested. Kernels were mechanically separated from cobs, and fresh grain mass determined. Grain was then dried to constant mass in a forced air oven, and dry mass determined. Maize yields were expressed in kg ha^{-1} at 13.5% moisture content.

2.4. Statistical analysis

Plant-available N and potentially mineralizable N were individually assessed with linear mixed effects models. Tillage (conventional tillage vs. zonal management), cover cropping (rye vs. none) and sample position (row vs. inter-row) were fitted as fixed effects. Growing season (year), site and block were fitted as nested random effects (year/site/block). Maize yield data were also analyzed using linear mixed effects models. Tillage and cover cropping were fitted as fixed effects, and the models had a year/site/block nested random effects structure. Models were fitted with heterogeneous variance structures to account for differences between years and sites (Zuur et al., 2009). All statistical analyses were conducted in R 3.2.2 (R Core Team, 2015), using package *nlme* (Pinheiro et al., 2015); figures were created with *ggplot2* (Wickham, 2009).

3. Results

3.1. Plant-available N and potentially mineralizable N

Zonal management exhibited enhanced N mineralization and N availability in crop rows relative to inter-rows, while conventional uniform tillage did not. Plant-available N and potentially mineralizable N both showed strong tillage × position (row vs. inter-row) effects (plant-available N: $F_{1,336} = 101.66$, $p < 0.001$; potentially mineralizable N: $F_{1,336} = 62.63$, $p < 0.001$). Across all site-years, plant-available N and potentially mineralizable N in zonal management rows were approximately double the amounts in zonal management inter-rows, while the opposite was true in conventional tillage (Fig. 1a, b). Importantly, plant-available N on a per-area basis was appreciably greater in zonal management rows than in conventional tillage rows; when combined with bulk density (data not shown) zonal management rows had on average 13 kg ha^{-1} more N than conventional tillage rows in the top 5 cm of soil. Cover cropping had no effect on plant-available N or potentially mineralizable N ($p > 0.05$).

3.2. Maize yields

Across site-years, maize grain yields ranged between 3000 and 16,500 kg ha^{-1}, and were greatest in Illinois and lowest in Michigan ($F_{3,195} = 37.86$, $p < 0.001$). Yields did not differ by tillage or cover crop treatments (Fig. 2).

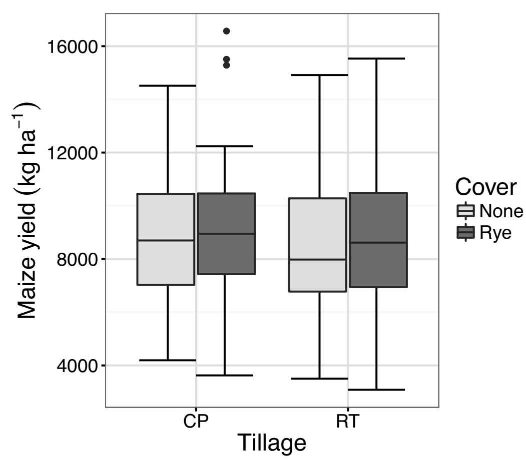

Fig. 2. Maize grain yields by tillage and cover crop treatments over all site-years. CP = chisel plow; RT = ridge tillage. Horizontal line within each box indicates the median; whiskers extend to 1.5 × interquartile range.

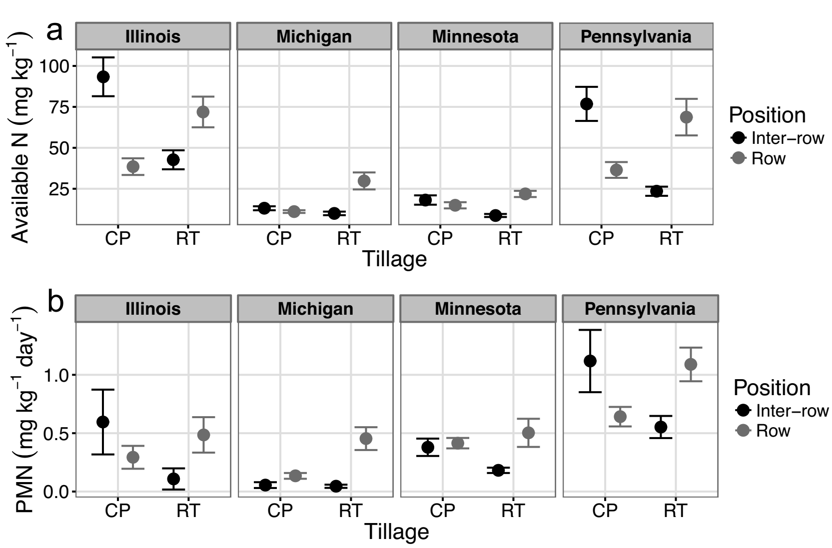

Fig. 1. (a) Soil plant-available nitrogen (N) shortly after maize six leaf stage by tillage and row position at each site. CP = chisel plow; RT = ridge tillage. Data are means averaged across 2012–2014 growing seasons ± 1 SE. (b) Soil potentially mineralizable N (PMN) shortly after maize six leaf stage by tillage and row position at each site. CP = chisel plow; RT = ridge tillage. Data are means averaged across 2012–2014 growing seasons ± 1 SE.

4. Discussion

Our results provide strong support for our hypothesis, and suggest that zonal management can direct soil N cycling processes in both space and time to concentrate N mineralization and availability close to crop roots in synchrony with crop developmental needs. Moreover, these results are consistent across variable growing season conditions, as well as different soil types and climates.

Managing the soil N cycle to reduce the harmful environmental impacts of fertilizer overuse is critical for ecological intensification of agriculture (Mueller et al., 2012). A key component of such intensification is active management of ecosystem services such as nutrient cycling (Bommarco et al., 2013). In the case of the soil N cycle, the goal is to maximize crop N-use efficiency and thereby reduce N losses via leaching and denitrification (Robertson and Vitousek, 2009; Tilman et al., 2002). The redistribution of labile crop residues from inter-rows to crop rows within ridge tillage has been shown to increase microbial activity and N availability in crop rows, which can in turn enhance crop N uptake (Grigera et al., 2007; Kane et al., 2015; Müller et al., 2009). Our results provide evidence of the efficacy of this management that spans a much wider range of soil types, climate, and inter-annual variation than previous studies. Our findings demonstrate how active management of soil N cycling processes under zonal management can promote efficient spatial targeting of soil N resources for crop uptake. This spatial efficiency in soil N cycling processes is absent under conventional chisel plow tillage.

Previous research has shown that in ridge tillage systems, crop root density is greatest in the surface layers of crop rows (0–10 cm) (Hilfiker and Lowery, 1988), and that the re-ridging process stimulates greater root development than occurs under conventional and no-tillage (Thomas and Kaspar, 1995). As such, the concentration of plant-available N and potentially mineralizable N around crop roots under zonal management, in synchrony with crop physiological N requirements, has potential to increase crop N-use efficiency. However, it should be noted that crop root density in ridge tillage is also high below 20 cm depth (Hilfiker and Lowery, 1988; Kovar et al., 1992). As such, more research is required to determine the fate of N resources concentrated on the surface of ridge tillage rows, and whether they actually enhance crop N-use efficiency or are lost from the system.

In contrast, under conventional tillage, plant-available N and potentially mineralizable N were both significantly greater in inter-rows compared with crop rows. This represents a mismatch between the location of the bulk of crop roots and the N required for crop development. It is unlikely that this spatial and temporal asynchrony of N resources has a negative impact on crop development at the high N fertilization rates that are currently used, as our own yield data from this experiment and long-term yield data from conventional tillage systems can attest (Karlen et al., 2013). However, it does indicate that these systems, relative to zonal management, have high potential for lower N-use efficiency and associated N loss (Tilman et al., 2002). Certainly, conventional tillage is known to result in higher rates of N loss via leaching compared with no-tillage and reduced tillage systems (Martens, 2001; Yagioka et al., 2015). Further research is required to determine if zonal management can increase resource-use efficiency, and whether this can allow reductions in N fertilizer application rates compared with conventional tillage systems, without compromising yields.

The effect of tillage on soil N loss via denitrification remains unclear. In general, no-tillage appears to carry a higher risk of nitrous oxide (N_2O) emissions than conventional tillage (Bayer et al., 2015; Martens, 2001), although this is by no means consistent (e.g. Drury et al., 2006). Research has demonstrated that zonal management can lower N_2O emissions compared with both conventional and no-tillage (Drury et al., 2006; Drury et al., 2012). This may be due to the active management of crop residues in zonal management, which are concentrated on the surface of inter-rows in early spring. This clears the row of carbon resources for denitrifying microbes, and combined with seedbed preparation, improves aeration of the crop row compared with no-tillage (Drury et al., 2012). Denitrification risk may be greater in conventional tillage due to the abundance of inorganic N in inter-rows, which have relatively fewer roots compared with rows (Kaspar et al., 1991). In northern temperate systems, peak N_2O emissions occur between June and August (Drury et al., 2006; Drury et al., 2012), which is when soil samples were taken in our study. The unutilized N in conventional tillage inter-rows is therefore at greater risk of gaseous loss compared with the N in zonal management rows, which is concentrated around crop roots in synchrony with crop peak N demand.

Our results demonstrate that zonal management can promote precision control of soil N cycling, allowing greater synchrony in both space and time of soil N availability and N turnover processes with crop physiological demands. The explicit focus that zonal management places on actively managing soil N cycling processes for initial storage (within crop residues) and later mobilization (re-ridging process) may enhance agricultural resource-use efficiency and reduce fertilizer requirements (Williams et al., 2016). Importantly, our multi-regional project shows no significant differences in yield between zonal and conventional tillage systems. Therefore, we find that zonal management of maize-soybean systems advances ecological intensification of these systems, insofar as active management of processes affecting soil N cycling improves the spatiotemporal efficiency of soil N availability while maintaining high yields. Enhancement of beneficial agroecological processes that sustain high yields while improving the environmental performance of agroecosystems is the essence of ecological intensification (Bender et al., 2016; Bommarco et al., 2013). While our study was limited to maize-soybean systems, various implementations of zonal management are used for a wide range of crops, covering cereal, vegetable and fruit production systems (e.g. Balota and Auler, 2011; Haramoto and Brainard, 2012; Müller et al., 2009). Research is urgently needed to examine whether zonal management can enhance resource-use efficiency and reduce fertilizer inputs across these different cropping systems, while maintaining the same level of yield productivity as conventionally managed systems.

Acknowledgements

Thank you Vincent Filicetti, Sheri Huerd, Matt Peoples, Martin du Saire and Lee Yang for help in data collection. This material is based on work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award number 2011-67003-30343. The use of trade, firm, or corporation names in this paper is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the USDA or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable. USDA is an equal opportunity provider and employer.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.07.010.

References

Balota, E.L., Auler, P.A.M., 2011. Soil carbon and nitrogen mineralization under different tillage systems and permanent groundcover cultivation between orange trees. Rev. Bras. Frutic. 33, 637–648.

Bayer, C., Gomes, J., Zanatta, J.A., Vieira, F.C.B., Piccolo, M.d.C., Dieckow, J., Six, J., 2015. Soil nitrous oxide emissions as affected by long-term tillage, cropping systems and nitrogen fertilization in Southern Brazil. Soil Till. Res. 146, 213–222 (Part B).

Bender, S.F., Wagg, C., van der Heijden, M.G.A., 2016. An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol. Evol. 31, 440–452.

Bommarco, R., Kleijn, D., Potts, S.G., 2013. Ecological intensification: harnessing ecosystem services for food security. Trends Ecol. Evol. 28, 230–238.

Drinkwater, L.E., Cambardella, C.A., Reeder, J.D., Rice, C.W., 1996. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Science Society of America, Madison, WI, pp. 217–229.

Drury, C.F., Reynolds, W.D., Tan, C.S., Welacky, T.W., Calder, W., McLaughlin, N.B., 2006. Emissions of nitrous oxide and carbon dioxide: influence of tillage type and nitrogen placement depth. Soil Sci. Soc. Am. J. 70, 570–581.

Drury, C.F., Reynolds, W.D., Yang, X.M., McLaughlin, N.B., Welacky, T.W., Calder, W., Grant, C.A., 2012. Nitrogen source, application time, and tillage effects on soil nitrous oxide emissions and corn grain yields. Soil Sci. Soc. Am. J. 76, 1268–1279.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Grigera, M.S., Drijber, R.A., Wienhold, B.J., 2007. Redistribution of crop residues during row cultivation creates a biologically enhanced environment for soil microorganisms. Soil Till. Res. 94, 550–554.

Haramoto, E.R., Brainard, D.C., 2012. Strip tillage and oat cover crops increase soil moisture and influence N mineralization patterns in cabbage. HortScience 47, 1596–1602.

Hatfield, J.L., Allmaras, R.R., Rehm, G.W., Lowery, B., 1998. Ridge tillage for corn and soybean production: environmental quality impacts. Soil Till. Res. 48, 145–154.

Hilfiker, R.E., Lowery, B., 1988. Effect of conservation tillage systems on corn root growth. Soil Till. Res. 12, 269–283.

Johnstone, P.R., Arnold, N., Pearson, A., Parker, M., 2009. Alternative tillage practice for establishing maize silage and reducing soil nitrogen mineralisation. Agron. New Zeal. 39, 23–32.

Kane, D.A., Snapp, S.S., Davis, A.S., 2015. Ridge tillage concentrates potentially mineralizable soil nitrogen, facilitating maize nitrogen uptake. Soil Sci. Soc. Am. J. 79, 81–88.

Karlen, D.L., Sadler, E.J., Camp, C.R., 1987. Dry matter, nitrogen, phosphorus, and potassium accumulation rates by corn on Norfolk loamy sand. Agron. J. 79, 649–656.

Karlen, D.L., Kovar, J.L., Cambardella, C.A., Colvin, T.S., 2013. Thirty-year tillage effects on crop yield and soil fertility indicators. Soil Till. Res. 130, 24–41.

Kaspar, T.C., Brown, H.J., Kassmeyer, E.M., 1991. Corn root distribution as affected by tillage, wheel traffic, and fertilizer placement. Soil Sci. Soc. Am. J. 55, 1390–1394.

Keeney, D.R., Nelson, D.W., 1982. Nitrogen—inorganic forms. In: Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 643–698.

Kovar, J.L., Barber, S.A., Kladivko, E.J., Griffith, D.R., 1992. Characterization of soil temperature, water content, and maize root distribution in two tillage systems. Soil Till. Res. 24, 11–27.

Müller, E., Wildhagen, H., Quintern, M., Heß, J., Wichern, F., Joergensen, R.G., 2009. Spatial patterns of soil biological and physical properties in a ridge tilled and a ploughed Luvisol. Soil Till. Res. 105, 88–95.

Martens, D.A., 2001. Nitrogen cycling under different soil management systems. Adv. Agron. 70, 143–192.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., R Core Team. (2015). nlme: Linear and Nonlinear Mixed Effects Models. R Package Version 3. 1–122. http://CRAN.R-project.org/package=nlme.

R Core Team. (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org.

Robertson, G.P., Vitousek, P.M., 2009. Nitrogen in agriculture: balancing the cost of an essential resource. Ann. Rev. Environ. Res. 34, 97–125.

Thomas, A.L., Kaspar, T.C., 1995. Maize nodal root response to soil ridging and three tillage systems. Agron. J. 87, 853–858.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Varvel, G.E., Wilhelm, W.W., 2011. No-tillage increases soil profile carbon and nitrogen under long-term rainfed cropping systems. Soil Till. Res. 114, 28–36.

Wickham, H., 2009. ggplot2: Elegant Graphics for Data Analysis. Springer, New York.

Williams, A., Kane, D.A., Ewing, P.M., Atwood, L.W., Jilling, A., Li, M., Lou, Y., Davis, A. S., Grandy, A.S., Huerd, S.C., Hunter, M.C., Koide, R.T., Mortensen, D.A., Smith, R. G., Snapp, S.S., Spokas, K.A., Yannarell, A.C., Jordan, N.R., 2016. Soil functional zone management: a vehicle for enhancing production and soil ecosystem services in row-crop agroecosystems. Front. Plant Sci. 7, 65.

Yagioka, A., Komatsuzaki, M., Kaneko, N., Ueno, H., 2015. Effect of no-tillage with weed cover mulching versus conventional tillage on global warming potential and nitrate leaching. Agric. Ecosyst. Environ. 200, 42–53.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R. Springer, Berlin.