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

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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

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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 × 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'