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Legacy effects of long-term nitrogen fertilizer application on the fate of nitrogen fertilizer inputs in continuous maize

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ABSTRACT

Nitrogen fertilizer management can impact soil organic C (SOC) stocks in cereal-based cropping systems by regulating crop residue inputs and decomposition rates. However, the impact of long-term N fertilizer management, and associated changes in SOC quantity and quality, on the fate of N fertilizer inputs is uncertain. Using two 15-year N fertilizer rate experiments on continuous maize (*Zea mays* L.) in Iowa, which have generated gradients of SOC, we evaluated the legacy effects of N fertilizer inputs on the fate of added N. Across the historical N fertilizer rates, which ranged from 0 to 269 kg N ha^{-1} yr^{-1}, we applied isotopically-labeled N fertilizer at the empirically-determined site-specific agronomic optimum rate (202 kg N ha^{-1} at the central location and 269 kg N ha^{-1} at the southern location) and measured fertilizer recovery in crop and soil pools, and, by difference, environmental losses. Crop fertilizer N recovery efficiency (NRE_{crop}) at physiological maturity averaged 44% and 14% of applied N in central Iowa and southern Iowa, respectively (88 kg N ha^{-1} and 37 kg N ha^{-1}, respectively). Despite these large differences in NRE_{crop}, the response to historical N rate was remarkably similar across both locations: NRE_{crop} was greatest at low and high historical N rates, and least at the intermediate rates. Decreasing NRE_{crop} from low to intermediate historical N rates corresponded to a decline in early-season fertilizer N recovery in the relatively slow turnover topsoil mineral-associated organic matter pool (0–15 cm), while increasing NRE_{crop} from intermediate to high historical N rates corresponded to an increase in early-season fertilizer N recovery in the relatively fast turnover topsoil particulate organic matter pool and an increase in crop yield potential. Despite the variation in NRE_{crop} along the historical N rate gradient, we did not detect an effect of historical N rate on environmental losses during the growing season, which averaged 34% and 69% of fertilizer N inputs at the central and southern locations, respectively (69 kg N ha^{-1} and 185 kg N ha^{-1}, respectively). Our results suggest that, while beneficial for SOC storage over the long term, fertilizing at the agronomic optimum N rate can lead to significant environmental N losses.

1. Introduction

Nitrogen inputs to cereal-based cropping systems are typically necessary to optimize crop yield and profitability over the short-term. In addition, by stimulating crop growth and residue inputs to the soil, N additions can increase soil organic matter (SOM) (Ladha et al., 2011; Poffenbarger et al., 2017), helping to improve soil productivity over the long-term (Pan et al., 2009; Williams et al., 2008). Synthetic N fertilizer is the largest source of N inputs to cropland, exceeding typical contributions from biological N fixation, atmospheric deposition, and animal manures (Liu et al., 2010). However, usually less than half of the fertilizer N applied to maize (*Zea mays* L.), rice (*Oryza sativa* L.), or wheat (*Triticum aestivum* L.) is actually taken up by the crop, and the remainder is stored in the soil or lost to the environment (Cassman et al., 2002). Nitrogen loss from cropland accelerates soil base cation depletion, decreases regional water and air quality, exacerbates coastal hypoxia, and contributes to greenhouse gas emissions (Robertson and Vitousek, 2009).

Minimizing the tradeoff between agricultural productivity and environmental quality requires efficient use of fertilizer N inputs. For this study, we define fertilizer N use efficiency as the proportion of fertilizer N that is taken up by the crop or stored in the soil (Cassman et al.,

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2002). Crop fertilizer N recovery efficiency (i.e., the proportion of fertilizer N that is taken up by the crop; NRE_{crop}) typically decreases with increasing N fertilizer rate because the yield boost provided by each unit of added N diminishes as total N supply approaches the yield-maximizing level (i.e., Law of Diminishing Returns; de Wit, 1992). However, at a given N fertilizer rate, NRE_{crop} increases with increasing availability of other resources (e.g., water) because the crop is able to produce more biomass from a given N supply when growth is not limited by other factors (i.e., Law of the Optimum; de Wit, 1992). Because SOM is positively associated with both plant-available N supply (Culman et al., 2013; Osterholz et al., 2017b; Spargo et al., 2011), as well as the availability of other key soil resources (e.g., porosity, plant-available water, other nutrients) (Loveland and Webb, 2003), SOM may be an important factor regulating NRE_{crop} through one or both of these mechanisms.

Soil organic matter content may also impact the proportion of fertilizer N that is recovered in the soil (NRE_{soil}) (Barrett and Burke, 2002; Castellano et al., 2011). As SOM levels increase, stable SOM pools, which include fractions that are physico-chemically protected from mineralization through mineral-association and/or microaggregation, can become saturated (Six et al., 2002; Stewart et al., 2008). Once saturated, these pools have limited capacity to stabilize new organic C, leading to an enrichment of labile, partially-decomposed plant litter and organic residues known as ‘particulate organic matter’ (POM) (Brown et al., 2014; Gulde et al., 2008). Particulate organic matter is decomposed relatively quickly, except when physically protected from decomposition by occlusion within aggregates (Six et al., 1998). Previous research indicates that organic and inorganic N, like organic C, can exhibit saturation behavior, meaning that soils with high SOM content have limited capacity to protect against the mineralization of added N that has been microbially-transformed into organic compounds (Castellano et al., 2011; Poirier et al., 2014). As a result, added N may accumulate as inorganic N, which is susceptible to environmental losses, or be immobilized and re-mineralized during the decomposition of POM (Burger and Jackson, 2003; Castellano et al., 2011; Compton and Boone, 2002; Ladd et al., 1977).

In this study, we determined how legacy effects of long-term N fertilizer application on stable and labile SOM pools would affect NRE_{crop} and NRE_{soil} as well as environmental losses. We proposed two alternative hypotheses regarding NRE_{crop}: 1) increasing SOM decreases NRE_{crop} by increasing the supply of plant-available N, thus reducing crop response to N fertilizer inputs, 2) increasing SOM increases NRE_{crop} by optimizing soil resources other than N. We also hypothesized that increasing SOM decreases NRE_{soil} by decreasing fertilizer N retention in mineral-associated organic matter. To test these hypotheses, we measured the recovery of fertilizer N in crop and soil pools along SOM gradients generated by long-term N fertilization of continuous maize.

2. Materials and methods

2.1. Nitrogen fertilization experiments

Long-term N fertilizer rate experiments were established in 1999 at two Iowa State University Research and Demonstration Farms – one located in central IA (42°01′N; 93°47′W) near Ames, IA and the other located in southern IA (40°58′N; 93°25′W) near Chariton, IA. Soils at the central location are classified as Hapludolls and Endoaquolls with predominantly loam surface texture, while soils at the southern location are classified as Argialbolls and Argiudolls with predominantly silt loam surface texture according to the USDA Soil Taxonomy (Soil Survey Staff, 2018). The N fertilizer rate experiment in central IA is underlain with artificial subsurface (‘tile’) drainage at a depth of 1.2 m. Tile drainage is common to the region and installed on approximately 50% of Iowa maize cropland. In contrast, the southern location does not have artificial subsurface drainage. Soils at the central location are generally more productive than those at the southern location: the dominant Corn Suitability Rating (CSR2) values for the central and southern locations are 88 and 41, respectively (Soil Survey Staff, 2018). Mean annual precipitation for 1999–2014 was 970 mm at the central location and 980 mm at the southern location; mean annual temperature over the same time period was 9.1 °C at the central location and 9.5 °C at the southern location (Iowa State University, 2017).

The experimental design at each location is a randomized complete block design with four replicates. Each replicate block is planted to maize every year and divided into five (central) or seven plots (southern), which each measure 4.6 m in width × 15.2 m in length and receive the same N rate every year. The N rates applied at the central location range from 0 to 269 kg N ha^{-1} yr^{-1} in 67 kg N ha^{-1} yr^{-1} increments (five rates), while those at the southern location range from 0 to 269 kg N ha^{-1} yr^{-1} in 45 kg N ha^{-1} yr^{-1} increments (seven rates). Maize is planted lengthwise in the plots with a row spacing of 0.8 m (six rows per plot). The trials are managed with fall chisel plowing and spring disking and field cultivation before planting. Nitrogen fertilizer is applied as either urea incorporated at planting or as urea ammonium nitrate solution injected 1–4 weeks after planting. Phosphorus, K, S, and soil pH are maintained for optimum production based on soil testing.

Average grain yields and selected soil properties for each location are presented in Table 1. Average grain yields from 2000 to 2014 were used to determine the agronomic optimum N rate (i.e., the N rate that maximizes yield; AONR) at each site using the quadratic-plateau method described in Cerrato and Blackmer (1990). The AONR was determined using grain yield data from only those years that followed a maize crop, therefore 1999 was excluded. The AONR for the central location was 202 kg N ha^{-1} yr^{-1}. The AONR could not be precisely defined at the southern location because grain yield increased up to the highest N rate applied (269 kg N ha^{-1} yr^{-1}), so we set the AONR to be 269 kg N ha^{-1} yr^{-1} at this site (Poffenbarger et al., 2017).

2.2. Subplot N applications

In spring 2015, two 4.6-m wide × 3.1-m long subplots were established within each plot. One subplot received no N fertilizer (zero-N subplot), while the other received the site-specific 2000–2014 AONR (optimum-N subplot) using NH_4NO_3 solution (4 l per subplot). The central portion of each optimum-N subplot (2.3-m wide × 3.1-m long, encompassing the second through fifth rows) received the AONR with $^{15}NH_4{}^{15}NO_3$ (3.6 atom % at central location and 3.3 atom % at southern location); the remaining area of each subplot received non-labeled NH_4NO_3. The N solutions were applied to the soil surface of each subplot using a handheld backpack sprayer after secondary tillage and maize planting, but before emergence. Maize was planted at a seeding rate of 89,000 seeds ha^{-1} on May 13 (central location) and on April 28, 2015 (southern location). Nitrogen applications for the subplots were made on May 19 and April 30, 2015 at the central and southern locations, respectively. The remaining area within each main plot received the same N fertilizer rate that it historically received as hand-broadcasted SuperU on the same day that the subplot N fertilizer applications were made. SuperU is a pelleted urea that contains a nitrification inhibitor and urease inhibitor (Koch Agronomic Services, Wichita, KS). Subplots were thinned at the two-leaf stage to achieve consistent populations among all subplots. Maize populations averaged 83,200 plants ha^{-1} (SE = 1178) at the central location and 86,800 plants ha^{-1} (SE = 600) at the southern location. Weed control was accomplished using pre- and post-emergence herbicide applications. Supplemental hand weeding was performed (with weed residue returned to the soil surface) to maintain weed-free subplots.

2.3. Residue cover

At the maize ten-leaf stage in 2015, residue cover from the previous year’s crop was visually assessed across the N input gradient. A 3-m