Can mineralization of soil organic nitrogen meet maize nitrogen demand?

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Abstract

Aims

High-yielding maize-based crop systems require maize to take up large quantities of nitrogen over short periods of time. Nitrogen management in conventional crop systems assumes that soil N mineralization alone cannot meet rapid rates of crop N uptake, and thus large pools of inorganic N, typically supplied as fertilizer, are required to meet crop N demand. Net soil N mineralization data support this assumption; net N mineralization rates are typically lower than maize N uptake rates. However, net N mineralization does not fully capture the flux of N from organic to inorganic forms.

Methods

Here we utilize a long-term cropping systems experiment in Iowa, USA to compare the peak rate of N accumulation in maize biomass to the rate of inorganic N production through gross ammonification of soil organic N.

Results

Peak maize N uptake rates averaged 4.4 kg N ha^{-1} d^{-1}, while gross ammonification rates over the 0-80 cm depth averaged 23 kg N ha^{-1} d^{-1}. Gross ammonification was highly stratified, with 63%

occurring in the 0-20 cm depth and 37% in the 20-80 cm depth. Across the three cropping systems with varied rotation lengths and fertilizer inputs, neither peak maize N uptake rate nor gross ammonification rate differed significantly.

Conclusions

Gross ammonification rate was 3.4 to 4.5 times greater than the peak maize N uptake across the cropping systems, indicating that inorganic N mineralized from soil organic matter may be able to satisfy a large portion of crop N demand and explicit consideration of gross N mineralization may contribute towards strategies that reduce the reliance of crops on large soil inorganic N pools that are easily lost to the environment.

Keywords

Nitrogen mineralization; ammonification; maize; cropping systems; nitrogen uptake

Introduction

Globally, maize (*Zea mays*) receives higher inorganic N fertilizer inputs (mean rate 136 kg N ha^{-1}) than any other cereal crop (FAO 2006). High N inputs to maize result from high crop N demand; for instance a 10 Mg ha^{-1} crop will take up between ~125 and 310 kg N ha^{-1} (Ciampitti and Vyn 2012). In situations with high yield potential, rates of N uptake by maize may exceed the rate of N supply from the soil. Indeed, Magdoff (1995) argued that N supply from mineralization of soil organic matter (SOM) is insufficient to match N demand during the peak growth phase of maize. This argument is supported by studies demonstrating that rates of net N mineralization are typically much lower than rates of maize N uptake (Ma et al. 1999, Pang and Letey 2000, Brye et al. 2003, Loecke et al. 2012).

However, net N mineralization may not fully represent the soil's ability to supply N to crops. In contrast to gross N mineralization, which measures the rate of production of inorganic ammonium (NH_4^+) by heterotrophic soil organisms, net N mineralization measures the change over time in the size of the soil inorganic N pool in the absence of roots (i.e., crop uptake). Historically, net N mineralization has been assumed to be an accurate indicator of plant N availability because roots are considered poor competitors against microbes for inorganic N and thus can only access N that is mineralized in excess of microbial demand (Schimel and Bennett 2004).

In contrast, a growing body of work questions the assumption that plants can only access N that is mineralized in excess of microbial demand (Kaye and Hart 1997, Schimel and Bennett 2004). Recent work has demonstrated that a cereal crop was able to accumulate a greater amount of added inorganic N than microbes by competing directly with microbes for inorganic N (Inselsbacher et al. 2010). If the rate of N supply from organic matter mineralization can meet or exceed the rate of N uptake of maize, dependence on large soil inorganic N pools could be greatly reduced. Agroecosystems that employ organic N sources rather than inorganic N sources can achieve better coupling of C and N cycling processes (Drinkwater and Snapp 2007), which may in turn enable a greater number of plant-microbe N competition events that allow for both sufficient plant N uptake as well as relatively small soil inorganic N pools. Small inorganic N pools could potentially increase the efficiency of N management because reliance on large soil inorganic N pools often leads to large environmental N losses (Robertson and Vitousek 2009).

Despite this potential, a comparison of the rates of potential N supply (i.e., gross ammonification) and crop N uptake has not yet been undertaken. Nitrogen can be supplied to a crop through application of inorganic N fertilizer, application of organic N fertilizer (manure) that is subsequently mineralized, biological N fixation, and through the mineralization of native soil organic N. For example, ^{15}N tracer studies show that N mineralized from SOM typically provides >50% the N assimilated by maize over a growing season despite large N fertilizer applications (Cassman et al. 2002, Stevens 2005, Gardner and Drinkwater 2009). The supply rate of N from mineralization of native organic N sources is limited by the rate at which organic N is mineralized by microbes into NH_4^+ (i.e. gross ammonification rate). This newly mineralized NH_4^+ is subject to various competing transformations: nitrification, immobilization into the microbial biomass, and uptake by plants (Robertson and Vitousek 2009). Most agricultural N management strategies assume that only net N mineralization – the mineral N remaining from gross ammonification after microbial immobilization demand has been satisfied – is available to plants. That is, plants are only able to access mineralized N that exceeds microbial demand. For this reason, much research effort has focused on using net N mineralization as a predictor of plant available N (Olfs et al. 2005), and multiple comparisons of cumulative seasonal net N mineralization and maize N uptake show that maize N uptake consistently exceeds net N mineralization (Ma et al. 1999, Brye et al. 2003, Zhao et al. 2004, Loecke et al. 2012, Hartmann et al. 2014). Based on the assumption that maize N demand exceeds the supply of N from the soil, conventional N management strategies aim to use inorganic N fertilizer applications to optimize inorganic N pool size and thus prevent shortfalls in N supply.

The use of net N mineralization measurements to estimate N supply is problematic if the crop can successfully compete with microbes for a limited supply of inorganic N. Immobilization of N by microbes has often been viewed as a challenge in agricultural nutrient management, but this process acts a critical short term sink for inorganic N and may increase nutrient use efficiency. While microbial immobilization can outcompete plant uptake for a limited inorganic N supply over the short term (hours to days), the relatively long lifespan of plant roots compared to soil microbes enables plants to eventually sequester inorganic N over longer time periods (days to weeks) (Hodge et al. 2000). In natural systems, plants have been shown to effectively compete with microbial immobilization for NH_4^+ (Kaye and Hart 1997), and recent laboratory studies have extended these results to agricultural crops (Xu et al. 2007, Inselsbacher et al. 2010). Thus, direct measurement of gross ammonification rates may provide a more complete indicator of potential N supply than net N mineralization assays.

The distinction between gross ammonification and net N mineralization is further illustrated by the weak correlation between gross ammonification rates and net N mineralization rates (Booth et al. 2005), as each of the N consumption processes that compete for mineralized NH_4^+ occur simultaneously and depend on a number of factors (Mary and Recous 1994, Schimel and Bennett 2004), precluding the determination of gross ammonification rates using net N mineralization data. Thus, efforts to predict the supply of inorganic N using net N mineralization measurements could lead to false conclusions regarding the true N supplying capacity of soil. The N supplying capacity of soil is an important biochemical indicator of SOM quality as it provides insight into potential plant N availability that cannot be provided by more commonly used chemical indicators such as total N (Gil-Sotres et al. 2005, Schomberg et al. 2009). Conventional agricultural N management strategies have largely lacked a strong focus on optimizing the indigenous soil N supply, instead relying on inorganic N fertilizer additions to achieve high levels of crop production, resulting in a failure to achieve high levels of synchrony between crop N demand and N supply (Cassman et al. 2002). Investigation of the true inorganic N supplying capacity of the soil, i.e. gross ammonification, could provide insights to help address this asynchrony and reduce N lossese to the surrounding ecosystem.

Here, we directly test the prediction that the potential rate of soil N mineralization is less than the peak rate of crop N uptake. We utilized a long-term experiment in Iowa, USA, to examine the relative rates of maize N uptake and gross ammonification in three cropping systems that vary in crop rotation length, N management, and SOM dynamics (Lazicki 2011, Davis et al. 2012). Our experiment site was particularly well suited to address this question because diversified cropping systems that utilize organic N fertility sources can maintain relatively small inorganic N pools yet still achieve high maize N uptake (Sanchez et al. 2004). We linked direct measurements of crop growth and N uptake with laboratory assays of gross ammonification in order to compare gross ammonification to a depth of 80 cm to peak maize N uptake rates. Our goals were to: 1.) investigate how maize N demand compares to the potential supply of inorganic N as measured by gross ammonification and 2.) explore the effect of conventional and alternative maize-based cropping systems on the relative rates of maize N uptake and gross ammonification.

Methods

The Marsden Farm cropping systems experiment was established in 2002 in Boone County, Iowa, USA (42°01’ N, 93°47’ W), and consisted of three cropping systems: a 2-year maize-soybean (*Glycine max*) rotation that utilized a conventional N fertilizer management program, a 3-year maize-soybean-oat (*Avena sativa*)/red clover (*Trifolium pratense*) rotation with composted manure application, and a 4-year maize-soybean-oat/alfalfa (*Medicago sativa*)-alfalfa rotation with composted manure application (Liebman et al. 2008, Davis et al. 2012). A 104-day maturity maize hybrid (Viking 72-04N) was planted at 79,600 seeds ha^{-1} on April 22, 2014. From the initiation of the experiment in 2002 through 2014 an average of 112 kg N ha^{-1} yr^{-1} of inorganic N fertilizer (as urea or urea-ammonium-nitrate) was applied at maize planting in the 2-year system only, while over the same period 11.5 Mg ha^{-1} yr^{-1} of composted cattle manure containing 164 kg total N ha^{-1} was applied in the fall preceding maize planting in the 3-year and

4-year systems. Soil testing was used to determine additional inorganic N fertilizer application rates in all three systems (Blackmer et al. 1997). During the measurement year (2014) supplemental N fertilizer was applied on June 11, 2014 at a rate of 56 kg N ha^{-1} 2-year system and 28 kg N ha^{-1} in the 3- and 4-year systems as urea-ammonium-nitrate solution (28% N). These rates were comparable to the 12-year average supplemental fertilizer rates (41, 27, and 18 kg N ha^{-1} in the 2-year, 3-year, and 4-year systems, respectively). Thus, total inorganic N fertilizer application in 2014 was 168 kg N ha^{-1} in the 2-year system and 28 kg N ha^{-1} in the 3- and 4-year systems. Symbiotic N fixation during cultivation of red clover and alfalfa also likely added significant quantities of N to the more diversified systems. These additions would play an important role in the N balance of the cropping systems, but N fixation was not addressed in this research as the magnitude of N fixation was not measured and previously reported rates of symbiotic N fixation are poorly constrained and site specific (Carlsson and Huss-Danell 2003, Gelfand and Roberston 2015). Additional management details can be found in the Appendix. Soils at the experiment site consisted of loam and clay loam Mollisols with 4.0-7.9% SOM, and after 12 years of management, there were no consistent differences in SOM between the three cropping systems (Table A-1). The experiment was arranged in a randomized complete block design with all entry points of the three crop rotations (i.e. all crops within each of the rotations) represented in four replicate blocks in each year of the study. Plots measured 18 m × 85 m.

Maize N uptake rate was determined by sequential sampling of aboveground plant materials and subsequent fitting of mathematical functions to growth data (Hunt 1982). Four whole maize plants were sampled from each plot on 10 dates during the 2014 growing season. Sampling intervals were chosen to coincide with plant growth stages V1, V4, V8, V11, V17, R1, R2, R4, R5, and R6 (Abendroth et al. 2011). Samples were dried at 60°C and weighed, then total

N in aboveground biomass was determined by homogenizing the entire plant sample and analyzing a subsample for N concentration by dry combustion elemental analysis in a LECO Truspec CHN analyzer (LECO Corp. St. Joseph MI, USA). Nitrogen content was then plotted against accumulated growing degree days (GDDs) (Base T=10°C, Max T=30°C) for the sampling dates as recorded by a weather station located ~1 km from the experiment site. Curves were then fit to plots of total N content against GDDs for each experimental plot using the Beta function (Yin et al. 2003) in SigmaPlot 11.0 (Systat Software Inc., London, UK). Uptake rate of N was determined by taking the derivative of the N mass curve. Maximum potential daily N uptake rate was estimated by multiplying the peak N uptake rate as determined by the N uptake curve by the maximum daily GDDs observed during the growing season (16.3 GDD). Maize N uptake estimates were conservative as they did not take into account root N, which typically comprises 15-20% of total plant N (Sanchez et al. 2002, Loecke et al. 2012). Maize yield was determined from the central six rows of the plots using a combine harvester and weigh wagon, and yields were corrected to a moisture content of 155 g H_2O kg^{-1} grain.

Gross ammonification rates in the three cropping systems were measured in the laboratory using the pool dilution method (Hart et al. 1994) on soil cores taken within one week of the peak corn N uptake rate. In each experimental plot 35 soil cores (18 mm diameter) from 0-80 cm depth were taken randomly throughout the plots on July 18-21, 2014. Cores were split into three depths (0-20 cm, 20-50 cm, and 50-80 cm), bulked by depth and stored at 4° C. Field moist soils were gently sieved by hand to pass though large mesh size (8 mm) in order to minimize disruption of macro- and micro-aggregates and avoid unnecessary stimulation of microbial activity. Within seven days of sampling, triplicate cores (3 cm diameter x 5 cm depth) were re-packed with field moist soil (moisture content ranged from 0.18 to 0.30 g H_2O g^{-1} soil) to a bulk density of 1.24, 1.30, and 1.36 g cm^{-3} for the 0-20 cm, 20-50 cm, and 50-80 cm depths, respectively, based on data collected in 2007 (data not shown). Preliminary data showed sieving and re-packing of cores was required due to high variability in inorganic N concentrations between intact paired soil cores, which violated a methodological assumption of equivalent inorganic N concentrations. The sample processing likely had only minor impacts on the gross ammonification measurements, as the sieving of soil at large mesh sizes has been shown to have minor impacts on microbial N cycling processes in tilled agricultural soils (Jones and Shannon 1998, Franzluebbers 1999). Additionally, laboratory-based measurements allowed us to avoid making assumptions regarding the consistency of inorganic N pool sizes that are required of in situ measurements (Weitzman and Kaye 2016). After re-packing, soil cores were injected with $^{15}NH_4$ solution (5 mL of 30 mg NH_4-N L^{-1} at 4% APE), whereby a side-port needle (15 cm length) was inserted into the core and slowly extracted as solution was injected to distribute solution throughout the core. Five injections of 1.0 mL each were made. The solution addition increased soil water content by ~0.1 g H_2O g^{-1} soil to 0.28-0.40 g H_2O g^{-1} soil, corresponding to a 35-60% increase. Initial ^{15}N enrichment and N concentration were determined after 10 minutes where one core per plot was homogenized by mixing in a plastic bag, then a 20 mg dry soil equivalent subsample was extracted in 100 mL 2 mol L^{-1} KCl, shaken on a reciprocal shaker at 150 rpm for one hour and subsequently filtered through Whatman No. 42 filter paper. The two remaining cores were capped and incubated at 23°C for 24 hours, then extracted by the same method. Ammonium concentrations of extracts were determined colorimetrically (Hood-Nowotny et al. 2010). Nitrogen isotope ratios were determined by diffusing NH_4^+ in the extracts onto filter paper (Brooks et al. 1989), then analyzing the filter papers at the University of California-Davis stable isotope facility with a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). Gross ammonification rates were calculated using the equation:

Gross ammonification rate = $(M_0 - M) / t \times (\log(H_0 M / H M_0) / \log(M_0/M))$

where M_0 is the mass of NH_4^+ at initial extraction, M is mass of NH_4^+ after incubation, t is time of incubation, H_0 is mass of $^{15}NH_4^+$ at initial extraction, and H is mass of $^{15}NH_4^+$ after incubation (Kirkham and Bartholomew 1954). Gross ammonification rate was determined separately for the duplicate cores. Values were converted to per ha basis using bulk density values measured in fall 2014 when bulk density was found to be 1.17, 1.22, and 1.33 g cm^{-3} for the 0-20 cm, 20-50 cm, and 50-80 cm depths. Excess gross ammonification was determined by calculating the difference between gross ammonification rate and maximum maize N uptake rate.

Gross ammonification rate was analyzed with split plot ANOVA, where individual plots were the main plot and depths were the split plot, with cropping system and depth treated as fixed factors and blocks treated as a random factor. Data were square root transformed to fulfill the assumption of normality of variance. Maximum maize N uptake rate, excess gross ammonification, and N uptake as a percentage of gross ammonification were analyzed by ANOVA with treatment as a fixed factor and block as a random factor. Analyses were done using proc MIXED of SAS 9.2 (SAS Institute Inc., Cary, NC).

Results

Gross ammonification rate was greatest in the 0-20 cm depth, intermediate in the 20-50 cm depth, and lowest in the 50-80 cm depth ($p<0.001$, Fig. 1). On average, the 0-20 cm, 20-50 cm, and 50-80 cm layers of soil accounted for 63%, 24%, and 13% of total gross ammonification, respectively. Mean gross ammonification was not significantly different among the three rotations ($p=0.44$), but trended towards greater ammonification in the extended rotations compared to the 2-year rotation; the average gross ammonification rate of the 3- and 4-year rotations was 27% greater. Across the three rotations the average total gross ammonification for the 0-80 cm depth was 23 kg N ha^{-1} d^{-1}. The rotation x depth interaction was not significant (p=0.62).

Maize N uptake rate peaked for all plots between 832 GDDs (July 24) and 917 GDDs (July 31), with an average of 877 GDDs (July 27) (Fig. 2) which coincided with the R2 stage of maize development. In contrast to the average gross N mineralization rate of 23 kg N ha^{-1} d^{-1}, maximum maize N uptake rates ranged from 3.6-5.7 kg N ha^{-1} d^{-1} and averaged 4.4 kg N ha^{-1} d^{-1} across the cropping systems (Fig. 3). While maximum N uptake rates were not significantly different in the three cropping systems (p=0.13, Fig. 3), there was a trend for greater maximum maize N uptake rate in the extended rotations compared to the 2-year rotation. Maize grain yields averaged 12.8, 13.2, and 13.6 Mg ha^{-1} in the 2-, 3-, and 4-year systems, respectively. Maize grain yields compared favorably with the 2014 county average yield of 11.4 Mg ha^{-1}.

Discussion

A comparison of maize N uptake rates with potential gross ammonification rates indicated an excess of gross ammonification ranging from 5.2 – 36 kg N ha^{-1} d^{-1} (Fig. 4). Maize N uptake accounted for only a small proportion of the potential rate of N mineralization (Fig. 5), which suggests that microbial production of NH_4^+ could potentially be sufficient to meet maize N demand. As maize required only 12-60% of the measured gross ammonification in this study, we believe there exists an opportunity to decrease dependence on inorganic N fertilizers through small inorganic N pools with high turnover rates, coupled with crops successfully competing with microbes for mineralized N. Utilization of organic N sources in order to enhance the reliance of crops on mineralized organic N is a well established strategy for efficient N management (Lowrance et al. 1984, Drinkwater and Snapp 2007), and management techniques including incorporation of legume residues and utilization of animal manures have been shown to increase net N mineralization (Wander et al. 1992, Sanchez et al. 2001). However, these strategies have focused on net N mineralization rates and have not explicitly considered the potential role of gross ammonification for plant N supply, and thus may underestimate the potential that exists for increasing reliance on N mineralization. Furthermore, the weak correlation between gross ammonification and net N mineralization (Booth et al. 2005) indicates that use of net N mineralization data to estimate potentially plant available N may lead to significant errors. We contend that an increase in efforts to measure gross ammonification rates could advance understanding of potential crop N availability and microbe-crop competition for potentially available N. However, the ^{15}N pool dilution method that is currently used to measure gross N cycling rates is both time consuming and costly, and relatively simple assays of N mineralization potential (e.g. potentially mineralizable N, Schomberg et al. 2009) measure net N mineralization rates but not gross ammonification. The development of new, less costly techniques that utilize spectroscopy may accelerate the measurement of gross ammonification (Kira et al. 2014). Additionally, the development of reliable indicators of gross ammonification could enable broader investigation of gross N cycling processes (Zaman et al. 1999, Luxhøi et al. 2006).

Gross ammonification rate and the degree to which maize plants are able to compete with other N consumption processes will determine whether gross ammonification is sufficient to meet crop N demand. Both gross ammonification and net N mineralization rates are enhanced in soils with high concentrations of organic substrates (Murphy et al. 2003, Booth et al. 2005, Zeller and Dambrine 2011), and agricultural management practices that increase labile organic matter, such as manuring, have been shown to enhance gross ammonification rates (Zaman et al. 1999, Flavel and Murphy 2006, Habteselassie et al. 2006). Soil food web complexity may be another important driver of gross ammonification and subsequent plant N uptake (Clarholm 1985, Mikola and Setälä 1998, Ferris et al. 2004), and management practices that optimize food web complexity could enhance gross ammonification rates. As microbial turnover is typically a much faster process than root turnover, greater rates of microbial turnover would increase the frequency of root-microbe N competition events. The ability of a crop to compete for mineralized N will depend on a number of factors including microbial immobilization demand, nitrification and denitrification rates, and soil characteristics that determine the mobility of different forms of N such as porosity, moisture, and clay content. Furthermore, it is likely that crop traits like root system morphology, quantity and quality of rhizodeposits, and N uptake efficiency could play an important role, suggesting an opportunity for breeding efforts to enhance fertilizer N use efficiency (Gregory 2011). Future research is needed to understand and predict how edaphic factors and crop genotypic identity influence gross ammonification rate and the competitiveness of maize and other crops for mineralized inorganic N.

Additional evidence suggests that inorganic N mineralized from SOM is often able to satisfy crop N demand despite net N mineralization rates that are surpassed by crop N uptake (Loecke et al. 2012). In seven of the 12 years since the Marsden Farm cropping systems experiment was established, maize in the 3- and 4-year rotations did not receive inorganic N fertilizer during the growing season but still achieved yields equal to or greater than in the conventionally fertilized 2-year rotation despite soil NO_3^- concentrations that were 33% lower (measured in June - data not shown). Furthermore, maize N fertilizer rate trials in the US Maize Belt often identify a significant proportion (> 30%) of sites where maize yield shows no response to inorganic N fertilizer application (i.e. yields are not enhanced by inorganic N fertilizers) (Lory and Scharf 2003). It is possible that in some of these non-responsive sites net N mineralization (or a combination of net N mineralization and inorganic N carryover from the previous growing season) meets or exceeds maize N demand, despite evidence showing net N mineralization rates to be much lower than maize N demand. Alternatively, maize plants may be meeting their N demand through competition with microbial immobilization for gross ammonification. Further research is needed to discern if these observations support our contention that organic N mineralization can fully satisfy maize N demand without diminshing the organic N pool.

Cropping system did not have a significant effect on gross ammonification rate, although other studies have shown that management factors can influence gross ammonification rates. In agroecosystems, cropping systems and practices that include forage crops and organic matter amendments have been shown to increase gross ammonification rates (Burger and Jackson 2003, Habteselassie et al. 2006, Flavel and Murphy 2006). These effects of management are likely due in part to associated increases in SOM, as a meta-analysis found that total soil C and N explained a significant amount of variation in gross ammonification rate (R^2=0.42) across a wide range of ecosystems (Booth et al. 2005). The lack of a significant cropping system effect on gross ammonification in the present study is likely due in part to limited cropping system effects on SOM. While the diversified cropping systems did maintain modestly greater labile soil C (particulate organic matter C) compared to the 2-year system in the top 20 cm of soil (Lazicki et al. 2016), similar differences could not be observed in the total SOM pool despite 12 years of consistent management differences between the cropping systems (Appendix), possibly because our experiment was established on Mollisols with high pre-existing SOM levels that may be C saturated (Brown et al. 2014). Thus the modest differences in labile C may not have led to observable changes in gross ammonification. Additionally, high variability in gross ammonification measurements restricted our ability to detect significant system effects, and it is possible that more intensive measurement could reveal such effects.

Gross ammonification rates from the maize agroecosystems in this study were relatively high compared to a collection of data from a range of agricultural ecosystems including grasslands and arable cropland (Booth et al. 2005), possibly due to the high SOM content in this study. Measurements of gross ammonification in agricultural systems are much less common than net N mineralization, and are particularly scarce at soil depths greater than 20 cm. While the majority of gross ammonification occurred in the surface 20 cm of soil where OM is typically concentrated, the 20-80 cm soil depths contributed a significant portion (37%) of the total gross ammonification and this is likely to play an important role in crop N supply; it is also one reason our results are relatively high compared to Booth et al. (2005).

Maize N uptake was only measured in above-ground biomass in this study. Adding root N at a rate of 20% of the aboveground N uptake (Loecke et al. 2012) would only slightly increase crop N uptake relative to gross ammonification, as the crop would need to obtain 12-60% of gross ammonification. While disturbance of soil samples and laboratory based measurements invariably influence results, soil homogenization has not been shown to significantly impact gross ammonification rates (Murphy et al. 2003, Luxhøi and Jensen 2005). Furthermore, in the agricultural systems studied here the top ~30 cm of soil is regularly disturbed via tillage and thus soil processing by sieving did not cause a novel degree of physical disturbance to the system. Our method for measuring gross ammonification rates was designed to minimize the impact of the measurement procedure on pre-existing rates in the field. A short measurement time period was utilized to avoid shortages in labile SOM induced by microbial activity, as well as to minimize recycling of the ^{15}N label. Measurements were conducted under soil moisture and temperature conditions favorable for aerobic microbial activity but near the range of soil conditions that may be observed over the maize growing season in this region, where soil moisture reaches 0.4 g g^{-1} soil following large precipitation events and soil temperatures often reach 27°C at 5 cm depth and 23°C at 50 cm depth. We did not attempt to address the influence of soil moisture and temperature conditions on gross ammonification rates, but drier and cooler soil conditions would likely reduce gross ammonification (Andersen and Jensen 2001, Booth et al. 2005); however, these conditions would also reduce the rate of maize N uptake (Zhang et al. 2002) and the overall effect on relative rates of N uptake and gross ammonification is unknown. Additionally, plants (including maize) have been shown to enhance N mineralization activity in the rhizosphere and thus the supply of N from organic N pools (Hamilton and Frank 2001, Sanchez et al. 2002), so that the utilization of soil in the absence of plants in this study likely caused some underestimation of the true gross ammonification rates. Despite the potential shortcomings of laboratory measurements, gross ammonification rates in this study compared favorably with field-based measurements in maize-based cropping systems (Weitzman and Kaye 2016), suggesting that the rates presented here are reasonable approximations of gross ammonification under field conditions and provide a useful first approximation of the potential N supplying capacity of these soils.

Conclusions

Inorganic N produced by gross ammonification of soil organic N was relatively high compared to maize N uptake, contradicting a common assumption of many N management strategies that maize N demand is greater than soil N supply. Across three maize-based cropping systems, gross ammonification rate was 3.4 to 4.5 times greater than the peak maize N uptake.

The feasibility of meeting maize N demand during periods of peak uptake with soil organic N mineralization will depend on the ability of the crop to compete with other consumption pathways for mineralized NH_4^+. Further research should focus on further quantification of gross ammonification in agricultural systems, outcomes of competition events between crop uptake and other fates of NH_4^+, and the effects of agronomic management on internal N cycling dynamics of agroecosystems.

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Figures

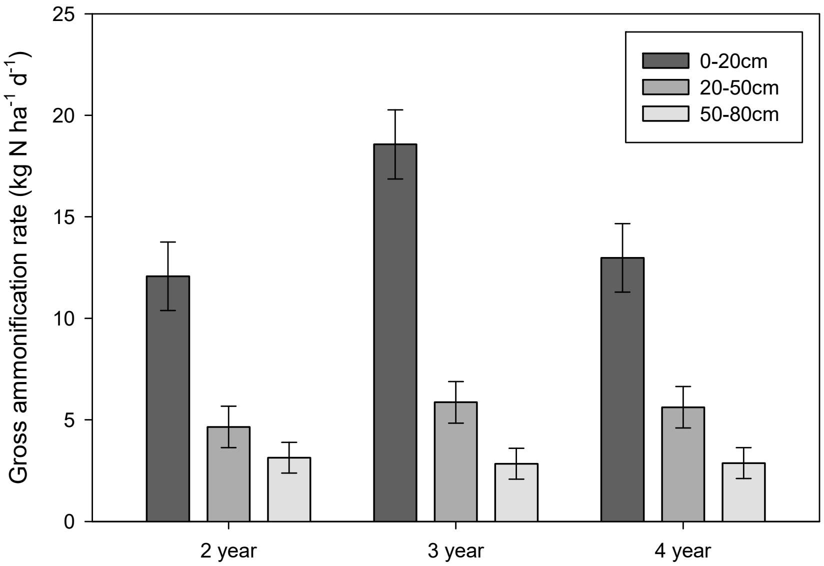

Figure 1. Gross ammonification rates at three depths in the three crop rotations. Gross ammonification was greatest in the 0-20 cm depth, intermediate in the 20-50 cm depth, and lowest in the 50-80 cm depth. Rates were not significantly different among crop rotation systems. Means and their standard errors are shown.

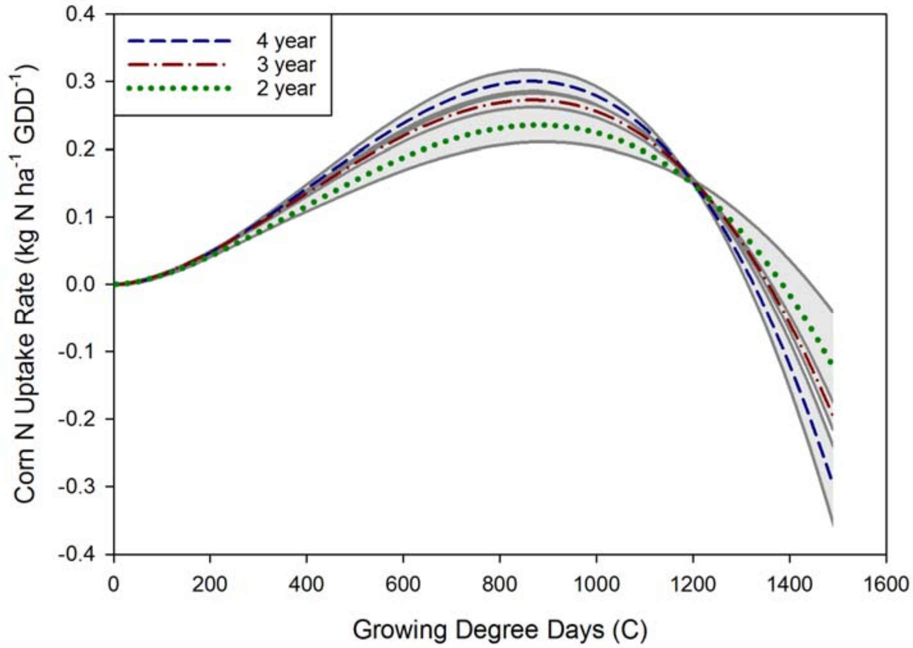

Figure 2. Maize N uptake rates over the course of the growing season in the three cropping systems. Colored lines are cropping system means and shaded areas represent standard errors of the means.

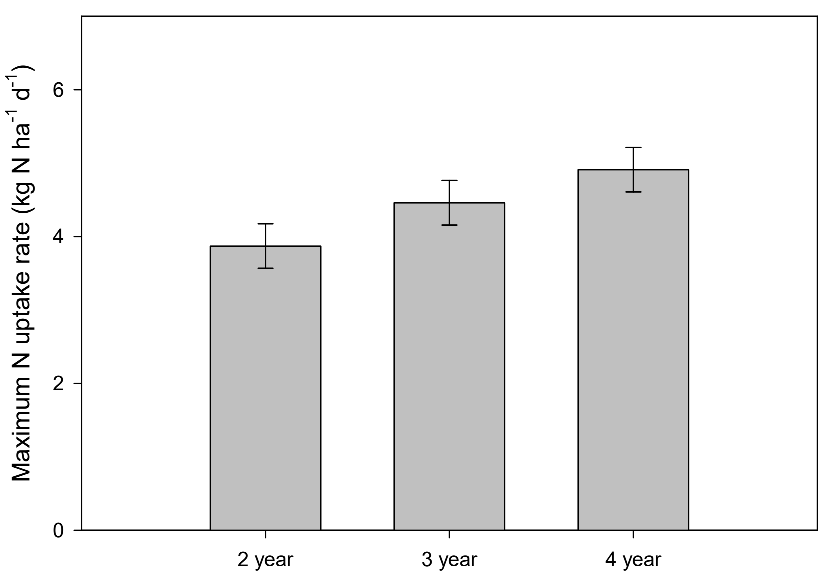

Figure 3. Maximum maize N uptake rates were not significantly different in the three cropping systems ($p=0.13$) and averaged 4.4 kg N ha^{-1} d^{-1} across the systems. Daily values of maximum N uptake rate were calculated by multiplying peak N uptake rate by the maximum observed daily GDDs (16.3).

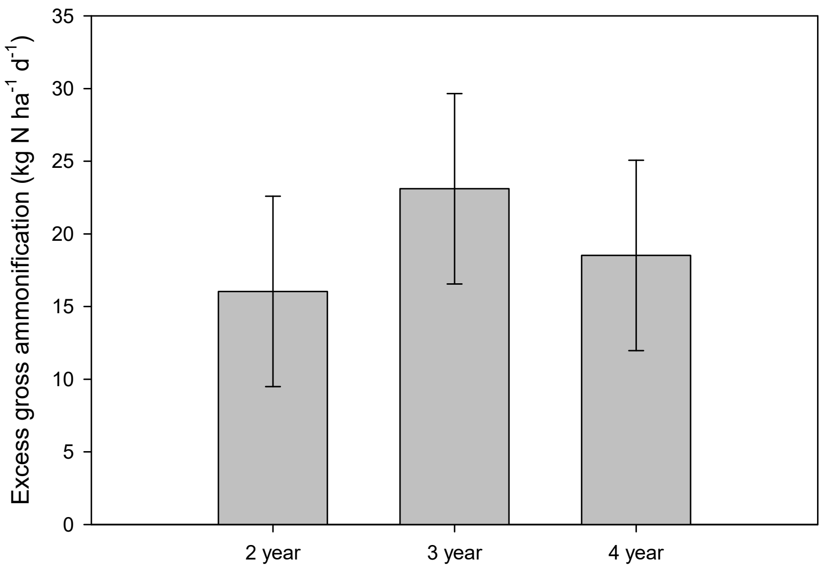

Figure 4. Excess gross ammonification (0-80 cm gross ammonification rate minus maximum maize N uptake rate) were not significantly different in the three crop rotations ($p=0.35$). Means and their standard errors are shown.

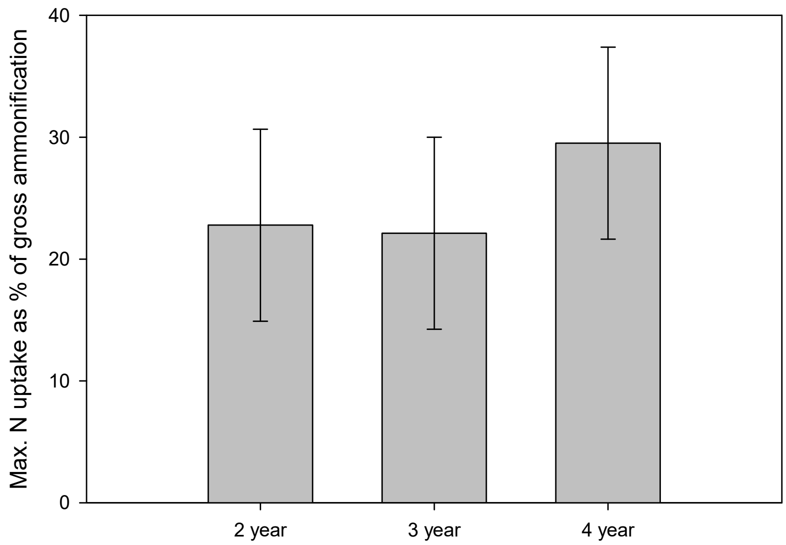

Figure 5. Maximum maize N uptake rate as a percentage of total gross ammonification rate (0-80cm) was not significantly different in the three crop rotations (p=0.6). Means and their standard errors are shown.

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Appendix

Table A-1. Timing of field operations and soil organic matter (SOM) levels in the corn phase of the three cropping systems at the Marsden cropping systems experiment in 2014.

System	SOM %*	Operation	Date	Notes**
2-year	5.1 ± 0.4	Field cultivation	4/21/2014	
		N fertilizer application	4/21/2014	112 kg N ha^{-1}
		Corn planting	4/22/2014	79,600 seeds ha^{-1} Viking 72-04N
		Herbicide application	4/22/2014	Thiencarbazone methyl (0.037 kg ha^{-1}), isoxa-flutole (0.092 kg ha^{-1})
		N fertilizer application	6/11/2014	56 kg N ha^{-1}
		Corn grain harvest	10/6/2014	12.67 Mg ha^{-1}
3-year	5.4 ± 0.4	Composted manure application	10/29/2013	11.5 Mg ha^{-1}, C:N = 12.7, 160 kg N ha^{-1}
		Field cultivation	4/21/2014	
		Corn planting	4/22/2014	79,600 seeds ha^{-1} Viking 72-04N
		Herbicide application	4/22/2014	Thiencarbazone methyl (0.037 kg ha^{-1}), isoxa-flutole (0.092 kg ha^{-1})
		N fertilizer application	6/11/2014	22 kg N ha^{-1}
		Corn grain harvest	10/6/2014	13.21 Mg ha^{-1}
4-year	6.0 ± 0.4	Composted manure application	10/29/2013	11.5 Mg ha^{-1}, C:N = 12.7, 160 kg N ha^{-1}
		Field cultivation	4/21/2014	
		Corn planting	4/22/2014	79,600 seeds ha^{-1} Viking 72-04N
		Herbicide application	4/22/2014	Thiencarbazone methyl (0.037 kg ha^{-1}), isoxa-flutole (0.092 kg ha^{-1})
		N fertilizer application	6/11/2014	22 kg N ha^{-1}
		Corn grain harvest	10/6/2014	13.87 Mg ha^{-1}

*Mean % SOM ± SE as calculated from total organic C measurements performed by elemental analysis of soil samples (0-20 cm) collected in fall 2013, where SOM = TOC / 0.58.

** Seeding rates, N fertilizer and herbicide application rates, and yields. Corn yields reported at 155 g H_2O kg^{-1} grain