In-situ soil nitrogen mineralization in response to nitrogen management for corn and soybean in poorly drained soils with and without tile drainage

Fabián G. Fernández[1], Karina Fabrizzi[1]
[1] University of Minnesota, 1991 Upper Buford Circle, St Paul, MN, 55801, http://www.swac.umn.edu/, fabiangf@umn.edu

Abstract
Greater understanding of N mineralization is needed to improve N rate guidelines and fertilizer efficiency. Our objective was to quantify N mineralization throughout the growing season when corn (Zea mays L.) and soybean [Glycine max (L.) Merr.] are grown under different N and soil drainage management. In-situ N mineralization incubations were conducted in drained and undrained soils with corn and soybean and different N rates over a two-year period. In the first three years of drainage installation 2.4 Mg C ha^{-1} yr^{-1} were lost. This factor combined with the effect of drainage on soil water content, N rate, and previous crop substantially influenced net mineralization and mineralization rate. However, substantial yearly differences due to moisture conditions often overshadowed the effects of these variables. Our results highlight the need to continue concerted research efforts to refine our understanding of how different factors influence the mineralization process to improve N management.

Key Words
ammonification, nitrification, inorganic nitrogen, sub-surface drainage

Introduction
Evaluation of N use efficiency in cropping systems is becoming more important as farmer-profit margins narrow and reactive N results in environmental degradation. While N fertilizer rate is not the only parameter influencing N use efficiency, optimizing N rates for agronomic and environmental considerations has—and likely will continue to—receive much attention. Some of the reasons for the focus on N rate are that N is commonly the most limiting nutrient for corn (*Zea mays* L.) production, it represents a major input cost, and losses to the environment typically increase when excess N is applied.

Selecting optimal N fertilizer rates is surprisingly difficult, however. While many laboratory studies have quantified potentially mineralizable N, in-situ field experiments are limited. Inadequate quantification of the mineralization potential of soil organic N and crop residue N and a lack of effectively integrating the various factors that impact mineralization across the growing season have posed limitations to our ability to more precisely predict fertilizer N response and improve N use efficiency. Inorganic N levels have an important role in controlling mineralization of soil organic matter and crop-residue N (Wu et al., 2008). It is been known for many year through incubation studies that considerable quantities of fertilizer N are immobilized during net mineralization of soil N. The addition of N fertilizer often invokes a priming response that enhances soil N mineralization. The consequence of priming of soil N is that the contribution of N from crop residue and soil organic matter is often underestimated or ignored when N fertilizers are added (Wu et al., 2008). Understanding N contributions from mineralization could be helpful to improve our N rate guidelines.

Finally, N mineralization from soil and crop-residue is controlled by many factors beyond N fertilizer rate, such as: organic matter, crop residue quality and microbial factors, which are highly controlled by soil drainage characteristics. In much of the US Midwest, crop production would not be possible without tile drainage. Yet, a recent survey (unpublished) showed that 53% of cropland has artificial drainage, but an additional 19% of the total cropland would benefit from tile drainage. Surprisingly characterization of N mineralization of N fertilized soils under different drainage and crop residue conditions is lacking. Our objective was to quantify N mineralization throughout the growing season when corn and soybean [*Glycine max* (L.) Merr.] are grown in a corn-soybean rotation under different N and soil drainage management.

Methods
The study was conducted in a field near Wells, MN (43°51'15.76"N; 93°43'47.28"W) on a poorly drained Marna silty clay loam (Fine, smectitic, mesic Vertic Endoaquolls) and a somewhat poorly drained Nicollet silty clay loam (Fine-loamy, mixed, superactive, mesic Aquic Hapludolls) soil. In the spring of 2011 tile drainage was installed (1.2-m depth and 9-m tile spacing) with control drainage structures to create eight blocks (four replications) with two drainage condition: 1) Undrained conditions with closed control drainage structures and 2) Drained conditions with fully opened control drainage structures. The year of drainage

installation the field was fallow and in 2012 a corn (Zea mays L.)-soybean [Glycine max (L.) Merr.] rotation was established by dividing in half each of the drainage blocks and randomly assigning either corn or soybean crops in each half. Since establishment, the drainage conditions and crop rotation have not changed.

The study was set up in a split-split-plot arrangement in a randomized complete-block design with four replications. Drainage: Drained and Undrained was assigned to the main plot, crop: Corn and Soybean was assigned to the split plot, and N rate was assigned to the split-split plot. The N rates were established in 3x9-m plots, with four crop rows (0.76-m row spacing) per plot. Urea-N (46-0-0) (N-P-K) was applied 22 May 2014 and 30 April 2015 as a broadcast application and incorporated by tillage within 24 hrs and N rates remained in the same plots during the study. The N rates for corn were in a rotation with soybean where soybean received no N and corn received no N (0N), or 135 kg N ha^{-1} (135N) (typical farmers practice). The N rates for soybean were in a rotation with corn where corn received 135 kg N ha^{-1} and soybean received no N (0N) or 45 kg N ha^{-1} (45N). Corn and soybean were planted on 23-24 May 2014 and 4-5 May 2015.

Weather data were collected from the nearest weather station. Volumetric water content (VWC) and temperature from the 0-15 cm depth was monitored continuously for each drainage and crop variable, using 5TM sensors and Em50 digital data loggers (Decagon Devices Inc., Pullman, WA). We used an in-situ sequential core sampling technique to measure net N mineralization and nitrification. Incubation PVC tubes (5.22 cm inner diameter and 20 cm length) were driven into the soil to a 15 cm depth and capped and at the same time a four-core (1.91-cm diameter) composite soil sample from the 0-15 cm depth was collected near the incubation tube. The four-core samples were weighed, a subsampled was removed to oven-dry (105°C) for moisture determination and to calculate soil bulk density, and the rest of the soil was dried at 35°C, ground, and extracted for NH_4^+ and NO_3^-. After the incubation period, the incubation tubes were removed and the soil was processed as described above. This process of obtaining initial and final extractions after incubation was repeated 7 times in 2014 and 11 times in 2015. Incubation periods were targeted at 14 days. If substantial precipitation (typically >30 mm) occurred before the targeted 14-day incubation period, a new cycle was started earlier to ensure similar moisture conditions inside the capped incubation tube and the surrounding soil where crops were growing. Moisture difference inside and outside the incubation tube at the end of each incubation period were minimal (mean difference was 0.5 cm^3 cm^{-3}). Net N mineralization and nitrification rates were calculated by subtracting final from initial N concentrations for each incubation interval, and summing over all incubation intervals to determine annual rates of N cycling.

Data analysis was done using PROC GLIMMIX procedure of SAS to test for differences among treatments. Means were compared using the DIFF option of the LSMEANS statement. Analysis of soil NH_4^+ and NO_3^- data over time was done using repeated measurement with compound symmetry as covariance structure. Total mineralized N at the end of growing season was analysed by fertilizer rate (fertilized or check), considering year, drainage and crop as fixed effects and block as random effect.

Results

Weather and Soil Conditions

Precipitation in the 2014 had a variable pattern distribution through the growing season (April to October). April and especially June were wetter than the 30-yr normal, 58 and 110 mm more respectively. May, July and October were drier than the 30-yr normal, 62, 76, and 30 mm less, respectively. August and September had near normal precipitation. The 2015 season (April to October) was characterized by an even distribution pattern of precipitation with April through July and September with slightly greater (6 to 26 mm) than normal precipitation and August only 13 mm below normal; but October was 41 mm drier than the 63 mm normal. In 2014 mean air temperature was cooler than the 30-yr normal for April, May and July and warmer than normal for June and August with September and October near normal. In 2015 mean air temperature was at or above normal for April through June and cooler than normal for July and August. September and October were substantially warmer with 3.6 and 2.0 °C warmer temperatures than the normal, respectively. Daily soil temperature followed closely the mean daily air temperature for both growing seasons and was not affected by drainage or crop variables (data not shown). The VWC of drained and undrained soils closely followed precipitation events in both years. The undrained soil had 12% greater (P <0.001) VWC in 2014 and 22% greater (P <0.001) VWC in 2015 than the drained soil. Only in 2014 there was an interaction with crop where the undrained soybean had 17% greater (P<0.001) VWC than the undrained corn, resulting from differences developed during the July-August period (data not shown).

At 0-15 soil depth, TOC and TN were greater in the undrained (41 Mg C ha^{-1} and 2.9 Mg N ha^{-1}) than drained (34 Mg C ha^{-1} and 2.4 Mg N ha^{-1}) soil regardless of crop variable. Since temperatures were similar between drainage variables, it is likely that greater soil water content in the undrained soil protected organic matter from decomposition. It is well known that drainage often is the most important local factor influencing organic matter accumulation. It is remarkable that in only 3 years since drainage variables were imposed, the soil lost 2.4 Mg C ha^{-1} yr^{-1} due to tile drainage.

Mineralization

Net mineralization of total inorganic N (TIN) was positive for all variables in both years except for 135N in undrained corn in 2015 (Table 1). Without N, mineralization rates were generally low (Fig. 1a,c) but N fertilization increase rates (Fig. 1b,d) that were as high as 9.6 kg TIN ha^{-1} day^{-1} for fertilized corn in the undrained soil in 2014. In 2014 N fertilization increased TIN mineralization and mineralization rate most noticeably in undrained corn whereas in 2015 the increase was most important for this N rate in the drained soil (Fig. 1b,d). The previous crop residue also influenced mineralization rate, in soybean (corn residue) mineralization rates were generally negative early in the growing season whereas in corn (soybean residue) mineralization rates were positive earlier in the growing season. While we did not measure N uptake rates by the crops, it is well established that early in the season crop uptake rates are low. This asynchrony between high mineralization rates early in the season and low uptake rates by the crop is unfortunate as the mineralized N is being supplied too early and has greater potential to be lost before the crop can use it. On the other hand, pre side-dress soil test are done during the early part of the growing season and the larger amount of mineralized N likely provides a better estimate of availability than otherwise would be possible.

Weather conditions in 2015 were favorable for crop production with corn producing 12.8 Mg ha^{-1} seed yield and 10% greater than 2014 with the 135N fertilizer rate and soybean producing 5.4 Mg ha^{-1} seed yield and 34% greater than 2014 with the 45N fertilizer rate. The favorable temperatures and uniform precipitation distribution also enhanced net mineralization in the unfertilized (control) soil by 2.5 times relative to 2014 (Table 1). When fertilizer was added the variability in net mineralization increased and it was not possible to establish a statistical difference, though numerically fertilizer N resulted in a 64% drop in net mineralization compared to 2014, likely due to denitrification losses in the undrained soil that was consistently wetter than the drained. Undrained conditions increased cumulative net mineralization by 20% over the drained conditions for the control and a similar pattern occurred for the fertilized treatment though there were not statistical differences. Greater mineralization in undrained conditions may be the result of greater TOC and TN compared to the drained soil. Soil in corn production increased cumulative net mineralization by 71% compared to soil in soybean production when no N was added. This substantial increase in mineralization in corn was likely the effect of the previous soybean crop residue that mineralized quickly compared to the previous corn crop residue in soybean that resulted in net negative mineralization early in the season as previously discussed (Fig. 1). When fertilizer was applied, soil in corn mineralized 3.8 times more TIN than the soil in soybean, likely due the differences in previous crop residue but also the fact that the corn crop received 90 kg N ha^{-1} more than the soybean crop. A significant year by drainage interaction when N was applied showed that for undrained soils a large amount (178 kg N ha^{-1}) of TIN was mineralized in 2014 whereas no TIN was mineralized in 2015. Uniform precipitation in 2015 kept the undrained soil sufficiently wet and the wet soil along with high N substrate from the fertilizer likely promoted season-long denitrification losses. This loss in 2015 compared to 2014 was also illustrated in corn grain yield. For the 135N rate undrained conditions caused only a 3% reduction in corn grain yield compared to the drained conditions in 2014, whereas in 2015 the yield reduction was 12%. These results highlight the importance of continuing to investigate and more fully understand the factors that influence the mineralization process.

In corn TIN mineralized from the total N in the 0-15 cm soil depth across years ranged from 0.6% (0N rate) to 4.4% (135N rate) in the drained and 1.5% (0N rate) to 4.6% (135N rate) in the undrained soils. In corn, averaged across all variables, soils mineralized 2.8% of the total soil N. This value is in keeping with the 1.9 to 3.1% of total soil N in the 0-20 cm soil depth for corn reported by (Wu et al., 2008). In soybean TIN mineralized from the total N in the 0-15 cm soil depth across years ranged from 0.4% (0N rate) to 1.1% (45N rate) in the drained and 0.8% (0N rate) to 1.4% (45N rate) in the undrained soils. In soybean, averaged across all variables, soils mineralized 1.3% of the total soil N. The soil provided through the process of mineralization 60% of the total N taken up by corn and 10% of the N taken up by soybean. Still, N fertilization was important to increase grain yield and enhance the capacity of the soil to mineralize N. Averaged across the two years corn produced 12.2 Mg ha^{-1} and 42% above the 0N with the 135N rate

(P<0.01). Averaged across crops and drainage conditions TIN mineralized from the total N was 3.5 times greater with N fertilizer than the unfertilized check. Our results highlight the fact that the soils in our study have a substantial capacity to supply N, but additional N inputs are needed to maximize corn productivity and to enhance the capacity of the soil to mineralize N.

Table 1. Mean cumulative total inorganic N (TIN) mineralized by the end of the 2014 and 2015 growing season as affected by crop and soil drainage with different N fertilizer rates (corn: 135 kg N ha^{-1}; soybean: 45 kg N ha^{-1}).

Variable	Control (0N)	Fertilized
	kg N ha^{-1}	
Year		
2014	13b†	115
2015	32a	41
P<F	0.0130	0.1823
Drainage		
Drained (D)	12b	68
Undrained (UD)	34a	88
P<F	0.0068	0.7060
Year x Drainage		
2014-D	7	53ab
2014-UD	19	178a
2015-D	17	84ab
2015-UD	48	-1b
P<F	0.2120	0.0690
Crop		
Corn	29a	124a
Soybean	17b	33b
P<F	0.0980	0.0925

†Within variable and fertilizer rate, means followed by the same letter are not significantly different based on the *P* values present in the table. Non-significant (P>0.1) interactions are not presented.

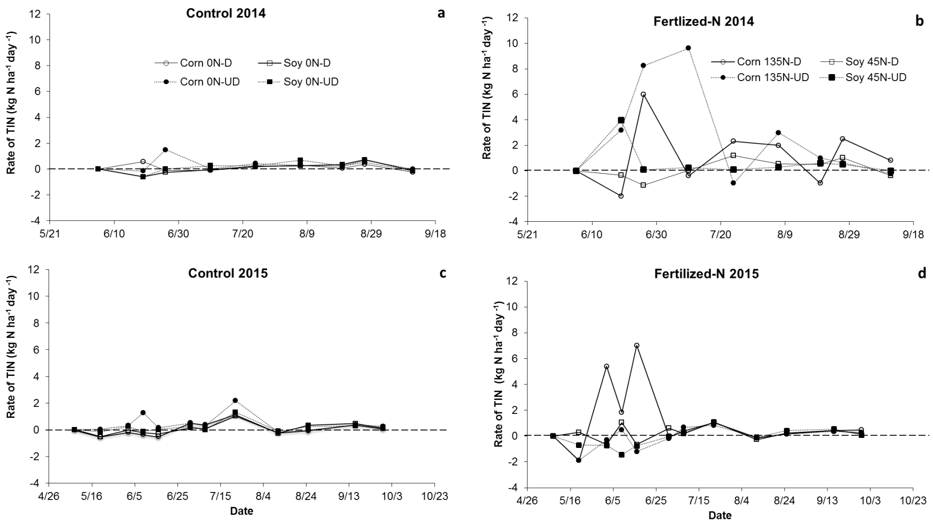

Figure 1. Rates of total inorganic N (NH_4^+-N + NO_3^-N) (TIN) production in the 0-15 cm soil depth increment during the 2014 and 2015 growing seasons for corn receiving 0 or 135 kg N ha^{-1} and soybean receiving 0 or 45 kg N ha^{-1} in drained (D) and undrained (UD) soil conditions.

Conclusion

Nitrogen rate, drainage, and previous crop residue influenced mineralization and mineralization rate. However, substantial yearly differences due to moisture conditions can make it difficult to predict the effect of these variables on the amount of mineralization, especially when N fertilizer is applied. Our results highlight the need to devote greater efforts towards better understanding the mineralization process.

References

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