Reactive nitrogen cycling and potential ecosystem services trade-offs in an eastern Corn Belt soil

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Abstract

Outcome of ecosystem services assessments across a range of agroecosystems can be governed by management choices. Additionally, systematic nitrogen (N) additions in agricultural fields can pose a crucial dilemma as N inputs are needed to achieve yield goals, but they also typically cause increases in edge-of-field N losses that frequently deteriorate both water and air qualities. This study examines potential ecosystem services trade offs in typical US Corn Belt managed ecosystems. We quantify long-term nitrate (NO_3^-) loads in subsurface drains, and nitrous oxide (N_2O) fluxes at soil surface in corn (*Zea mays* L.) monocultures (CC) receiving annually-repeated N inputs of spring- or fall-applied liquid swine manure (SM and FM, respectively), or spring-applied urea-ammonium nitrate (UAN), and in an unfertilized, restored prairie grass (PG). Losses of both N_2O and NO_3^- from PG were negligible. The greatest N_2O emissions occurred in CC's receiving either UAN or SM (6.4-8.2 kg N_2O-N /ha/yr), while CCFM exhibited an intermediate magnitude (3.3 kg N_2O-N /ha/yr). Conversely, CCFM increased NO_3^- losses by roughly 1.7-fold relative to all other CC treatments (33 vs. 19 kg NO_3^--N /ha/yr) revealing a clear directional trade off between N_2O and NO_3^- outcomes when shifting between FM and SM managements.

Key Words

Ecosystem resilience, soil quality, life cycle assessment, provisioning, regulating, and supporting services.

Introduction

Conceptually, "ecosystem services" refers to any benefit that human society can derive from natural or managed ecosystems (Tilman 2002; Daily and Matson 2008). Ecosystem services are typically classified as provisioning (e.g., water, grain, biomass, energy), supporting (e.g., nutrient cycling and dispersion), regulating (e.g., climate regulation, water purification), and cultural types (e.g., recreational, ecotourism). Within conventional agricultural systems, management choices have been disproportionally made toward enhancing provisioning services (i.e., harvested grain), and performance assessments for these systems have been typically based only on achievement of pre-established yield goals (Tilman 2002). Consequently, other potentially beneficial ecosystem functions such as efficient nutrient cycling and removal of contaminants from the environment are usually ignored and/or neglected resulting in detrimental outcomes for these ecosystem services (Palmer and Filoso 2009; Vitousek 2009). The dilemma regarding these apparently competing ecosystem services becomes even more critical in the case of N cycling as N inputs are typically key factor for sustaining high productivity in agroecosystems, but the associated increases in N losses to the atmosphere (e.g., N_2O) and surface and groundwater bodies (e.g., NO_3^-) can substantially diminish environmental quality. Lately, it is being recognized the need to use methodologies that would allow to comprehensively assess all the known ecosystem services and environmental consequences in a given scenario. This information would be useful for decision making processes based on the premise that management choices can alter the overall outcome of ecosystem services from agroecosystems. Basic steps in these balanced, integral assessments include to enhance data availability as well as to assess the directional outcomes of multiple ecosystem services. Thus, the objective of this study was to examine the potential ecosystems services trade offs within typical US Corn Belt managed ecosystems particularly focusing on NO_3^- vs. N_2O losses from soils as well as other associated components of the terrestrial reactive N cycling such as soil and plant N pools and grain yield.

Materials and methods

This study was conducted at the Water Quality Field Station located at Purdue University ACRE farm, West Lafayette, IN (40°29'55" N, 86°59'53" W, 215 m elevation). Soil series are Drummer silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll) and Raub silt loam (fine-silty, mixed, superactive, mesic Aquic Argiudoll). Between 1998 and 2006, we quantified NO_3^- effluxes at subsurface drains by determining both drainage water flow and dissolved NO_3^- concentrations using conventional colorimetric analytical methods, corn grain yield, N pools in both corn plant and surface soil (Hernandez-Ramirez *et al.* 2009b), and

soil surface N_2O emissions as point measurements using static chamber (Hernandez-Ramirez et al. 2009b). The experimental site has 12 treatments in a randomized complete block design with four replicates and experimental plots with dimensions of 10.8×48 m^2. Treatment arrangement includes four factors: managed ecosystem, N source, rate, and timing. The managed ecosystems were corn-soybean [Glycine max (L.) Merr.] rotation with sets of experimental plots for both crops (corn: CS and soybean: SC) in any given year, continuous corn (CC), and an unfertilized restored prairie grass (PG) dominated by big bluestem (Andropogon gerardii Vitman) served as a control. The N sources for corn treatments were UAN [28% (w/w) N] injected either in preplant (PP) or side-dressed (SD) at corn growth stage V5, and liquid swine manure [C/N ratio: 2:1, 80% (w/w) of N as NH_4^+] injected into CC at a rate of 255 ± 24 kg N /ha/yr in either the spring (SM) or the fall (FM). The UAN application rates and timings for CS treatments were 135 at SD, and 157 at PP and 180 at PP, and for CC treatments were 157 at SD, and 180 at PP and 202 kg N /ha/yr at PP. Both UAN and manure were placed at a depth of 0.10 m in the soil. The resulting treatment combinations were PG, CCSM, CCFM, CCUAN 157SD, CCUAN 180PP, CCUAN 202PP, CSUAN 135SD, SC (~ 135SD), CSUAN 157PP, SC (~ 157PP), CSUAN 180PP, and SC (~ 180PP). To clearly differentiate our three SC treatments, we included in parentheses in their acronyms the N rates and timings of the corresponding three CS treatments in crop rotations in our study. Analyses of variance models and Tukey test at a critical value of 0.05 were run to examine treatment effects.

Results and discussion
Effects of management choices on soil-water-air quality aspects
Environmental quality assessment of the managed ecosystems at this long-term experimental site primarily encompasses quantification of critical components and fluxes within the reactive compartment of the N cycle including NO_3^- losses, N_2O emissions as well as soil and plant N pools. Regarding NO_3^- leaching to drainage water, one of the most novel, striking findings was the substantially increased NO_3^- loss caused by annually-repeated FM additions which resulted in roughly 1.7-fold greater NO_3^- losses than SM as well as CCUAN's treatments (33 vs. 19 kg N /ha/yr; $P< 0.001$; Figure 1A). These highest NO_3^- losses from CCFM can be directly attributed to abundant precipitation (i.e., rain and snow; data not shown) and the associated major drainage events taking place during the winter and early spring after manure-N additions in the late fall. Another interesting-unique feature of this dataset is that PG restoration system consistently minimized NO_3^- quantities resulting in relatively negligible NO_3^- losses (2.5 kg N /ha/yr; Figure 1A). This outcome can be explained because PG management consists in N additions, no tillage operations, and annual burning of aboveground biomass residues that could increase gaseous N losses (Hernandez-Ramirez et al. 2009a). Tillage and/or N additions would have stimulated organic matter mineralization and associated NO_3^- production in these soils. In addition, PG typically has a longer growing season than maize cultivation resulting in greater overall water uptake and a consequent decreased percolation in PG fields as well as increased N uptake and storage by PG perennial roots (Huggins et al. 2001). Hence, these several combined factors likely suppressed NO_3^- losses from PG fields. It is also remarkable the changes in magnitude of NO_3^- losses between the corn (CS) and soybean (SC) phases of these crop rotations (Figure 1B). Irrespective of UAN rate and time of N addition, all three corn-soybean rotations registered approximately 15% increased NO_3^- losses in SC relative to CS ($P<0.001$). This pattern can be explained by carry over effects from a given corn growing season into the immediately following fall-to-spring period before soybean cultivation. High soil residual NO_3^- after corn years (Kaspar et al. 2007) and lower soil N uptake by soybean can be concomitant causes for enhanced NO_3^- exportation from these fields within SC phase. As expected, FW NO_3^- concentrations mirrored NO_3^- flux patterns (Figure 1A; Figure 1B).

Quantification of N_2O emissions from soil surface to the atmosphere in selected treatments revealed the greatest N_2O losses in CC fields receiving either spring-applied manure or UAN (8.2 or 6.4 kg N_2O-N /ha/yr, respectively; Figure 2). Nitrogen management using fall-applied manure for CC resulted in significantly lower N_2O losses. These patterns could be explained by enhanced soil N uptake and use efficiency in CS rotation phase and by manure additions in CC during the late fall shortly prior to cold-wet soil conditions that can limit nitrification and denitrification processes (Hernandez-Ramirez et al. 2009b). These sharp FM vs. SM differences support the pronounced effect of time of N additions in agricultural soils on the outcomes of N_2O emissions as well as NO_3^- losses as discussed above. Spring UAN addition in CS rotation phase also registered numerically reduced N_2O losses perhaps due to increased soil N uptake and associated improved N use efficiency by corn. As noted above, PG system received minimum management and also soil N availability in PG is likely limited in part due to effective N competition between microbes and plant roots. These various factors can explain the negligible soil N_2O emission levels in PG (0.24 kg N_2O-N /ha/yr).
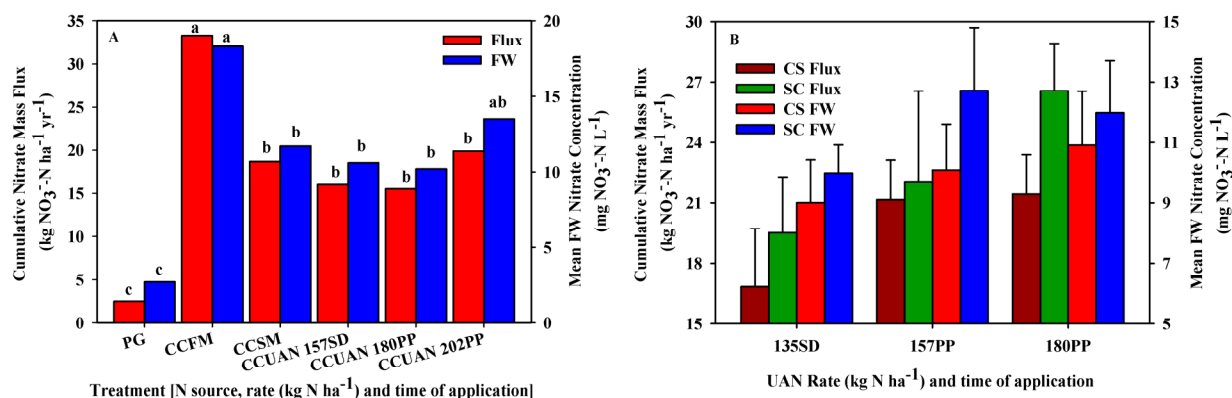
Figure 1. Annual cumulative loads and mean flow-weighted (FW) concentrations of nitrate in subsurface drainage water for (A) prairie grass (PG) and continuous corn (CC) systems, and (B) corn (CS) and soybean (SC) rotation phases. Urea-ammonium nitrate (UAN) rates and time of N additions are noted. Within each variable, treatments labelled by the same letter are not different based on Tukey's HSD test ($\alpha = 0.05$). Values are averages of six hydrological years. Error bars are SE. Note the different scales across panels.
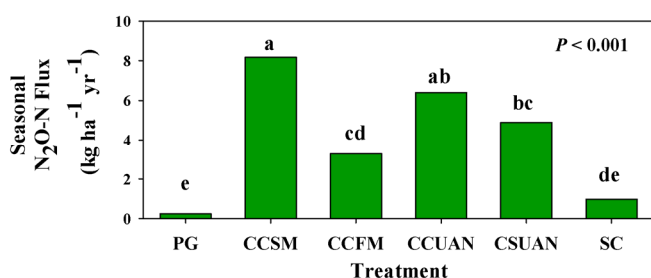
Figure 2. Annual cumulative nitrous oxide emissions (2-yr mean) at soil surface for selected treatments. Treatments labelled by the same letter are not significantly different based on Tukey's HSD test ($\alpha = 0.05$).
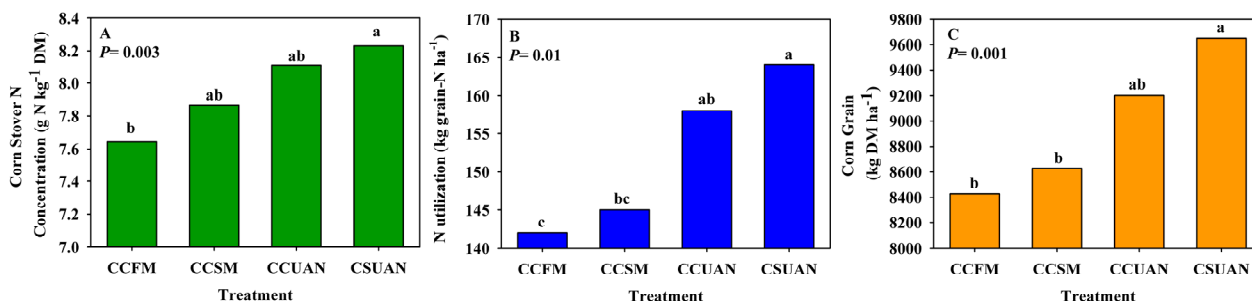
Figure 3. (A) Corn yield, (B) nitrogen utilization, and (C) stover nitrogen content for selected treatments. Treatments labelled by the same letter are not significantly different based on Tukey's HSD test ($\alpha = 0.05$).

Differential responses of soil and plant N pools to the assessed N management practices further substantiate our findings for both NO_3^- losses in drainage water and N_2O emissions to the atmosphere. Fractional analyses of PG soils indicate that PG soil was strongly N limited as C:N ratios were markedly wider when compared to cropping systems in both whole soil (15 vs. 13) and fine particulate organic matter (28 vs. 16; data not shown). These divergent C/N ratios between cropped and PG soils can also suggest the differential nature of soil organic matter between crop and PG systems as biomass characteristics, N inputs, and tillage management also differ (Hernandez-Ramirez *et al.* 2009a). Likewise, analyses of aboveground plant tissues across selected treatments also showed general agreement of plant N status with our observations of NO_3^- and N_2O losses. The N contents in corn stover trended lower in manured fields (Figure 3A), and this can be in part attributed to losses of N species to both subsurface drainage water and the atmosphere as discussed above. Moreover, results of N mass allocated into corn grain indicated even sharper differences in plant N utilization between fields receiving UAN vs. manure (Figure 3B). Relatively increased soil N uptake and associated enhanced N use efficiency by corn in fields receiving UAN could account for this outcome. The strong driving role of N management in these cropping systems is also reflected in corn productivity (Figure 3C) which in general mimicked the patterns of N contents in both stover and grain.

Ecosystem services trade offs: nitrate leaching vs. nitrous oxide emissions

Summarizing the divergent results generated by spring vs. fall manuring in corn fields, several directional trade offs in ecosystems services can be clearly identified. In contrast to CCSM, CCFM showed a beneficial ecosystem service by mitigating N_2O emissions. However, CCFM exhibited detrimental ecosystems services outcomes compared to CCSM such as reduced grain yield and much larger NO_3^- losses. Furthermore, as agriculturally-sourced NO_3^- is leached from soils and transported via drainage networks and surface watercourses, certain biological N_2O production (e.g., denitrification) typically takes placed. Therefore, as a direct result of the relatively larger NO_3^- leaching for CCFM vs. CCSM, the estimates of indirect N_2O emissions following IPCC (2006) methodology are also greater for CCFM vs. CCSM (i.e., 0.25 vs. 0.14 kg N_2O-N /ha/yr, @ IPCC default value of 0.0075). However, these additional amounts of indirect N_2O emissions are relatively small, and they do not alter the pre-existent treatment hierarchy (i.e., CCSM > CCFM) based only on quantities of measured direct N_2O emissions.

Conclusions

This study suggests that time of N addition in corn fields had a significant driving effect on ecosystem services outcomes such as magnitudes of grain yield, N_2O emissions, and NO_3^- leaching. Overall ecosystem services performance could be enhanced by selecting the best time for N addition to effectively synchronize plant N demand with soil N availability as well as by implementing nutrient management plans assigning proper credits to N contributions by legume and manure additions. Fine tunning of both N budgets and fertilizer recommendations for corn production systems need to consider other components of the N cycle such as N mineralization of soil organic matter and corn residues, N release from soil mineral fraction, deep N percolation below drains, N in runoff, gaseous N losses (different than N_2O), and wet and dry N deposition. This study also indicates that PG restoration in cropland can cause beneficial environmental outcomes by minimizing effluxes of both N_2O and NO_3^-; however, it remains unknown the potentially adverse impacts of PG biomass removal (i.e., due to growing interest in biofuel fabrication) and associated repeated N additions with the aim of maximizing biomass productivity in these PG systems. Comparative life cycle assessments for a broad variety of agroecosystems would need to encompass all known ecosystem services and environmental impacts using a common base methodology. Additional data is also needed as predictions of near-future climate changes indicate increased variability and changeable outcomes.

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