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Fertilizer Management and Environmental Factors Drive N_2O and NO_3 Losses in Corn: A Meta-Analysis

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Effective management of nitrogen (N) in agricultural landscapes must account for how nitrate (NO_3) leaching and nitrous oxide (N_2O) emissions respond to local field-scale management and to broader environmental drivers such as climate and soil. We assembled a comprehensive database of fertilizer management studies with data on N_2O (417 observations, 27 studies) and NO_3 (388 observations, 25 studies) losses associated with 4R fertilizer N management in North American corn-cropping systems. Only one study measured both losses, and studies of N_2O and NO_3 differed by location, time period, and management practices. Meta-analysis of side-by-side comparisons found significant yield-scaled N_2O emission reductions when SUPERU replaced urea or UAN, and when urea replaced anhydrous ammonia. Hierarchical regression models found near-equivalent magnitude effects on N_2O emissions of 1°C rise in average July temperature (+), increase in soil C by 10 g kg^{-1} (+), nitrification inhibitors (–), side-dressed fertilizer timing (–), broadcast fertilizer (–), and 100 kg N ha^{-1} decrease in fertilizer rate (–). Average NO_3 leaching response to 100 kg N ha^{-1} reduction in fertilizer rate (–) were comparable to effects of 100 mm less annual precipitation (–), 10 g kg^{-1} more soil C (–), or replacing continuous corn with corn-soybean rotations (–). The large effects of climate and soil, and the potential for opposite reactions to some management changes, indicate that more simultaneous measurements of N_2O and NO_3 losses are needed to understand their joint responses to management and environmental factors, and how these shape tradeoffs or synergies in pathways of N loss.

Core Ideas

- **Systematic review and meta-analysis demonstrate key factors for reducing agricultural N losses.**
- **Nitrification inhibitors and side-dress fertilizer N each reduce N_2O losses by ~30%.**
- **Temperature controls N_2O emissions and precipitation controls NO_3 leaching losses.**
- **Higher levels of soil carbon reduce NO_3 losses, but increase N_2O emissions.**
- **Lack of simultaneous data for $N_2O$and NO_3 impedes understanding of tradeoffs and synergies.**

Inorganic N in excess of plant demand creates high potential for export of unused N from farm fields. Worldwide, N fertilizer recovery as crop biomass varies considerably (Dinnes et al., 2002), but is usually less than 50% (Fageria and Baligar, 2005); the remainder accumulates in soils, is exported to the atmosphere (from nitrification, denitrification, and volatilization), or is lost to surface and groundwater (leaching and erosion). Agriculture is a major source of nitrate (NO_3) to groundwater, streams, lakes, estuaries, and coastal oceans, where elevated NO_3 concentrations contribute to eutrophication, coastal dead zones and fish kills (Camargo and Alonso, 2006). Nitrate concentrations above the US Environmental Protection Agency's maximum contaminant level for drinking water have also led some rural communities to search for alternative water sources (Spalding and Exner, 1993). Nitrate leaching loss rates can vary widely, with reported values ranging from 3 to 54% of applied N (Di and Cameron, 2002a). Nitrous oxide (N_2O) is both a potent and significant greenhouse gas (GHG; Forster et al., 2007) and the most substantial ozone-depleting anthropogenic emission in the stratosphere (Ravishankara et al., 2009). Although only an estimated 2% of fertilizer N applied to corn is lost as N_2O (Grace et al., 2011), agriculture accounts for 75% of total annual N_2O emissions in the United States. (Cavigelli et al., 2012). Joint studies of N_2O and NO_3 losses, and their responses to agricultural practices, are essential for effective agricultural management to understand where there may be trade-offs

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or opportunities for synergistic management (Robertson and Swinton, 2005; Tilman et al., 2011), but joint study of these N loss pathways is uncommon.

The potential for farmers to reduce N losses while maintaining or increasing yield depends on the responses of yield and N losses to fertilization rate, fertilizer types, application techniques, and variability among regions due to soil, climate, and other environmental factors. A comprehensive understanding of these relationships would permit quantification of the potential for fertilizer management to reduce NO_3 or N_2O losses. Concentration of high N use crop production might also be directed toward low N loss geographies. In assessing these alternatives, it is essential to understand when N_2O and NO_3 respond similarly, and when reductions in one loss pathway incur increases in the other.

Best practices in fertilizer management seek to match the amount, timing, placement, and source of application to better match crop demand with minimal sacrifices in yield (Fageria and Baligar, 2005; Power et al., 2001; Raun and Johnson, 1999). Recent syntheses and models provide evidence of nonlinear exponential responses of N losses to fertilization rate (Qi et al., 2012; Shcherbak et al., 2014), but the effects of other fertilization practices on N losses remains unclear. Because of the very different controls on N_2O production and NO_3 leaching, it is likely that responses of these processes to fertilizer management practices differ in magnitude or even direction. For the same reason, these joint responses have the potential to vary regionally with climate, soil, and other environmental factors.

This research sought to address three questions regarding the controls on N_2O emissions and NO_3 leaching: first, how do N_2O emissions and NO_3 leaching losses respond to N fertilizer application rate, source, timing, and placement? Second, how do effects of fertilizer management compare to effects of, and potentially depend on, variation in climate and soil? And finally, how do NO_3 and N_2O losses co-vary with management, climate, and soil? To address these questions, we compiled a database of fertilizer management field studies from North American corn-based systems, all of which measured yield plus either NO_3 leaching or N_2O emissions or both. We evaluated the pairwise effects of fertilizer management using standard meta-analysis. We also used hierarchical multi-level models to simultaneously evaluate multiple management and environmental drivers including soil and climate. Both statistical approaches use data from multiple studies to determine the overall impact of management, identifying significant factors that may not be otherwise observed in individual studies, and conversely, finding other effects that apply only under specific conditions and cannot be broadly anticipated. The hierarchical models also allow us to incorporate data from studies that do not directly compare fertilizer management techniques, so that with far more observations as well as joint consideration of multiple factors we can achieve a more robust picture of N loss responses than is possible with standard meta-analysis effect sizes.

METHODS

Study Scope

This study draws on data from corn-based field research reporting the N_2O and NO_3 loss implications of N fertilizer management in North America. Corn occupies one-quarter of all harvested cropland in the United States. (USDA ERS, 2016) and accounts for more than 40% of the fertilizer N used (USDA NASS, 2016), and much existing field research pertains to rotations dominated by corn. Limiting data analysis to one crop also narrows the impact of unknown and unquantified differences between crops that could be further complicated by climate, soil, and other management characteristics.

Data Compilation

Data collection began with a comprehensive literature search for field studies of North American corn-based systems published through July 2014. A search of ISI Web of Science with terms related to agricultural N losses (fertilizer, nitrogen, nutrient management, agriculture, nitrous oxide, nitrate, leaching, and emissions) identified about 4400 papers in the scientific literature. A review of titles and abstracts excluded all papers that were not about agriculture or N losses, addressed N losses and transport after the field, did not examine N fertilizer management, were not in North America, or were in non-corn systems. Laboratory and greenhouse studies were also excluded.

From this triage, 237 papers with potential for field data on fertilizer N management and losses were selected for further examination. Forty-eight of these studies reported crop yield and either or both N_2O and NO_3 losses from field experiments of corn-based cropping systems in the United States or Canada for which N fertilizer management treatments were applied. While Mexico was included in the search, no available research data were identified. Manure and other organic fertilizer were not included because of uncertainty and variability in nutrient composition and availability. All observations in the final database were in the corn phase of a given rotation and recorded: (i) measured losses of either or both N_2O and NO_3 over at least 55 d during the growing season, (ii) crop yield, (iii) N application rate, and (iv) number of replicates.

With a priori expectations that many different management and climatic factors affect crop yield and N dynamics, we also compiled numerous other observation-level details, filling in some information from publicly available soil and weather databases. Thus, most observations include data on crop rotation; previous year crop and N fertilizer amount; the presence of irrigation or other water management (e.g., tile drains); tillage intensity (no-till, conservation, or conventional); winter cover crops; fertilizer source, timing, and placement; N uptake; and residual soil inorganic N. Nitrification and urease inhibitors added to different N sources were included both as individual products and as broad categories. We connected soil and climate characteristics for each location with all relevant observations. These data included soil texture, drainage class, and surface layer carbon (C) concentration (most often 0–15 cm), as well as long-term

(30-yr) averages for total annual precipitation and July temperature, and annual precipitation for the study year. Experimental methods were also recorded, such as the total time period of loss measurements, frequency of measurements, maximum N_2O flux rates, the placement of N_2O emission collection chambers, and the method of determining total leachate volume. For further details on data collection, see Supplemental Material A.

Data Description

Data originated from studies with divergent geographic, management, and other characteristics (see Supplemental Material B for a list of studies with summary statistics). The final dataset consisted of 417 observations of N_2O field losses from 27 studies (19 distinct locations) and 388 observations of NO_3 field losses from 25 studies (16 distinct locations). Only one study (16 observations) reported simultaneously measured N_2O and NO_3 losses. The data cover much of the area of North America for which corn is a primary crop (Fig. 1), but studies are lacking in several regions of corn agriculture such as the east and west coasts, the southern states, and certain parts of the Corn Belt for one or both N losses of interest.

Studies of N_2O emissions, the largest proportion in Colorado, tended to be more recent than those of NO_3 leaching, with more no-till, irrigation, and side-dressing of fertilizer N (Table 1). Studies of NO_3 leaching, the largest number in Iowa, were more likely than N_2O experiments to use UAN and anhydrous ammonia fertilizer, to knife-inject fertilizer, to be in systems identified as tile-drained, and to measure N losses for a longer period of time. Therefore, not only do the available data for the two different types of N losses largely come from different locations, but they also capture different combinations of management practices within corn-based cropping systems.

Data Analysis

Of the N_2O observations, 91 (22%) were from studies that compared responses from at least five fertilizer N rates, including a control, and 162 (42%) of the NO_3 observations came from studies with at least three rates. With these observations, we modeled the yield and N loss responses to fertilizer rate by individual site-year. Equations and some examples are provided in Supplemental Material C.

We then used two different modeling approaches to assess the management and environmental drivers of N_2O emissions and NO_3 leaching in North American corn systems. First, standard meta-analysis with effect sizes was applied to a sub-set of the data that included direct simultaneous comparisons of two or more fertilizer management techniques. This approach considers these pairwise comparisons individually, and does not incorporate broader environmental or management factors. The second, more robust, method used hierarchical, multi-level regression models. This approach allowed us to evaluate the entire dataset

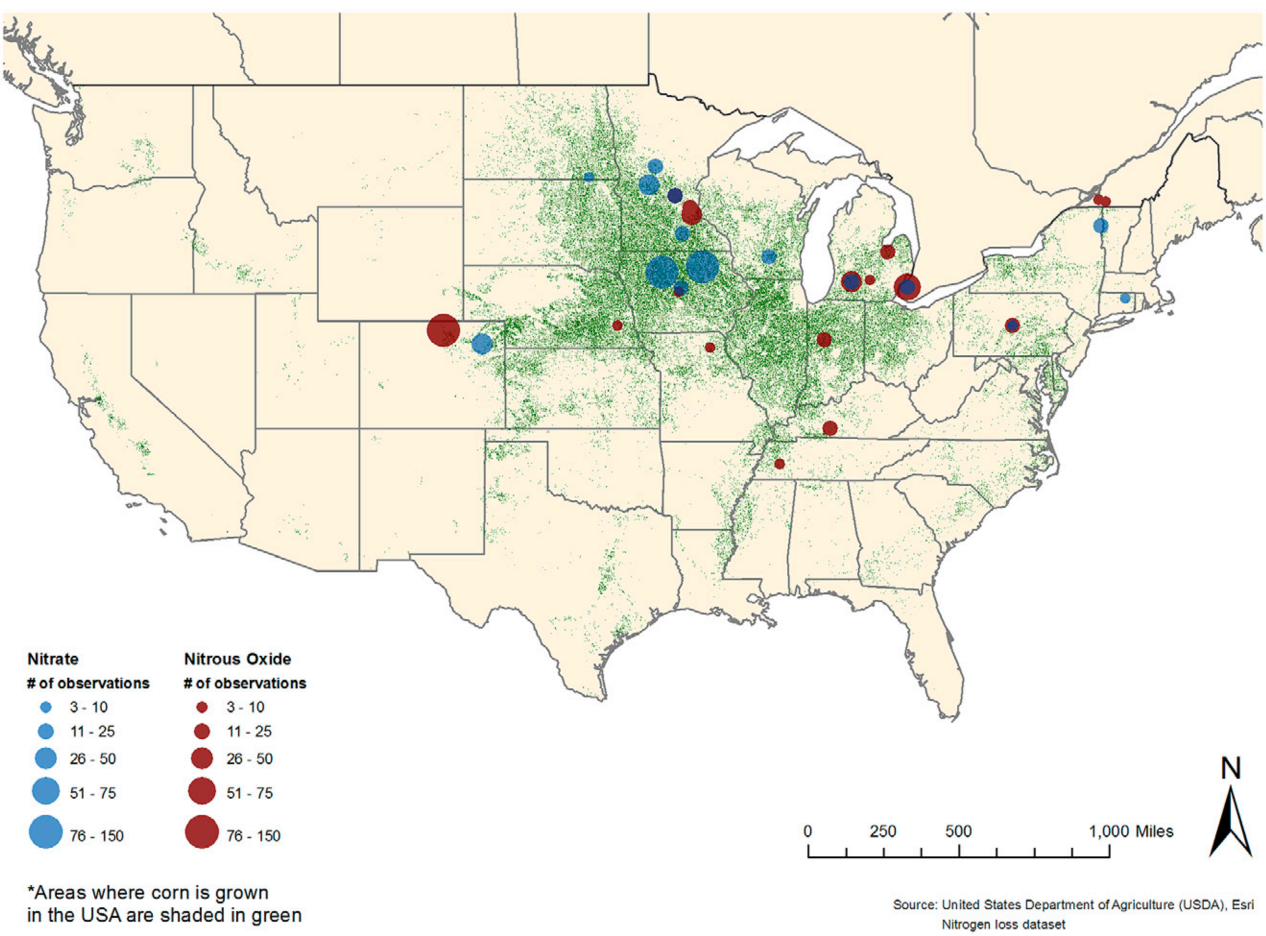

Fig. 1. Geographic distribution of agricultural nitrogen (N) loss dataset.

Table 1. Key characteristics of corn field studies included in database that report nitrous oxide emissions and nitrate leaching along with crop yield. Percentages indicate proportion of observations in each category. Totals for non-binary items may not sum to 100% due to rounding.

Characteristic	N_2O observations	NO_3 observations
	All observations	
Location	Colorado (32%); Minnesota (18%); Eastern Canada (15%); Michigan (13%); Other U.S. (21%)	Iowa (42%); Minnesota (28%); Colorado (10%); Other U.S. and Canada (20%)
Mean July temp	18.9–26.3°C (median = 22.4)	20.0–23.5°C (median = 22.7)
Soil carbon	0.7–3.9% (median = 1.3)	0.6–3.5% (median = 2.3)
Year of study	1993–2012 (median = 2007)	1980–2010 (median = 1994)
Tillage	Conventional (30%); Reduced tillage (23%); No-till (42%); Other or unknown (5%)	Conventional (55%); Reduced tillage (27%); No-till (7%); Other or unknown (11%)
Water management	Irrigated (42%)† Tile-drained (1.4%)	Irrigated (33%)† Tile-drained (45%)
Time-frame for N loss measures (if reported)	9 mo or more (2%); 6–9 mo (39%); 3–6 mo (55%);<3 mo (4%)	9 mo or more (56%); 6–9 mo (36%); 3–6 mo (8%); <3 mo (0%)
	Only observations with N application > 0	
Fertilizer N source	Urea (28%); UAN (20%); Polymer coated urea (17%); SUPERU (10%); Ammonium nitrate (9%); Other (16%) [note: including SUPERU, a total of 15% with nitrification inhibitors]	Urea (16%); UAN (36%); Ammonium nitrate (8%); Anhydrous ammonia (22%); Ammonium sulfate (8%); Other (10%) [note: a total of 10% with nitrification inhibitors]
Fertilizer N placement	Banded (39%); Knife-injected (20%); Broadcast (28%); Broadcast/incorporated (12%); Other (1%)	Banded (3%); Knife-injected (61%); Broadcast (17%); Broadcast/incorporated (17%); Other (3%)
Fertilizer N timing‡	Fall only (1%); Spring only (32%); Side-dress only (50%); Split, with side-dress (16%); Other (1%)	Fall only (9%); Spring only (64%); Side-dress only (11%); Split, with side-dress (14%); Other (1%)

† Note that some "irrigated" systems were only irrigated sparingly to address drought conditions.

‡ Fertilizer timing treatment applicable to main N fertilizer application only, excluding small amounts that may have been present in starter fertilizer.

with multiple explanatory variables at the same time, to evaluate the influence of environmental factors, and to incorporate data from studies that lacked direct side-by-side comparisons.

The standard meta-analysis estimated N loss responses as effect sizes—here the percent change in yield-scaled N losses—for side-by-side comparisons of specific management practice changes. While variance-based weighting is preferred in meta-analysis, incomplete reporting of variability in the data made this impossible without losing much of the data; variance was reported for 28% of yield observations, 57% of N_2O observations, and only 10% of NO_3 observations. Therefore, sampling variance was approximated using sample sizes (Gurevitch and Hedges, 1999). We estimated mean effect sizes with individual observations weighted by the inverse log of the number of observations in each location. In this way, locations with very large numbers of observations do not suppress results from less-studied sites.

Only practices with a sufficient number of consistently defined controls and treatments within the dataset could be tested, and the meta-analysis was limited to timing, source, and placement treatments with at least nine side-by-side comparisons from two or more locations. Data meeting these criteria captured the effects of only a few fertilizer source comparisons (N_2O) and one fertilizer timing comparison (NO_3), and come from 177 N_2O observations and 40 NO_3 observations (42 and 10% of all N_2O and NO_3 observations, respectively). The small number of observations for each management option makes further separation into groups by tillage, crop rotation, climate, or other factors impractical.

With observational data coming from varying management, climate, and soil regimes, conventional meta-analysis can be misleading by not taking these characteristics into account (Qian and Harmel, 2016). Our second modeling approach addressed this issue with multi-level or hierarchical regression models, which are increasingly being applied to ecological and agricultural data (Gelman and Hill, 2007; Qian, 2017). Estimated using the STATA *mixed* command, the models jointly assessed the N loss implications of all applicable fertilizer management practices, along with geographic variation in climates and soils and varied management in tillage, crop rotations, and drainage. Separate models for N_2O and NO_3 losses incorporated many more observations than could be used in standard meta-analysis, and corrected for the effects of multiple factors at the same time. These models can also handle continuous dependent variables—such as fertilizer rate, temperature, and precipitation—without requiring them to be grouped into discrete categories as would be the case for standard meta-analysis.

All potential explanatory factors (i.e., the management, soil, climatic, and experimental method variables described above) were tested for overall effects. Grouping by location in the hierarchical model accommodates the non-independent nature of these observations, and goes beyond a standard regression model by allowing possible response differences between locations (Woltman et al., 2012). The hierarchical models also address unbalanced data by reducing the weight of individual observations from well-represented locations and those with greater variability (i.e., more uncertainty). Such weighting is necessary for these datasets, with between 2 and 135 observations per location for N_2O and 2 to 78 observations per location for NO_3. Additional details on hierarchical model weighting and between group testing are given in Supplemental Material D.

To assess overall responses of N losses to management and climatic factors, we estimated multi-level models with all observations for each of N_2O and NO_3. Models restricted to observations with fertilizer N application rates between 110 and

270 kg N ha^{-1} yr^{-1} were then estimated to examine management and other effects in typical field conditions. Models were first estimated with losses on an area basis (i.e., kg N ha^{-1} yr^{-1}) to allow comparison with the bulk of other research on N losses in agriculture, and then compared with equivalent models for which the dependent variables were yield-scaled losses (i.e., kg N Mg $grain^{-1}$).

RESULTS

Fertilizer N Rate Impacts

In site-years with multiple fertilizer N rates, the effects of N rate on yield and N losses varied by location and also by year within locations (Fig. 2). Across the range of applied fertilization rates, yield typically followed the expected saturating response curve, although the shape and magnitude of the response varied among sites and years. The intercept (yield with N rate of 0) ranged from 3.1 to 6.4 Mg ha^{-1} and corn grain yield at 180 kg N ha^{-1} ranged from 3.7 to 12.7 Mg ha^{-1}. The modeled half-saturation rate (fertilizer rate at which to expect half of the maximum yield gain) ranged from 19 to 1050 kg N ha^{-1}. For the 27% of observations where these values exceeded the highest fertilizer rate, this suggests a nearly linear yield response to N fertilizer rate within the tested range. The best relationship between fertilization rate and N_2O losses was exponential (with a log-transformed dependent variable). For these rate-trial observations, N_2O emissions increased by between 2.8 and 11.9% with each additional 10 kg N ha^{-1} of fertilizer N. Nitrate losses were highly variable. The relationship of NO_3 to fertilizer N rate was best described by a linear function and not improved with an exponential treatment. Based on these rate-trial observations (and limiting only to those with $R^2 > 0.4$), between 0 and 74% of each additional unit of fertilizer N was lost as NO_3. Thus, while losses increased with rate within individual site-years, rate alone explained little of the variability in observed losses.

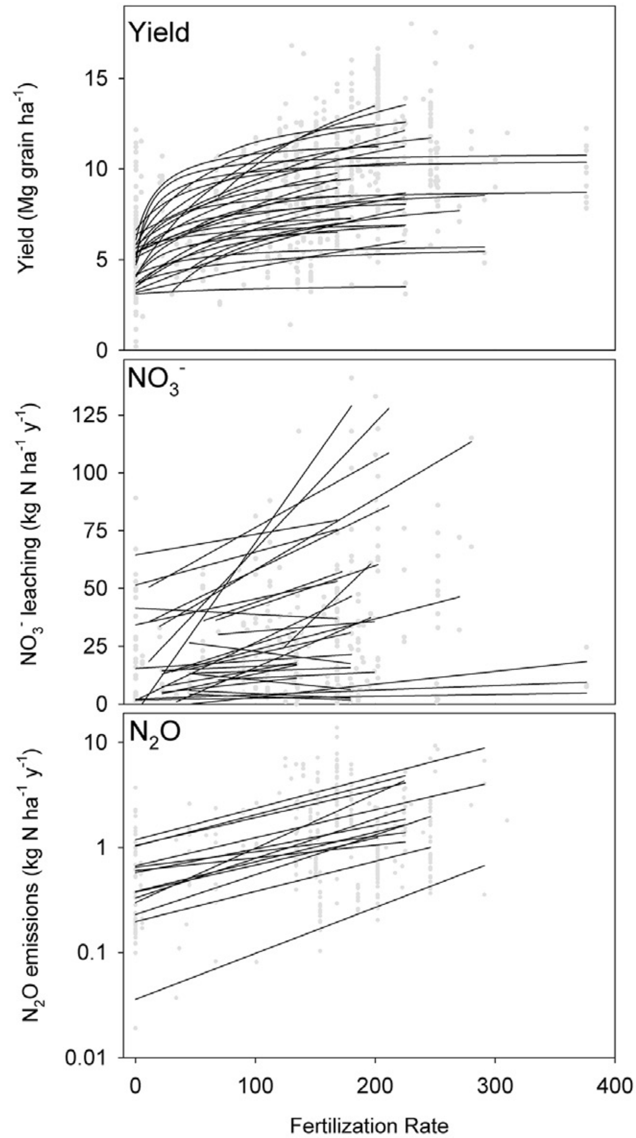

Fig. 2. Response to fertilizer N rate of crop yield, nitrate leaching and nitrous oxide emissions in field experiments, separated into individual site-years. Best fit lines are shown for site-years with at least five different N fertilizer rates for N_2O and at least three N rates for NO_3.

Side-By-Side Comparisons of Management Factors

Looking at effect sizes determined from direct side-by-side comparisons, fertilizer source had some significant effects on N_2O emissions (Fig. 3). Substantial reductions in yield-scaled N_2O emissions resulted when switching to urea from anhydrous ammonia (45%) and to SUPERU from urea (26%) or polymer-coated urea (15%), across various studies. We found no significant N_2O loss difference between urea and polymer-coated urea, or when AGROTAIN PLUS was added to UAN. Spring versus fall fertilizer timing was the only factor for which we had sufficient data on NO_3 losses to test effect size, but no significant effect was detected (Fig. 3). Insufficient numbers of direct comparison studies precluded effect size determination for any other fertilizer management practices on either N_2O or NO_3 losses.

Hierarchical Models

All available management, climatic, and soil factors were tested in hierarchical models for both N_2O emissions and NO_3 leaching losses, and the variables included in the final models proved significant throughout various robustness tests. For both N_2O and NO_3, the loss measurement time frame (e.g., whether year-round or only during the growing season) and frequency of measurement did not affect reported losses, suggesting that researchers using various measurement periods and frequencies still tended to capture a similar proportion of total losses. Interaction effects were not significant (e.g., rate did not have a differential impact at varied levels of temperature). With four models for each loss type (two with a full cohort of data, and two with N fertilizer rate restricted to typical levels, and each of these estimated for both area-based and yield-scaled losses) we validated the strength of relationship in the final specifications.

Nitrous Oxide

In the hierarchical models, N_2O emissions were best predicted by environmental factors including July temperature and soil C, as well as fertilization practices including rate, sidedress application timing, and the use of nitrification inhibi-

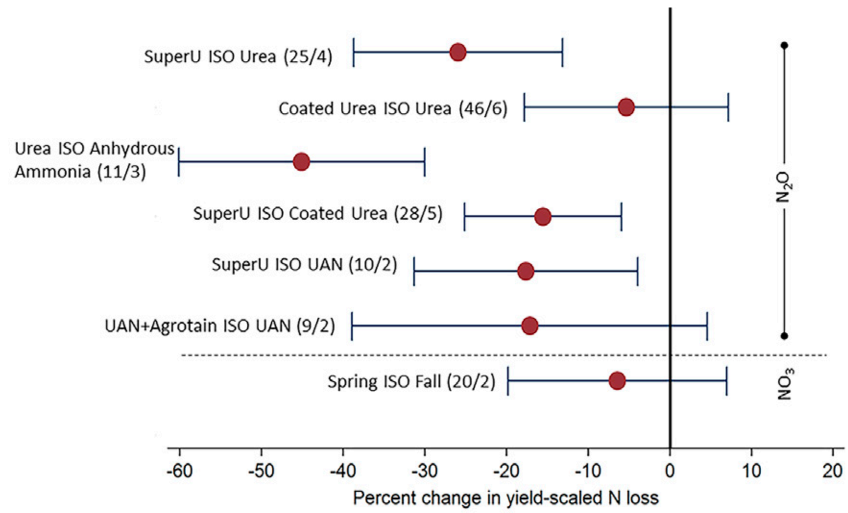

Fig. 3. Effect sizes of N_2O and NO_3 losses from selected fertilizer management treatments, yield-scaled percent change with 95% confidence intervals. ISO = "Instead of" and values in parentheses are (number of comparisons / number of locations).

tors (Table 2). Trends among treatments and environmental predictors were similar for area-based and yield-scaled models. Model interpretation—for which more details can be found in Supplemental Material E—is limited to area-based values, for the sake of brevity and to facilitate comparison with area-based fertilizer application rates and other research.

In the full model (over all N rates), each additional 10 kg N ha^{-1} yr^{-1} produced a 6.7% increase in N_2O emissions on average; the impact of the same rate change decreased to 2.7% when only fertilizer rates between 110 and 270 kg N ha^{-1} were considered. Each one degree rise in average July temperature increased N_2O emissions by 18 and 28% in the full and restricted models, respectively. Higher levels of soil carbon may also increase N_2O losses, although the relationship was somewhat weak and management practices known to affect soil C such as tillage or cover crops did not themselves prove to be significant. Nitrification inhibitors reduced N_2O losses by 31% on average, and changing from all pre-plant application (spring or fall) to applying at least a portion of fertilizer N as a side-dress fertilizer reduced average losses by 20% in the full model and by 26% at typical N application rates. Broadcasting N fertilizer instead of injecting or banding also reduced emissions, by 25 and 33% in the respective models. Even when controlling for other available factors, N_2O emissions were positively related to crop yield and tended to be lower in the more recent research studies.

The characteristic exponential response of N_2O to fertilizer N rate means that the absolute effect of a management change varies depending on baseline losses (i.e., it is a percent reduction). At the typical fertilizer application rate of 180 kg N ha^{-1} and with other factors (e.g., temperature, soil C) held at their mean, the 50% emission reduction from combining both side-dressing nitrification inhibitors in the restricted model translate to a decrease in N_2O losses from 2.6 to 1.3 kg N ha^{-1} yr^{-1} N (Fig. 4).

A likelihood ratio test comparing the multi-level model with a one-level ordinary linear regression was highly significant, indicating that there is enough variability between locations to favor the multi-level model. The total model variance between location clusters (Ψ) is of similar magnitude to the remaining variance within clusters (Θ); grouping by location explained between 38 and 52% of the remaining model error.

Table 2. Hierarchical (multi-level) regression models of N_2O emissions in North American corn cropping systems. The dependent variable for Models 1 and 3 is the natural log of N_2O emissions (kg N ha^{-1} yr^{-1}), and for Models 2 and 4 is the natural log of yield-scaled N_2O emission (kg N Mg $grain^{-1}$). Values in main table are model coefficients.

	Model 1	Model 2	Model 3	Model 4
	n = 417, 19 clusters N rates: 0–310 kg N ha^{-1} yr^{-1}		*n* = 313, 18 clusters N rates: 110–270 kg N ha^{-1} yr^{-1}	
N rates, kg N ha^{-1} yr^{-1}	0.0064***	0.0054***	0.0027*	0.0032*
Yield, Mg grain ha^{-1}	0.046***	—	0.039*	—
Irrigated	—	–0.434**	—	–0.406*
July temp, °C	0.162*	—	0.247***	0.228***
Soil carbon, g kg $soil^{-1}$	0.023†	—	0.020†	—
Nitrification inhibitors	–0.357***	–0.385***	–0.387***	–0.431***
Side-dress fertilizer	–0.218**	–0.299***	–0.302***	–0.415***
Broadcast fertilizer	–0.293***	–0.355***	–0.398***	–0.476***
Year of study	–0.089***	–0.100***	–0.069***	–0.078***
Constant	–4.668**	–1.909***	–5.731***	–6.656***
Ψ, variance between clusters	0.267	0.343	0.179	0.205
Θ, variance within clusters	0.285	0.314	0.287	0.309
R^2	0.480	0.450	0.491	0.563

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† For Soil carbon in Models 1 and 3, p = 0.100 and 0.113, respectively.

Nitrate

In the NO_3 models (Table 3), leaching losses increased with fertilizer application rate and precipitation (including irrigation). In the full model, 7% of each additional kg of fertilizer N was lost via NO_3 leaching. While significant data variability at typical fertilizer application rates (110–270 kg N ha^{-1}) resulted in no discernable impact of rate across all sites, the impact of yield (+) and corn-soybean rotations (–) point toward higher losses at higher N application rates. Areas with greater natural precipitation experienced higher losses (Fig. 5); rain-fed sites with more than 800 mm of annual precipitation lost an average of twice as much (25 kg N ha^{-1} yr^{-1} more) NO_3 by leaching than non-irrigated sites with less than 800 mm annual precipitation. With all other factors held constant, irrigation increased losses by 11 kg N ha^{-1} yr^{-1}, although somewhat higher soil C levels in irrigated systems (compared to dryland sites that have similar rainfall) reduced this effect to an average of 5 kg N ha^{-1} yr^{-1} for the studies in this dataset. Overall, an increase of soil C by 10 g kg^{-1} soil reduced average NO_3 leaching loss by 8 to 13 kg N ha^{1} yr^{-1}. Higher NO_3 losses were also observed with aqueous ammonia when compared with other N fertilizer sources, and lower losses with banded urea compared to other source-placement configurations. However, even though these source and placement factors improved overall model fit, the aqueous ammonia and banded-urea treatments were limited to one study each, so extension to other sites may not be appropriate.

Nitrate leaching losses increased with higher crop yield (as was the case for N_2O emissions), and total reported losses were lower in more recent studies. Yield-scaling the dependent variable (NO_3 losses) again had little effect on both direction and magnitude of the significant factors. For all NO_3 models, grouping the data by location explained a significant amount of the variability (i.e., Ψ, the variance between clusters, accounted for between 42 and 52% of the total variance in the four models).

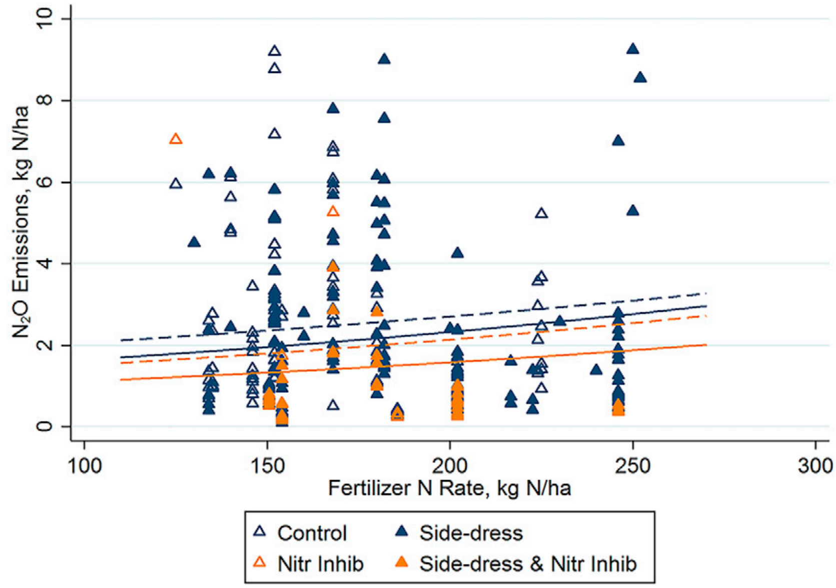

Fig. 4. Nitrous oxide emissions in response to fertilizer N rate, nitrification inhibitors, and side-dress timing of N fertilizer. Observations (triangles) and modeled lines (N_2O Model 3) originate from corn field experiments in North America for which yield data are available, and are limited to those with fertilizer N application rates between 110 and 270 kg N ha^{-1} yr^{-1}.

DISCUSSION

Our synthesis yielded three important findings regarding controls on N loss from corn fields in North America. First, we found that yield, N_2O emission, and NO_3 leaching each respond differently to fertilization practices. Second, regional-scale environmental drivers have substantial effects on N_2O emissions and NO_3 losses that match and potentially exceed effects of fertilizer application rate and other in-field practices. And finally, the scientific literature is deficient in co-located, concurrent measurements of N_2O and NO_3 losses in response to fertilizer management treatments.

Effects of Fertilizer Management

Fertilizer rate has a positive effect on both area- and yield-scaled losses of N_2O and NO_3, although the exact relationship is highly variable and specific to site-year characteristics. Since the yield and loss responses to fertilizer rate are both heterogeneous and nonlinear, a simple, uniform fertilizer rate reduction may not maintain yield, or reduce environmental N losses, to the greatest possible extent. Nitrous oxide emissions best fit response to rate was exponential, which is consistent with other recent meta-analysis results (Kim et al., 2013; Shcherbak et al., 2014; van Groenigen et al., 2010). In contrast, even though some recent research predicts a nonlinear relationship between fertilizer application rate and NO_3 leaching (Qi et al., 2012), our NO_3 leaching models were not improved with nonlinear treatments. Estimates of N balance did not improve model predictions over absolute rates, although this may be related to high uncertainty in such estimates that arose from limited crop N uptake data reporting. Rate responses of N_2O and NO_3 were observed across application rates that typically saturated yield, indicating the potential for reduced losses with lower application rates without corresponding declines in yield in at least some regions. This is consistent

Table 3. Hierarchical (multi-level) regression models of NO_3 leaching losses in North American corn cropping systems. The dependent variable for Models 1 and 3 is NO_3 losses (kg N ha^{-1} yr^{-1}) and for Models 2 and 4 is yield-scaled NO_3 losses (kg N Mg $grain^{-1}$). Values in main table are model coefficients.

	Model 1	Model 2	Model 3	Model 4
	n = 388, 16 clusters N rates:0–376 kg N ha^{-1} yr^{-1}		*n* = 272, 16 clusters N rates:110–270 kg N ha^{-1} yr^{-1}	
N rates, kg N ha^{-1} yr^{-1}	0.074***	0.004*	—	—
Yield, Mg grain ha^{-1}	1.863**	—	2.379**	—
Annual Precip, mm	0.086***	0.010***	0.094***	0.010***
Irrigated	—	—	10.986*	0.920†
Soil carbon, g kg $soil^{-1}$	–0.813*	–0.101*	–1.295***	–0.137**
Urea banded	–51.380***	–6.664***	–45.866***	–5.980***
Aqueous ammonia	29.856***	3.180***	37.278***	3.816***
Corn/soybean rotation	—	–1.037***	–12.689**	–1.633***
Year of study	–1.809***	–0.191***	–1.252**	–0.133***
Constant	–44.565***	–2.461*	–32.093*	–1.146
Ψ, variance between clusters	375.2	5.703	288.1	4.474
Θ, variance within clusters	392.5	5.377	401.0	4.594
R^2	0.302	0.268	0.393	0.372

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† For Irrigated in Model 4, $p = 0.076$.

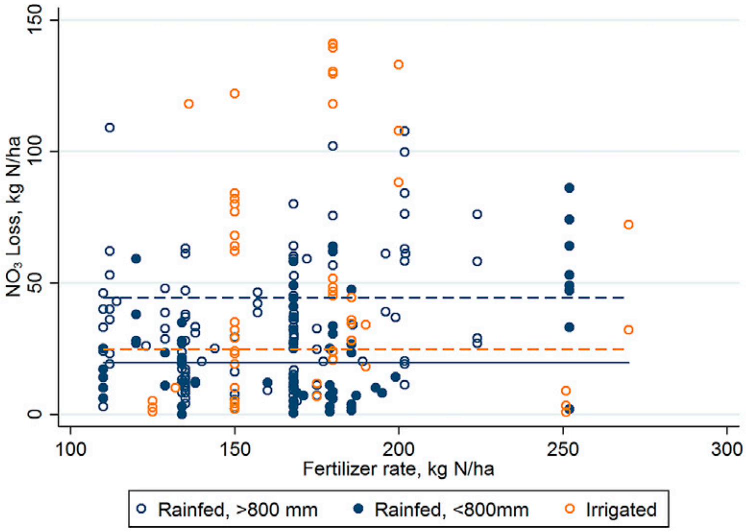

Fig. 5. Nitrate leaching loss response to fertilizer N rate, precipitation, and irrigation. Observations (circles) and modeled lines (NO_3 Model 3) come from corn field experiments in North America for which yield data are available, and are limited to those with fertilizer N application rates between 110 and 270 kg N ha^{-1} yr^{-1}. Open (closed) circles correspond to dotted (solid) lines. To show the effect of precipitation, observations are divided into those above and below 800 mm total annual precipitation.

with results from Zhou and Butterbach-Bahl (2014), whose meta-analysis of NO_3 leaching from maize and wheat cropping systems determined that the lowest yield-scaled losses occurred at fertilization rates below those typically recommended (e.g., at 90% of maximum yield for corn).

Meta-analysis effect sizes and hierarchical models indicate that changes in fertilizer source, timing, and placement can reduce N_2O losses substantially. Meta-analysis effect size comparisons suggest the following order of preferred fertilizer N sources for minimizing N_2O emissions in the regions represented by the source data: SUPERU > UAN + AGROTAIN PLUS ≥ UAN ≥ polymer-coated urea ≥ urea > anhydrous ammonia. The hierarchical model similarly finds that nitrification inhibitors (contained within SUPERU and AGROTAIN PLUS) reduced N_2O emissions in North American corn systems by an average of 32%. This is comparable to the 38% decrease in N_2O emissions from nitrification inhibitors in two previous standard meta-analyses of globally distributed field experiments (Akiyama et al., 2010; Thapa et al., 2016). While other shifts in N fertilizer source (besides adding nitrification inhibitors) have reduced N_2O emissions in certain locations (Halvorson et al., 2010; Venterea et al., 2010), these trends were not substantiated at the broader geographic scale by the hierarchical models. On the other hand, the picture is certainly more complex than that seen in overall responses. Fertilizer source can also affect the timing of N_2O losses (Delgado and Mosier, 1996) as well as crop yield (Venterea et al., 2011); the latter of which then impacts yield-scaled emissions.

Side-dressing fertilizer (delaying application until a crop is actively growing) reduced area-based N_2O emissions by 30 to 39%. In this case, hierarchical model meta-analysis—combining data across multiple studies and correcting for other factors—was able to discern a clear relationship not identified in the effect-size analysis of side-by-side comparisons or within individual studies. For example, neither splitting fertilizer N application instead of all pre-plant (Smith et al., 2011) nor side-dressing instead of pre-plant (Phillips et al., 2009; Zebarth et al., 2008) affected area and yield-scaled N_2O emissions from corn systems in a consistent manner. Broadcast fertilizer (as opposed to injecting or banding) reduced overall N_2O emissions by 25 to 33%, a response that has also been noted in individual studies both in Colorado (Halvorson and Del Grosso, 2013) and Minnesota (Maharjan and Venterea, 2013). The hierarchical model found that the use of nitrification inhibitors, delaying fertilizer N application until side-dress timing, or broadcasting instead of banding or injecting fertilizer cut average N_2O emissions by a similar magnitude as would a rate reduction of 100 kg N ha^{-1} yr^{-1}.

Aside from rate, the only fertilizer management practices that affected NO_3 leaching were aqueous ammonia (+) and banded urea (–), but a lack of replication across locations constrains broad implication. The lack of NO_3 loss response to nitrification inhibitors in the overall analysis, as well as in individual corn experiments (Maharjan et al., 2014; Randall and Vetsch, 2005; Walters and Malzer, 1990), seems a stark contrast to noted reductions in total NO_3 losses in grassland and vegetable cropping systems by up to 76 and 59%, respectively (Cui et al., 2011; Di and Cameron, 2002c). Further, even though split fertilizer applications are commonly recommended for reducing NO_3 losses (Dinnes et al., 2002), we found no evidence of loss reductions. Switching from fall fertilizer application to spring also produced no consistent effects on either N_2O or NO_3 losses, in contrast to 70% lower N_2O emissions by shifting application from fall to spring in a wheat-canola rotation (Hao et al., 2001) and 40% lower NO_3 losses in grassland with a similar change (Di and Cameron, 2002b). However, the inability to identify overall trends for a number of management practices may be due primarily to insufficient data, which is moreover spread across a wide range of soil and climatic types.

Regional and Environmental Controls

Climate and soil characteristics improved predictions of N_2O emissions and NO_3 leaching. Specifically, we found that N_2O emissions were highly sensitive to temperature, with greater losses associated with higher temperatures. In fact, one degree of difference in mean July temperature was statistically equivalent to the differences associated with nitrification inhibitors, side-dress planting, which were the most effective management practices for reduction of N_2O. This effect also implies that an average rise in July temperatures of 1°C would produce the same difference in N_2O emissions, on average, as would increasing the fertilizer N application rate by over 100 kg N ha^{-1}.

Precipitation rather than temperature was the climate variable most closely associated with NO_3 leaching, and this relationship was strengthened when we accounted for the preferential use of irrigation in drier climates. On average, we estimated that each additional 100 mm of precipitation increased NO_3 leaching losses by 8 to 9 kg N ha^{-1}, or the equivalent of an average fertilizer rate increase of approximately 100 kg N ha^{-1}. The effect of irrigation was equivalent to approximately 200 mm of precipitation. Overall, these patterns are consistent with the prevailing view that nitrate export is under strong hydrologic control, because of its mobility and potentially because of prior accumulation of nitrate beneath the rooting zone (Van Meter and Basu, 2015; Van Meter et al., 2016). The year-over-year decrease in annual NO_3 load observed in our models suggest that these accumulation rates could be in decline as a result of improved management, if results can be extended beyond the research sites. Plot-to-plot flow variability and spatial variation in deeper soil pools might also account for at least some of the substantial among-site variation in NO_3 leaching, and for the linear rather than exponential response of NO_3 leaching to fertilizer rate. Future efforts to correct for these issues might include using flow-weighted concentrations and soil available N data (both of which are not available for much of the current dataset).

The greater rates of N loss associated with increased temperature and precipitation could mean that efforts to reduce losses may be most effective, or most needed, in warmer and wetter regions. Plus, anticipated changes in temperature and precipitation due to climate change may further alter the amount and distribution of N losses from agriculture. Indeed, amplified flooding and drought situations associated with climate change are expected to cause more eutrophication in fresh and ocean water systems and additional drinking water risks (Suddick et al., 2013). Models of climate change impacts have also associated higher temperatures with increased N_2O emissions (Abdalla et al., 2010). Such implications add further urgency to the mitigation of both N_2O emissions and NO_3 leaching losses.

With no evidence of heterogeneity in responses by location, the results imply, for example, that significant management factors such as nitrification inhibitors impact N_2O in a similar manner across the given geography. Even though responses did not vary by location, the hierarchical model grouped in this way is preferable to an ordinary regression model because it uses group level variance and the imbalance of observations to give more weight to studies with greater certainty, and less individual weight to observations from highly represented locations. Still, the high variability in responses suggests caution in applying these results to specific farms.

Co-management of N_2O and NO_3

In the multivariate hierarchical models, we found a number of differences in how NO_3 and N_2O losses responded to management and other factors. At the timescale of typical experimental treatments, N_2O production depended more strongly on fertilization practices (source and timing) than did NO_3 leaching. Soil carbon was positively associated with N_2O production and negatively with NO_3 leaching. Temperature was the primary climatic control on N_2O, while precipitation was the best climatic predictor of NO_3 leaching.

However, our analysis suggests that in most cases N_2O and NO_3 loss responses to fertilizer management practices are directionally similar. Thus, practices that reduce N_2O emissions will generally either also reduce NO_3 leaching (in the case of rate reductions), or have limited effect (in the case of timing and source changes). Differences in magnitude may reflect the very different biological and physical processes that control these important N losses. Such process variation is suggested by the N_2O emission response to temperature in relation to the more significant NO_3 loss response to precipitation.

Of all the variables assessed, only soil organic carbon (SOC) had opposite effects on N_2O emissions and NO_3 leaching. An increase of 10 g C kg $soil^{-1}$ (e.g., from 2% SOC to 3% SOC) was associated with an average 24% increase in N_2O emissions (0.4 kg N ha^{-1} yr^{-1} at the mean), and an 11 kg N ha^{-1} yr^{-1} decrease in NO_3 leaching (31% at the mean). While largely related to climate and native vegetation, soil C can also be managed through practices such as tillage, residue return, and cover crops (although none of these practices on their own had any significant effect on either N_2O or NO_3 losses when tested in the models). Whether such management of soil organic carbon would in fact affect N losses depends on whether the statistical relationship we derived represents a causal one, or whether it reflects broader conditions (e.g., soil drainage) that influence NO_3 leaching and N_2O emissions. Initial evidence that soil texture had no effect on either NO_3 leaching or N_2O losses in our hierarchical model provides little support for the latter hypothesis.

Our confidence in the conclusions about trade-offs or interactions between NO_3 and N_2O losses is necessarily tempered by the near-complete lack of studies that simultaneously assess responses of N_2O emissions and NO_3 leaching; by the poor temporal, spatial, and management practice overlap of the studies that assess these responses individually; and by the covariation of many environmental factors and practices. Even after accounting for these factors, grouping by location in the hierarchical model was able to explain about half of the remaining variance, suggesting that regional or local differences in some unmeasured factors exerts an important influence on N loss rates. The finding that losses tended to be lower in more recent studies also suggests the potential influence of other unmeasured changes in management, crop variety, or environmental elements. Further, the positive relationship between crop yield and losses implies that covariation with rate may be an important statistical confounder, and accentuates the importance of considering losses and remediation of losses on a yield-scaled basis, as has recently been done for both N_2O (Johnson et al., 2011; van Groenigen et al., 2010; Venterea et al., 2011) and NO_3 (Zhou and Butterbach-Bahl, 2014). Reduction of N losses on a yield-scaled basis is critical to avoid *leakage*—in which local declines in production are met by increased production in another location—along with associated N losses and other environmental consequences (Holland, 2012).

While there were no significant impacts of tillage, cover crops, and certain other management practices that have otherwise been found to affect N_2O or NO_3 losses (Basche et al., 2014; Six et al., 2004; Tonitto et al., 2006), the current dataset was also not developed to specifically address such practices. An expansion beyond the fertilizer-management data would better serve an exploration of the potential interactions of these variables with yield and N loss outcomes.

Uncertainty and Future Research Needs

Although the prospect of characterizing and understanding the remaining variability is daunting, the differential response of yield, N_2O, and NO_3 to in-field fertilizer management and broader environmental variability certainly indicates the potential for effective farm practices and strategy to reduce N losses while maintaining or increasing yields. A coordinated effort to address the existing gaps in data and understanding is essential to achieving this goal.

Our literature synthesis identifies several major uncertainties and knowledge gaps. The foremost of these is that the existing literature lacks concurrent measurements of N_2O and NO_3 losses. Despite the clear need to understand concurrent responses of yield, N_2O emissions, and NO_3 leaching, only one study reported both types of loss. We also found that the geography, timing, and agricultural setting differed markedly between published studies of NO_3 leaching and N_2O emissions. For example, most NO_3, but only a few N_2O observations, were reported from fields identified as tile drained; far more N_2O observations were in no-till systems; and fertilizer source, timing, and placement differed significantly between NO_3 and N_2O studies. Moreover, many important corn-producing regions were without any suitable studies of one or both of N_2O emissions or NO_3 leaching (Fig. 1). The substantial site-level variation and the strong climatic and soil controls on N_2O and NO_3 losses suggest caution in extending conclusions outside of the limited environments within our study. Ongoing and future experiments that focus on either N_2O emissions or NO_3 leaching could efficiently address many of these gaps by adding measurements of the other form of N loss. As the effects of many management practices on N losses have received only limited attention in field studies or particular environmental settings, such integrated experiments would help address gaps in combinations of practices and loss pathways, and enable more robust study of potential interactions between setting and practice.

A second major limitation of the existing literature is the inconsistent and incomplete availability of supporting data, especially regarding N pools and transformations. Few studies (11.3% of N_2O and 5.4% of NO_3 observations) reported soil available N (NO_3 and NH_4) at either pre-plant or side-dress dates, and grain or whole plant N uptake data were available for only 34 and 54% of N_2O and NO_3 observations, respectively. Thus, it was not possible to fully determine the relationships between N losses and available N that was used by the plant. More direct measures of N availability and uptake would improve assessment not only of the efficiency of plant use of N and its effect on losses, but also the effects of antecedent fertilizer and crop management, both of which themselves were not always well-documented. Finally, because plot-scale variability in losses was not generally reported, the uncertainty around final loss estimates and management impacts could not be well-determined. Such information on risk and probability would especially be advantageous for environmental market design.

Process-based models that can jointly predict yield, N uptake, NO_3 leachate loading, N_2O emissions—and if possible also ammonia (NH_3) and runoff NO_3—will remain essential tools to estimate the responsiveness of N losses to in-field fertilizer management (e.g., De Gryze et al., 2011; Kim et al., 2014). Ideally, such models are calibrated to local soil, climate, crop, and management conditions, but data for calibration and validation are often limited. For example, a commonly used version of COMET-Farm (a model based on DAYCENT) was built primarily on data from only the state of Michigan (Davidson et al., 2014). Therefore, process models and meta-analyses alike would benefit from data spanning a fuller range of soil types, climates, and fertilizer management practices that have been poorly studied and reported to date.

CONCLUSIONS

With two meta-analytic approaches, we documented the effects of fertilizer management and environmental factors on N_2O and NO_3 losses from corn-based cropping systems in North America. Using data synthesized from multiple experiments, we assessed practices across a broad geographic scale. Lower fertilizer N rates reduced both N_2O emissions and NO_3 leaching; appropriate source and timing provided additional controls on N losses. Cutting typical N fertilizer rates by 10 kg N h^{-1} (more likely than any more drastic rate adjustments) reduced average N_2O emissions by 4% (or 0.08 kg N ha^{-1} under average conditions), and reduced average NO_3 leaching losses by 1.0 kg N ha^{-1} (or 2.9% under average conditions). Nitrification inhibitors, side-dress timing, and broadcast placement of fertilizer N had much more significant impacts on N_2O emissions, reducing average losses by between 23 and 31%. Aqueous ammonia fertilizer and banded urea, respectively, were associated with higher and lower NO_3 losses compared with other sources, but with treatments limited to one study each, the trend might not be expected under other conditions. No other fertilizer management practices had statistically significant effects on either N_2O or NO_3 losses.

Climatic and soil conditions had a strong influence on NO_3 leaching and N_2O emissions, suggesting that broader scale distributions of corn agriculture as well as future climatic change may drive the magnitude and form of N losses. We found a 23% increase in N_2O (0.4 kg N ha^{-1} yr^{-1} on average) with a 1°C increase in average July temperature, and a 9 kg N ha^{-1} yr^{-1} increase in NO_3 leaching (average of 27% more) with a 100 mm rise in annual precipitation. Knowing these relationships can help guide both the geography and timing of management efforts for the greatest impact. The tradeoff observed between N_2O and NO_3 with different levels of soil C illustrates the need to consider the comparative environmental costs as well as other co-benefits of managing for soil organic matter content.

Certainty around effect sizes and potential interactions is limited by scarcity of data for some fertilizer management practices, uneven regional distribution, and the fact that only one study reported concurrent measurements of N_2O and NO_3. Such joint measurement of multiple N loss pathways is essential to understanding the whole system, and current data collection efforts attempt to remedy this problem. Existing agricultural research sites with drainage monitoring provide a potential network for strategically coordinated gaseous loss measurements to compliment crop production and nitrate loss data already being collected. Further, the otherwise unexplained effects of crop yield and time on N losses also suggest that other practices and regional characteristics may play a role. Improvements in data collection and reporting could ensure that more of these explanatory variables are made available for future analysis. Targeted research and research guidance to address these gaps would strengthen the predictive ability of future empirical modeling, process modeling, and, by extension, determinations of environmental benefit to be gained from practice change.

SUPPLEMENTAL MATERIAL

The supplemental material includes detailed information on systematic data collection, summary statistics describing the peer-reviewed studies that contribute to the final dataset, equations and examples of yield and N loss curves as related to N rate, additional details on multi-level hierarchical modeling, and an interpretation of regression coefficients.

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Supplemental Materials for:

Fertilizer management and environmental factors drive N_2O and NO_3 losses in corn: A meta-analysis

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16 pages

Supplemental Materials A. Data Collection

If crop yield, N losses, soil water NO_3, and soil extractable N values were only presented in graphical form without directly reporting in the literature, numerical values were requested from and provided by individual data owners for research published post-2004. Full-factorial data from combined treatments were also received from individual data owners when available. Any remaining data in graphical form were quantified using DataThief III (B. Tummers, http://datathief.org).

All corn yield values were reported at (or corrected to) 15.5% moisture. In the small number (7%) of cases where yield was reported as total plant biomass, it was converted to grain yield using a harvest index of 0.53. This harvest index is based on a literature review of typical ratios of corn grain as a fraction of total above-ground biomass. A small number of observations were removed from further analysis because of severe drought.

When possible, we included fertilizer rate and crop type from the previous year, as well as variability measures for yield and N losses. Methods for N loss measurements were also documented, including equipment, relevant time-frame, measurement frequency, and peak N loss rates. Nitrous oxide emissions were measured solely with in-field chamber methods. Leaching losses in the database were calculated from NO_3^- concentrations measured in porous-cup-collected soil water in combination with hydrological modeling (14%), by measuring tile water drainage volume and NO_3^- concentrations (61%), or by using lysimeters (25%).

Where not provided within the published studies, climate data were retrieved from the nearest weather station with complete precipitation and temperature records. Also when not directly provided, best estimates for soil organic matter content were obtained from the SSURGO database and matched to the nearest available location.

Supplemental Materials B. Peer-reviewed Studies with N Loss Data

Table S3. Studies used in the nitrous oxide (N_2O) meta-analysis and hierarchical models, with summary of study and management details. Records listed below the solid heavy line report loss data, but not crop yield, so while they are not incorporated into models they are included here as references.

Ref.	No of obs.	Location	Year(s)	Soil texture	Tillage	Water mgmt	Fert N source and Inhibitors	Fert N rates (kg N/ha)	Fertilizer timing	Fertilizer placement	N_2O losses (kg N/ha)	Msrmt time frame	Plant N uptake
Adviento-Borbe et al. (2007)	10	NE/USA	2003–05	Silty clay loam	CP	IRR	AN, Combo	0–310	Sp, Sp (PP+SD)	Brd/Inc	1.4–9.2	GS	N
Almaraz et al. (2009)	4	QC/Canada	2002–03	Clay loam	MB, NT	None	AN	0–180	Sp	Bnd	2.3–5.5	Unk	N
Dell et al. (2014)	32	PA/USA	2009–12	Silt loam	NT	None	ESN, PiNT, SupU, UAN+AP, UAN, Urea	0–154	SD+St	Bnd, Brd	0.1–2.9	GS	N
Drury et al. (2006)	18	ON/Canada	2000–02	Clay loam	NT, CsT, MB	None	AN	182	SD+St	KI(d), KI(s)	1.3–9.0	GS	N
Drury et al. (2012)	36	ON/Canada	2004–06	Fine sandy loam	NT, CsT, MB	None	PCU, Urea	152	AP, SD+St	Bnd	1.2–9.2	Unk	N
Fujinuma et al. (2011)	8	MN/USA	2009–10	Loamy sand	MB	IRR	AA, Urea	37–223	Sp+St	Brd/Inc, KI(d), KI(s)	0.1–1.6	GS	Y
Halvorson and Del Grosso (2012)	14	CO/USA	2009–10	Clay loam	NT	IRR	ESN, SupU, UAN, UAN+AP, Urea	0–202	SD	Bnd SR, Bnd SS	0.2–1.8	GS	Y
Halvorson and Del Grosso (2013)	20	CO/USA	2010–11	Clay loam	CsT, NT	IRR	ESN, Urea, SupU, UAN	202	SD	Bnd SR, Brd	0.3–1.7	GS	Y
Halvorson et al. (2008)	20	CO/USA	2005–06	Clay loam	MB, NT	IRR	Combo	0–246	AP, Sp	Bnd SR	0.2–1. 8	GS	N
Halvorson et al. (2010a)	14	CO/USA	2007–08	Clay loam	NT	IRR	ESN, PCU, SupU, UAN+AP, UAN, Urea	0–246	SD	Bnd SR	0.2–0.9	GS	Y
Halvorson et al. (2010b)	21	CO/USA	2007–08	Clay loam	MB, NT	IRR	ESN, SupU, Urea	0–246	SD	Bnd SR	0.1–2.6	GS	Y
Halvorson et al. (2011)	18	CO/USA	2009–10	Clay loam	CsT	IRR	ESN, UAN+Nf, SupU, UAN+AP, UAN, Urea	0–202	SD	Bnd SR, Bnd SS	0.1–1.7	GS	Y
Hoben et al. (2011)	36	MI/USA	2007–08	Loam, Sand	CP	None	Urea	0–225	PP	Brd	0.3–5.2	GS	N
Maharjan and Venterea (2013)	15	MN/USA	2011–12	Silt loam	Unk	None	Combo, ESN, SupU, Urea	0–180	SD	Bnd MR, Brd/Inc	0.4–6.2	GS	N
Maharjan et al. (2014)	16	MN/USA	2009–10	Loamy sand	CP	IRR	ESN, SupU, Urea	6–186	PP+St, Sp+St	Brd/Inc	0.2–0.4	GS	Y
McSwiney and Robertson (2005)	18	MI/USA	2001–03	Loam	CP	IRR	Combo, UAN	0–291	Sp (PP+SD)	Brd/Inc, KI	0.02–6.9	ST, GS	N

Ref.	No of obs.	Location	Year(s)	Soil texture	Tillage	Water mgmt	Fert N source and Inhibitors	Fert N rates (kg N/ha)	Fertilizer timing	Fertilizer placement	N_2O losses (kg N/ha)	Msrmt time frame	Plant N uptake
Mosier et al. (2006)	28	CO/USA	2002–04	Clay loam	MB, NT	IRR	UAN	0–224	PP	KI(s)	0.2–3.6	GS, YR	N
Nash et al. (2012)	6	MO/USA	2009–10	Silt loam	NT, CsT	IRR	Urea, ESN	0–140	AP	Bnd, Brd	1.1–6.1	GS	N
Parkin and Hatfield (2010)	4	IA/USA	2006–07	Silty clay loam	CsT	None	AA, AA+NP, Combo, Combo+NP	125–168	F	KI	5.3–7.0	YR	N
Pelster et al. (2011)	6	QC/Canada	2004	Clay loam	NT, MB	TD	AN	0–160	Sp	Bnd	0.8–2.8	Unk	N
Phillips et al. (2009)	2	ND/USA	2008	Clay loam	NT, MB	None	Urea	70	PP, SD	Brd	0.27–0.33	GS	N
Sistani et al. (2011)	14	KY/USA	2009–10	Silt loam	NT	None	AN, ESN, Urea, SupU, UAN, UAN+AP	0–168	SD	Brd	1.0–5.9	GS	N
Smith et al. (2011)	15	IN/USA	2005–07	Silt loam	CsT, CP, NT	None	UAN	0–168	AP, Sp (PP+AP), Sp (PP+SD)	Bnd, KI	0.5–11.2	YR	N
Thornton and Valente (1996)	3	TN/USA	1993	Silt loam	NT	None	AN	0–252	SD	Brd	1.9–8.5	GS	N
Thornton et al. (1996)	3	TN/USA	1994	Silt loam	NT	None	AA, Urea	0–168	SD	Bnd MR	1.4–13.8	GS	N
Venterea et al. (2010)	12	MN/USA	2006–07	Silt loam	CP	None	AA, Urea	0–146	PP	Brd, KI	0.6–3.4	GS	N
Venterea et al. (2011)	24	MN/USA	2008–10	Silt loam	MB, NT	None	Urea, ESN, SupU	5–151	SD+St	Brd	0.4–1.1	GS	Y
Bronson et al. (1992)	10	CO/USA	1989–90	Clay loam	MB, CP	IRR	Urea, Urea+NP, Urea+ECC	0–218	SD	KI	0.1–3.4	GS	N
Duxbury and McConnaughey (1986)	3	NY/USA	1981	Silt loam	Unk	None	CN, Urea	0–140	SD+St	KI	0.3–2.5	ST	N
Hernandez-Ramirez et al. (2009)	4	IN/USA	2005–06	Silty clay loam	CP	None	UAN	0–157	SD	KI	4.4–6.9	GS+	N
Johnson et al. (2010)	9	MN/USA	2004–06	Silty clay loam	CsT, MB	None	AN, AA	0–150	SD+St	Brd, KI	4.2–6.4	YR	N
Mitchell et al. (2013)	3	IA/USA	2011	Loam	NT	None	UAN	0–225	SD	Bnd SR	1.3–5.1	GS	N
Omonode and Vyn (2013)	8	IN/USA	2011–12	Silt loam	NT, CsT	None	UAN, UAN+NP	200	SD	KI	0.3–16.3	ST, GS	N
Smith et al. (2011)	5	IN/USA	2004	Silt loam	CsT, CP, NT	None	UAN	168	AP, PP, Sp (PP+SD)	Bnd, KI	2.9–3.8	YR	N
Venterea et al. (2005)	12	MN/USA	2003–04	Silt loam	CP, MB, NT	None	AA, UAN, Urea	120	PP, SD	Brd, KI	0.4–4.2	GS	N
Zebarth et al. (2008)	8	NB/Canada	2004-05	Silt loam	Unk	None	AN	45–209	Sp (PP+SD)	Bnd, Brd/Inc	1.0–3.3	GS	N

Abbreviations

Tillage Practice: CP - Chisel plow; CsT - Conservation tillage (reduced, strip, ridge, precision, vertical); MB - Moldboard plow; NT - No till; Unk - Unknown

Water Management: IRR - Irrigated; SIRR - Subirrigation; TD - Tile drainage

N source, as well as co-applied nitrification and urease inhibitors: AA - Anhydrous ammonia; AN - Ammonium nitrate; AP - AGROTAIN® PLUS; CN - Calcium nitrate; Combo - combination; ECC - encapsulated calcium carbide; ESN - ESN®, Environmental Smart Nitrogen, a polymer-coated urea; Nf - NITAMIN NFUSION®; NP - Nitrapyrin; PCU – Polymer-coated urea, other than ESN® or brand not specified; PiNT - a cation-stabilized amine N product; SupU - SUPERU™; UAN - Urea ammonium nitrate

Fertilizer timing: AP - At planting; F - Fall; PP - Preplant; SD - Side dress; Sp - Split; St - Starter

Fertilizer placement: Brd – Broadcast; Brd/Inc - Broadcast and incorporated; Bnd - Banded; Bnd MR - Banded midrow; Bnd SR - Banded siderow; Bnd SS - Banded subsurface; KI - Knife injected; KI(d) - Knife injected deep; KI(s) - Knife injected shallow

Measurement Timeframe: ST - Short-term, <90days; GS - Growing Season; GS+ - Growing season plus, when ground not frozen; YR - Year-round

Table S4. Studies used in the NO_3 meta-analysis and hierarchical models, with summary of study and management details. Records listed below the solid heavy line report loss data, but not crop yield, so while they are not incorporated into models they are included here as references.

Ref.	No of obs.	Location	Year(s)	Soil texture	Tillage	Water mgmt	Fert N source and Inhibitors	Fert N rates (kg N/ha)	Fertilizer timing	Fertilizer placement	NO_3 losses (kg N/ha)	Msrmt time frame	Plant N uptake
Bakhsh et al. (2002)	24	IA/USA	1993–98	Silty clay loam	CP, NT	TD	UAN	93–195	PP, SD	KI	3–46	GS+	N
Bakhsh et al. (2007)	3	IA/USA	1999–2000	Loam	CP, NT	TD	UAN	140–177	PP	KI	9–20	GS+	N
Bakhsh et al. (2010)	10	IA/USA	2001–05	Silty clay loam	CP	TD	UAN	168	AP, PP	KI, LCD	0.4–28	GS	N
Basso and Ritchie (2005)	12	MI/USA	1994–99	Loam	MB	None	Urea	0–120	Sp	Brd	11–89	GS	N
Drury et al. (2009)	12	ON/Canada	1996, 1998	Clay loam	NT	TD, SIRR	Urea	150–175	Sp	Bnd	4.0–33	YR	N
Guillard et al. (1999)	6	CN/USA	1995–96	Fine sandy loam	MB	None	AN	34–196	PP, SD, Sp	Unk	4–61	GS	N
Helmers et al. (2012)	20	IA/USA	1990–93	Clay loam	CP	TD	UAN	0–224	AP	KI	4–76	GS	N
Jayasundara et al. (2007)	2	ON/Canada	2003	Silt loam	MB, NT	None	UAN, Urea	60–150	AP, SD	Brd/Inc, KI	1.9–2.1	GS	Y
Jaynes (2013)	6	IA/USA	2006, 2008	Clay loam	CP	TD	UAN	134–157	SD, Sp	KI	22–46	GS	N
Jaynes and Colvin (2006)	8	IA/USA	2002, 2004	Clay loam	CP	TD	UAN	69–199	SD, Sp	KI	11–37	GS	N
Jaynes et al. (2001)	6	IA/USA	1996, 1998	Loam	CP, MB	TD	AA, UAN	57–202	PP, SD	KI	37–61	YR	Y
Jemison and Fox (1994)	9	PA/USA	1988–90	Silt loam	CP	IRR	AN	0–200	AP	Brd	24–133	Unk	N
Kanwar et al. (1997)	24	IA/USA	1990–92	Silty clay loam	CP, CsT, NT	TD	AA	168–202	PP	KI	4.5–108	Unk	N
Kucharik and Brye (2003)	12	WI/USA	1996–2000	Silt loam	CP, NT	None	AN	0–180	PP	Brd	3.2–102	GS	Y
Lawlor et al. (2008)	42	IA/USA	1990–2000	Clay loam	CP	TD	UAN	0–252	AP	KI	0–109	GS	N
Lawlor et al. (2011)	16	IA/USA	2001–04	Clay loam	CP	None	AqA	168–252	F, AP	KI	25–86	GS+	N
Maharjan et al. (2014)	16	MN/USA	2009–10	Loamy sand	CP	IRR	ESN, SupU, Urea	6–186	PP+St, Sp+St	Brd/Inc	1.4–47	GS	Y
Porter (1995)	36	CO/USA	1991–93	Silty clay loam	Unk	IRR	AS	0–376	PP	Brd/Inc	0.8–25	Unk	Y
Prunty and Greenland (1997)	4	ND/USA	1993, 1995	Loamy sand	Unk	IRR	UAN, Urea	82–136	Sp	Bnd SS	3–118	YR	N
Randall and Vetsch (2003b)[a]	24	MN/USA	1987–93	Clay loam	CsT	TD	AA, AA+NP	150	F, PP, Sp	KI	2–122	GS	Y
Randall and Vetsch (2005b)[b]	24	MN/USA	1994–99	Clay loam	CsT	TD	AA, AA+NP	135	F, PP	KI	4–63	GS	Y
Sexton et al. (1996)	16	MN/USA	1991–92	Sandy loam	MB	IRR	Urea	20–280	Sp+St	Brd	15–141	GS	Y

Ref.	No of obs.	Location	Year(s)	Soil texture	Tillage	Water mgmt	Fert N source and Inhibitors	Fert N rates (kg N/ha)	Fertilizer timing	Fertilizer placement	NO_3 losses (kg N/ha)	Msrmt time frame	Plant N uptake
Sogbedji et al. (2000)	17	NY/USA	1992–94	Clay loam, Loamy sand	MB	None	UAN	22–134	AP, SD+St	Bnd, KI	5.9–35	GS+	Y
Tan et al. (2002)	12	ON/Canada	1998–2000	Clay loam	MB	TD	AN	0–129	Sp	Brd	2.5–48	Unk	N
Walters and Malzer (1990b)[c]	27	MN/USA	1980–82	Sandy loam	Unk	IRR	Urea, Urea+NP	0–180	AP	Brd, Brd/Inc	6.9–141	GS	Y
Kalita et al. (2006)	16	IL/USA	1992–00	Silty clay loam	CsT	TD	Unknown	0–254	PP	Brd	3.3–73	YR	N
Kaluli et al. (1999)	5	QC/Canada	1994	Sandy loam	CP	TD, SIRR	AN	0–270	SD + St	Brd	2.6–22	YR	Y
Toth and Fox (1998)	9	PA/USA	1991, 1994	Silt loam	CP	IRR	AN	13–213	PP+St	Brd	4.5–92	YR	N
Zhu and Fox (2003)	6	PA/USA	1997, 1999	Silt loam	CP, NT	None	AN	0–200	PP+St	Unk	8–135	YR	N

[a] Yield data reported in Randall et al. (2003a)
[b] Yield data reported in Randall and Vetsch (2005a)
[c] Yield data reported in Walters and Malzer (1990a)

Abbreviations

Tillage Practice: CP - Chisel plow; CsT - Conservation tillage (reduced, strip, ridge, precision, vertical); MB - Moldboard plow; NT - No till; Unk - Unknown

Water Management: IRR - Irrigated; SIRR - Subirrigation; TD - Tile drainage

N source, as well as co-applied nitrification and urease inhibitors: AA - Anhydrous ammonia; AN - Ammonium nitrate; AS - Ammonium sulfate; AqA - Aqueous ammonia; ESN - ESN®, Environmental Smart Nitrogen, a polymer-coated urea; NP - Nitrapyrin; SupU - SUPERU™; UAN - Urea ammonium nitrate

Fertilizer timing: AP - At planting; F - Fall; PP - Preplant; SD - Side dress; Sp – Split; St - Starter

Fertilizer placement: Brd - Broadcast; Brd/Inc - Broadcast and incorporated; Bnd - Banded; Bnd SS - Banded subsurface; KI - Knife injected; LCD - Localized compaction and doming; Unk – Unknown

Measurement Timeframe: ST - Short-term, <90days; GS - Growing Season; GS+ - Growing season plus, when ground not frozen; YR - Year-round

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Supplemental Materials C. Yield and Loss Curves

Using observations from experiments that included at least three different fertilizer N rates for NO_3 and five different fertilizer N rates for N_2O, models were generated by site-year to look at the rate responses of corn grain yield, N_2O emission, and NO_3 leaching. Figure 1 shows an example of corn grain yield response of eight different site-years. Yield response for each site-year generally followed a Michaelis-Menten type saturation curve, but with an added y-intercept (instead of starting at zero). The equation is

(3) $$Y_{fert} = Y_0 + \frac{Y_{inc}[N_{fert}]}{K_m}$$

where Y_{fert} is yield at a given fertilizer rate, Y_0 is yield without fertilizer N, Y_{inc} is the maximum yield increase possible, N_{fert} is N fertilizer rate, and K_m is a saturation constant equal to the fertilizer rate at which half of the maximum yield increase has been achieved. There were some significant differences between locations and some variation between years at the same location. The yield in plots without fertilizer N varied (i.e., different y-intercepts), and so did the yield response to fertilizer N additions (affecting the shape of the curve).

Nitrous oxide emissions responded differently to fertilizer N rate than corn grain yield. Figure 2 illustrates examples from the data. In some locations, N_2O emissions even at high fertilizer rates remained much lower than emissions at low fertilizer rates in other locations. As with yield, the baseline emissions (at zero N fertilizer) varied by location and from year-to-year within some locations, demonstrating that available N for the crop and for losses is variable. Nitrate, exhibited even greater variability than N_2O, and while NO_3 losses did increase with rate, there was not always a clear relationship. The best fit for the relationship of fertilizer N rate to was linear (Figure 3).

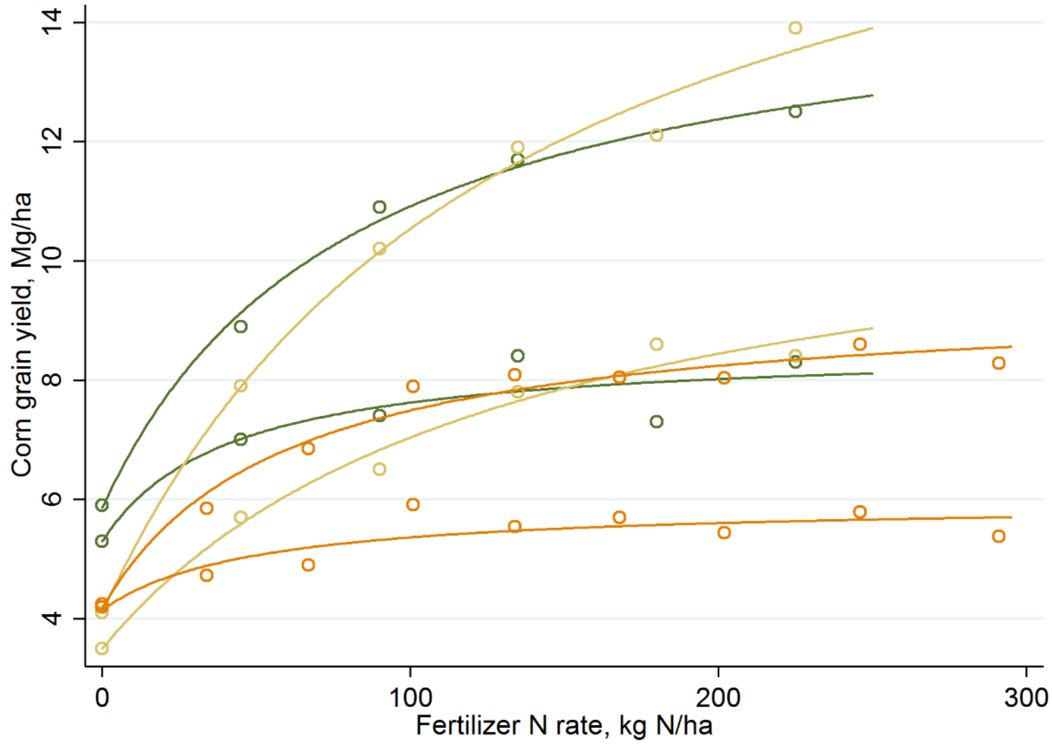

Figure S4. Corn grain yield response to fertilizer N rate in different site-years. Curves with the same color are the same experimental site, but a different year.

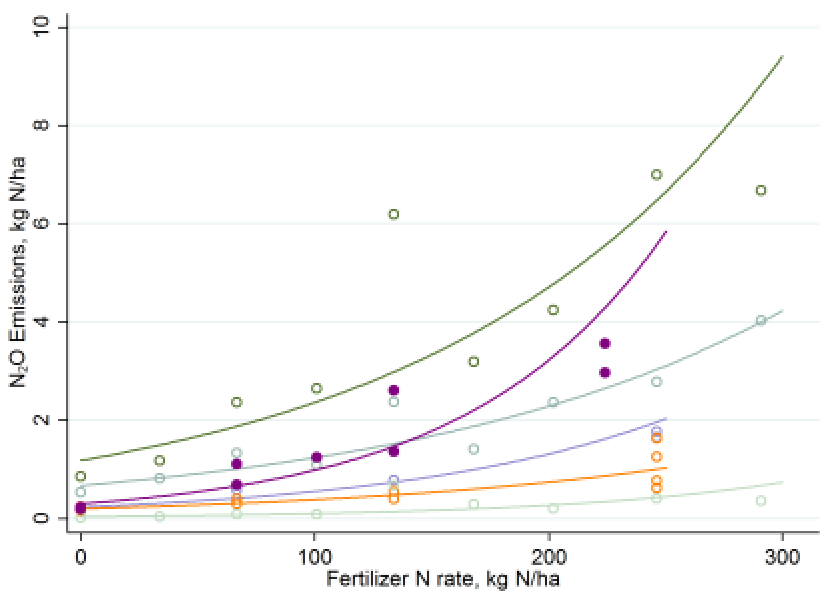

Figure S5. Nitrous oxide (N_2O) emission response to fertilizer N rate in six example site-years

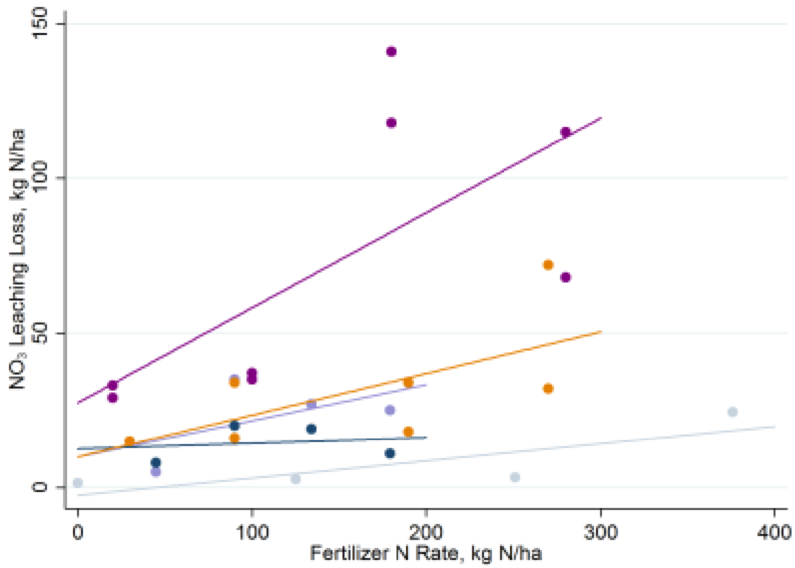

Figure S6. Nitrate (NO_3) leaching response to fertilizer N rate in five example site-years

Supplemental Materials D. Multi-level (Hierarchical) Models

The multi-level model initially looks like your typical regression,

$$(1) \quad y_{ij} = \beta_1 + \beta_2 x_{2ij} + \cdots + \xi_{ij} \qquad \xi_{ij} = \sigma_j + \epsilon_{ij}$$

where y_{ij} is nitrogen loss of observation *i* at location *j*, β_1 is the constant or intercept, and x_2 and following are covariates with coefficients of β_2 and following. The residual error term is ξ_{ij}. Since we expect the losses at a certain location to be correlated with each other in this model, the error term, ξ, can be split into two components – σ_j, the error shared by all observations at the same location; and ϵ_{ij}, the remaining residual unique for each observation. This error term at the group level (σ_j) represents the combined effects of omitted characteristics or unobserved heterogeneity for each location.

A likelihood ratio test examines the total variance at the group level (i.e., between groups) and the total variance at the individual level (i.e., within groups). This test determines whether group level variance is sufficient to favor the multi-level regression over an ordinary regression model.

In addition to correcting for unknown or un-quantified differences between groups, the multi-level model addresses unbalanced observations, so that the overall effect of an independent variable (or $\hat{\beta}$) is a weighted mean of the cluster means. Therefore,

$$(2) \quad \hat{\beta} = \frac{\sum_{j=1}^{J} \mathrm{w}_j \bar{y}_{.j}}{\sum_{j=1}^{J} \mathrm{w}_j} \quad , \qquad \text{where} \quad \mathrm{w}_j = \frac{1}{\hat{\varphi} + \hat{\theta}/n_j}$$

and $\bar{y}_{.j}$ is the average for each cluster, now weighted by the weighting factor w_j. The weighting factor, or the contribution of a specific group to the overall mean, increases with increasing group size (i.e., n_j is greater. Similarly, as the variance increases, both within groups ($\hat{\theta}$) and between groups ($\hat{\varphi}$), the weighting factor decreases and the contribution of that group is reduced.

Supplemental Materials E. Interpretation of Regression Coefficients

When the dependent variable in a regression model is log-transformed (with the natural log), the co-efficient can be approximated as the percent change in the non-transformed value (since adding 0.05 to ln(X) is *almost* equivalent to increasing X by 5%). However, this is not exact, and for coefficients above 0.05 (a change of more than 5%), the approximation starts to become less accurate, and the % change trends higher than the coefficient in the model. To be precise, we calculated the change in emissions from the model coefficients as follows:

$$Y_1 = Y_0 * (\exp((X_1 - X_0)*\text{coeff})).$$

Where the change in fertilizer rate X is 1 unit, and the coefficient is small, the % change in Y (i.e., (Y_1 – Y_0)/Y_0) is nearly the same as the coefficient (e.g., for N_2O Model 1, exp(0.0064) = 1.00646, so the change is 0.65%). In the case of a 10 unit increase in N fertilizer rate, the % change in Y is somewhat higher (e.g., exp(10*0.0064) = 1.066518, giving a 6.7% increase). Also, in the case of a switch from standard fertilizer to using nitrification inhibitors, the % change also differs from the coefficient (e.g., exp (1*-0.357) = 0.700, which is a 30.0% decrease; (1 - 0.700)/1 = 0.300). Thus, while the coefficients are often seen as the % change, it is only an approximation.