 

# Assessing effects of agricultural management on $N_2O$ emissions from corn cropping systems in the USA and Canada

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## Summary

One of the undesirable nitrogen (N)-loss pathways from cropland is the emission of nitrous oxide ($N_2O$), a potent greenhouse gas and ozone depleting substance. This study explores the potential of alternative agronomic management practices to mitigate $N_2O$ emissions from corn cropping systems in major corn producing regions in the USA and Canada by synthesizing available data from peer-reviewed literature. An acceptable number of side-by-side comparisons for meta-analysis was available for manure versus synthetic fertilizer, polymer coated urea versus conventional urea fertilizer application, synthetic fertilizer with versus without urease plus nitrification inhibitor, no-till versus tilled cropping systems, and continuous corn cropping systems versus corn-soybean rotations. For studies that included unfertilized control N-treatments, fertilizer induced emissions (FIE) were determined as the difference in $N_2O$ emissions in fertilized and unfertilized plots, divided by the N-rate. FIE normalizes $N_2O$ emissions for differences in environmental characteristics and N-rate between studies. Consequently, FIE was used to assess effects of agronomic management practices across studies, as a way to overcome the gap in data availability. Based on currently available data, the use of the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) in combination with the nitrification inhibitor dicyandiamide (DCD) was the only management strategy that consistently reduced $N_2O$ emissions. Manure application caused higher $N_2O$ emissions compared to the use of synthetic fertilizer N. This warrants further investigation in appropriate manure N-management, particularly in the Lake States where up to 30% of corn cropland typically receive manure. The $N_2O$ response to increasing N-rate varied by region (USDA Land Resource Regions in the USA and Ecozones in Canada), and was either linear, exponential or not significant. $N_2O$ emissions did not show a better fit to N-surplus, defined as the difference between N applied and grain N removed by harvest, compared to N-rate. In general, great variability around $N_2O$ emissions and a highly significant effect of region on FIE suggest that $N_2O$ emissions and appropriate mitigation strategies are best assessed on a regional as opposed to national or international level. Furthermore, more data on side-by-side comparisons of common and alternative management practices, especially those pertaining to N-placement, N-timing and N-source, will be needed to further develop and improve $N_2O$ mitigation strategies for corn cropping systems in the major corn producing regions in the USA.


## 1 Introduction

Agronomic management affects soil properties such as pH, carbon, nitrogen and oxygen availability. Those soil properties control emissions of $N_2O$, a potent greenhouse

gas and ozone depleting substance. The purpose of this study is to synthesize effects of agronomic management, especially management pertaining to IPNI's 4R nutrient strategy, on $N_2O$ emissions from corn cropping systems in major corn production regions in the USA and Canada.

Emissions of $N_2O$ from annual cropping systems are predominantly mediated by nitrifying and denitrifying bacteria. Nitrifiers release $N_2O$ as a by-product during the oxidation of $NH_4^+$ to $NO_3^-$, and are particularly active under aerobic (oxygen-rich) conditions, when $NH_4^+$ is abundant and when pH ranges between 8 and 9. Nitrifiers are also known to reduce $NO_2^-$ to $N_2O$ under oxygen-limited conditions when $NO_2^-$ pressure is high. Denitrifiers produce $N_2O$ during the reduction of $NO_3^-$ to $N_2$ under anaerobic conditions (oxygen-poor). Denitrification is favored when $NO_3^-$ concentrations are high and pH ranges between 7 and 9. Because denitrifiers are heterotrophic bacteria, denitrification is also stimulated as C availability increases. In addition to preventing high rates of nitrification and denitrification, $N_2O$ emissions could be mitigated by enhancing the reduction of $N_2O$ to $N_2$. $N_2O$ reduction relative to production increases with increasing pH, increasing oxygen limitation, and when carbon availability is high relative to $NO_3^-$ availability.

Under field conditions, $N_2O$ emissions typically occur in pulses following weather or agronomic events such as precipitation, fertilization, or tillage. During those events, pH and availability of carbon, nitrogen and oxygen often line up favorably for $N_2O$ production by nitrifiers or denitrifiers. In between such events, $N_2O$ emissions are typically low. Because of the complex set of microbial pathways and controlling factors on $N_2O$ production and reduction, predicting $N_2O$ emissions is often challenging. Therefore, this report guides interested researchers, extension specialists, field practitioners, policy makers and other relevant stakeholders through $N_2O$ responses that can be anticipated after altering N-rate, N-timing, N-placement, N-source, tillage type or crop rotation. Furthermore, major effects of various agronomic management practices as observed in corn cropland in major corn producing regions in the USA and Canada are presented and promising strategies to reduce $N_2O$ emissions in those cropping systems are discussed.

## 2 Approach

Through an exhaustive literature search, data on $N_2O$ emissions from corn cropping systems in major corn producing regions of the USA and Canada was collected. To be eligible for inclusion in our database, studies needed to adhere to the following criteria: (1) The study is peer-reviewed, or reviewed and considered acceptable by at least two other research scientists who have published papers on $N_2O$ emissions; (2) The study period is sufficient to capture the full growing-season and preferably the full year. Growing season refers to the period from planting to harvest; (3) temporal and spatial sampling frequency is sufficient to reliably calculate cumulative emissions. Measurements need to capture emissions from both the berm and the furrow, with at least biweekly measurements in between $N_2O$ peaks, and more frequent measurements following agronomic events such as tillage and fertilization; and (4) $N_2O$ data collection and analysis followed appropriate methodologies as per GRACENET (Parkin *et al.*, 2003). Data for a suite of ancillary variables pertaining to management practices and

environmental characteristics was also collected. With respect to management practices, variables included in the database were N-rate, N-placement, N-timing, N-source, nitrification inhibitor, tillage, rotation and irrigation. When available, yield and grain N-content at harvest were recorded, and used for the calculation of N-surplus (i.e. N applied minus N removed by harvest). N-rate, yield and N-surplus were recorded as continuous variables, whereas distinct categories were defined for the other management related variables (Table 1). Variables for environmental characteristics mainly pertained to weather, climate and soil properties. Definitions and sources of ancillary variables are described in more detail in Supplementary Materials A.1. In order to place results from the meta-analysis in a broader context, trends in adoption of various management practices in the landscape were assessed based on survey data from the United States Department of Agriculture's Annual Agricultural Resource Management Survey (USDA-ARMS). Variables and associated categories relevant to our meta-analysis are listed in Table 1. More detailed information on the USDA-ARMS data can be found in Supplementary Materials A.1.3.

**Table 1** Categories for agronomic management practices included in the meta-analysis and observed in USDA-ARMS survey data.

| Agronomic management practice | Meta-analysis categories | USDA survey data categories |
|---|---|---|
| N-placement | *Across all N sources*<br>▪ Banded<br>▪ Broadcast | *Synthetic N:*<br>▪ No broadcast<br>▪ All broadcast with incorporation<br>▪ All broadcast without incorporation<br>▪ Mixed N-application method with incorporation<br>▪ Mixed N-application method - without incorporation<br>*Manure N:*<br>▪ Broadcast without incorporation<br>▪ Broadcast or sprayed with incorporation<br>▪ Injected/knifed in |
| N-timing | *Across all N sources*<br>▪ Before or at planting vs. After planting<br>▪ Split N application vs. Single N application | *Synthetic N:*<br>▪ In fall before planting<br>▪ In spring before planting<br>▪ At planting<br>▪ After planting<br>*Manure N:*<br>▪ Fall before planting<br>▪ Spring before planting |
| N-source | *Conventional fertilizers*<br>▪ Solid manure<br>▪ Liquid manure<br>▪ Anhydrous ammonia (AA)<br>▪ Urea ammonium nitrate (UAN)<br>▪ Ammonium nitrate (AN)<br>▪ Urea (U)<br>*Enhanced efficiency fertilizers*<br>▪ Polymer coated urea (PCU)<br>▪ UAN + DCD + NBPT<br>▪ U + DCD + NBPT | ▪ Use of manure<br>▪ Manure type: Slurry liquid, Semi-dry or dry, Lagoon liquid (as % of applied manure) |
| Nitrification inhibitor | ▪ DCD<br>▪ ECC<br>▪ Nitrapyrin<br>▪ None | ▪ Use of 'Nitrogen inhibitors', (i.e. all enhanced efficiency fertilizers are aggregated) |
| Tillage | ▪ Tilled<br>▪ No till | ▪ No till<br>▪ Mulch till<br>▪ Ridge till<br>▪ Reduced till |
| Rotation | ▪ Continuous corn (CC)<br>▪ Corn-soybean rotation (CS) | ▪ Previous crop is corn<br>▪ Previous crop is soybean |
| Irrigation | ▪ Rainfed<br>▪ Irrigated | Irrigated and total corn acres |
| Organic agriculture | Not available | Organic corn production (acres or % of total) |
| Precision agriculture | Not available | ▪ Use of precision agriculture<br>▪ Use of variable rate technology for N application |

NBPT = N-(n-butyl) thiophosphoric triamide, DCD = dicyandiamide, ECC = encapsulated calcium carbide, nitrapyrin = 2-chloro-6-(trichloromethyl) pyridine. NBPT + DCD is commercially sold under the trademark Agrotain Plus ®. Urea impregnated with NBPT + DCD is commercially available under the trademark SuperU ®. Studies included in this meta-analysis that applied PCU used the commercially available product ESN ®.

For management practices for which sufficient pairwise comparisons between alternative treatments were available, meta-analyses were performed using the natural logarithm of the response ratio (ln*R*) as effect sizes:

$$\ln R = \ln(X_A/X_B)$$

Where $X_A$ and $X_B$ are the mean values for cumulative $N_2O$ emissions in treatment *A* and treatment *B*, respectively. Such analyses were achievable for manure versus synthetic N application, continuous corn versus corn-soybean rotations, no-till versus tilled systems, conventional urea versus polymer-coated urea, and no inhibitors versus the urease inhibitor N-(n-butyl) thiophosphoric triamide in combination with the nitrification inhibitor dicyandiamide (NBPT + DCD). Various weights and meta-analytic models were evaluated as described in more detail in Supplementary Materials A.2.1. Results presented in this final report are based on a random effects meta-analytic model, using the pooled variance as a weighting function, and with confidence intervals that are generated non-parametrically by bootstrapping.

For studies that included control treatments (i.e., treatments with no or a minimal amount of starter fertilizer N application, see Supplementary Materials A.2.1 for more details), the natural logarithm of the fertilizer induced emissions (FIE) could be used as an effect size in meta-analytic moderator analyses. The natural logarithm of FIE is calculated as follows:

$$\ln(FIE) = \ln\left(\frac{X_A - X_{Control}}{N_A - N_{Control}}\right)$$

Where $X_A$ and $X_{Control}$ are the cumulative $N_2O$ emissions for treatment *A* and the control treatment, respectively; $N_A$ and $N_{Control}$ are the N-rates applied to treatment *A* and the control treatment, respectively. The variable FIE normalizes $N_2O$ emissions from individual observations for differences in N-rates and background emissions between observations and studies (Eichner, 1990). Therefore, FIE can be used as an effect size in meta-analytic moderator analyses to assess effects of agronomic management practices on $N_2O$ emissions across observations and studies that received different amounts of fertilizer N and are exposed to different environmental conditions. Meta-analytic moderator analysis is similar to analysis of variance in the sense that average effects of each category of the moderator variable on the dependent variable can be assessed, but meta-analytic moderator analysis takes into account weighting functions to evaluate effects of the moderators. In meta-analysis, variability in the data is referred to as heterogeneity, and the parameter $Q_m$ estimates the amount of heterogeneity explained by the moderator. By dividing $Q_m$ by the estimate for the total heterogeneity ($Q_t$), the percentage of heterogeneity that is explained by a particular moderator can be determined (further referred to as $Q_m/Q_t$).

Given the unbalanced design of the database, the large number of missing values for ancillary variables, and potential publication bias, it was necessary to investigate the validity of overall effects of management practices on FIE and $N_2O$ emissions. One way of testing the validity of the results was by assessing whether trends were consistent across subsets of the data. Moderator analyses elucidated that ‘region’ and ‘soil order’

explained a large portion of the heterogeneity in the observations (40% and 25%, respectively, see results for more details). Therefore, effects of management practices on FIE (or $N_2O$ emissions for N-rate and N-surplus) were assessed on a per-region and per-soil-order basis. Regions comprise Land Resource Regions (LRR) in the USA and Ecozones in Canada. The soil orders observed in the dataset were Alfisols, Mollisols and Inceptisols. Regions and the location of observations associated with different soil orders are shown in Figure 1. More information on the regions considered in this study can be found in Supplementary materials A1.2. In addition to subsetting the data, all comparisons were tested for potential bias by N-rate and yield between the caterogeries of each variable (See Supplementary Materials C for results). N-rates and yields included in the analysis where those for fertilized plots for which FIE could be determined. In this report, differences in N-rate and yields between categories are noted only when they were significant. All meta-analytic models were fitted using MetaWin© Version 2.1 (Release 5.10).

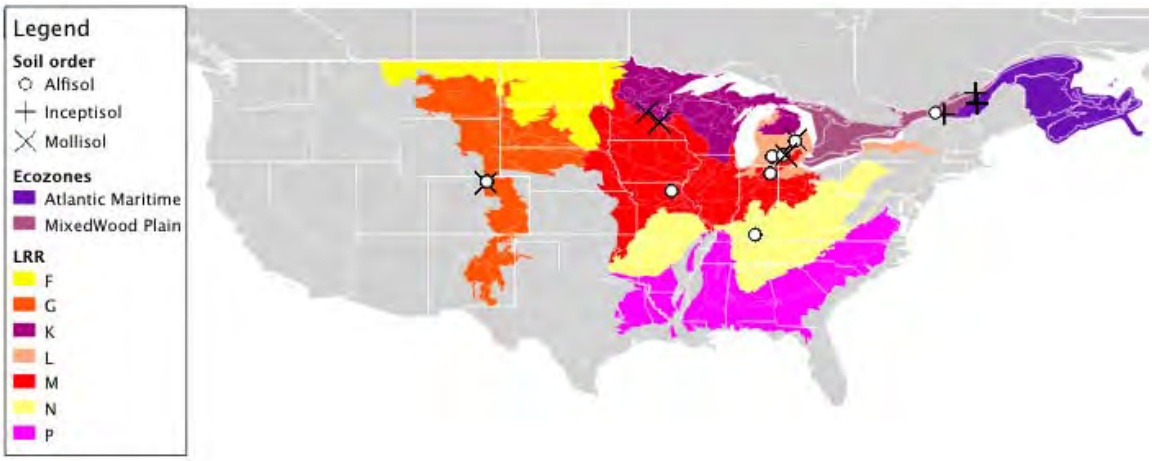


**Figure 1:** Map illustrating Regions of interest (i.e. selected Ecozones and LRRs) and locations of observations associated with the soil orders Alfisol, Inceptisol and Mollisol. LRR F and LRR P only include studies without control treatments. Consequently, no FIE are available for those regions.

Effects of N-rate and N-surplus on $N_2O$ emissions were assessed using regression analysis. Linear and exponential models were fitted to the data and parametric confidence intervals were constructed. Overall, as well as per-region and per-soil order, effects of N-rate and N-surplus on $N_2O$ emissions were evaluated. R project for statistical computing was used to perform statistical analyses.

Finally, effects of N-rate and N-surplus on $N_2O$ emissions and of continuous ancillary variables on the natural log of FIE (ln(*FIE*)) were evaluated using the boundary line approach (Webb, 1972; Schmidt *et al.*, 2000). In the boundary line approach, lines are fitted to the rim of datapoints in a scatterplot; in other words, trends in the maximum values of the dependent variable *y* in function of the independent variable *x* are assessed. This line can be interpreted as the response of *y* to *x*, under the condition that all variables controlling *y* other than *x* would be non-limiting. We assessed boundary lines following a standardized approach outlined by Schmidt et al. (2000). More details on boundary line procedures can be found in Supplementary Materials A.2.2.

# 3 Major findings

## *3.1 Data availability*

Data on $N_2O$ emissions from 48 studies (publications) were included in our database, accounting for a total of 548 observations for specific year-field-treatment combinations. The 48 studies cover 33 different field sites, distributed fairly evenly throughout the major corn producing regions in the USA and South-Eastern Canada (Figure 2). Remarkably, we did not find any $N_2O$ field data for corn-based cropping systems in Illinois, one of the proposed focus areas of the meta-analysis.

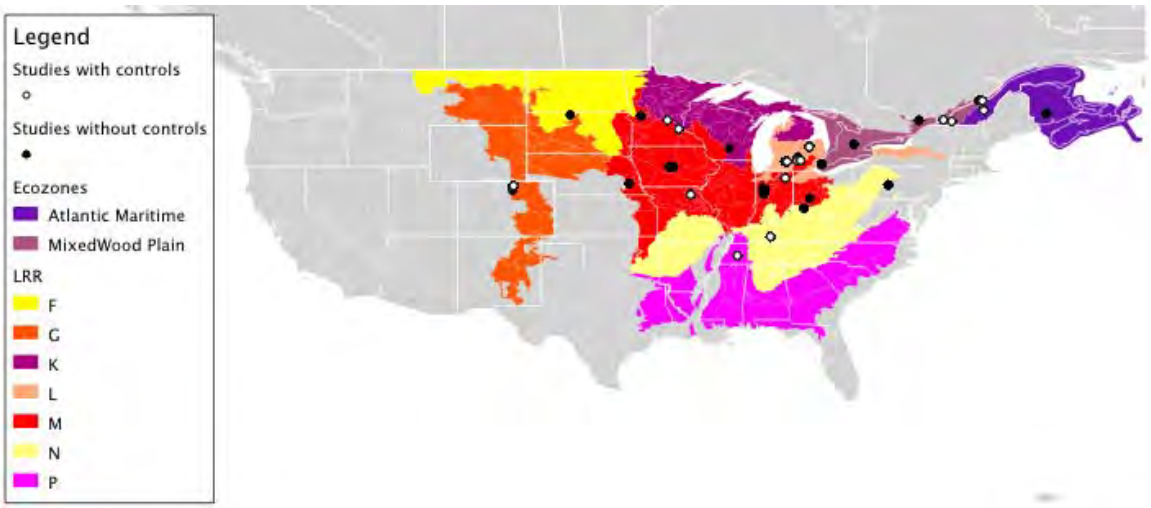


**Figure 2:** Map of locations of field experiments measuring N2O emissions from corn-based cropping systems in major corn producing regions in the USA and Canada. Open and solid circles represent experiments with and without control treatments, respectively.

Only 33 out of 48 studies were accompanied by corn yield data (417 observations), and 7 studies reported crop N export (88 observations) (Table 2). Ten out of 48 studies reported cumulative $N_2O$ emissions from year-round measurements, accounting for 74 observations. Therefore, the other 474 observations solely represent growing-season $N_2O$ emissions. In addition, 18 out of 48 studies included control treatments with no fertilizer N application (control treatments in 3 out of 18 studies received a small dose of starter N application, see Supplementary Materials A.2.1 for more details), resulting in 258 observations for which FIE could be determined. The availability of accompanying yield and N export data is essential for the quantification of intensity-based $N_2O$ emissions (also known as yield-scaled or output-based $N_2O$ emissions, e.g. Venterea et al., 2011), and for quantifying $N_2O$ emissions in function of N surplus (e.g. Van Groenigen et al., 2010). Finally, the low availability of year-round $N_2O$ data urges more research efforts to quantify non-growing season $N_2O$ emissions.

**Table 2:** Summary table of the number of studies and observations that report or provide sufficient information for the determination of cumulative $N_2O$ emissions, FIE, crop yield, crop N export, and year-round (as opposed to growing-season) cumulative $N_2O$.

| | Cumulative $N_2O$ | FIE | Corn yield | Crop N export | Year-round measurements |
|---|---|---|---|---|---|
| Number of studies | 48 | 18 | 33 | 7 | 10 |
| Number of observations | 548 | 258 | 417 | 88 | 74 |

### *3.2 Overall effects of management and environment on $N_2O$ emissions*

Meta-analytic moderator analysis indicated that across all observations for which FIE could be determined, only the N-source, nitrification inhibitor and split versus single N application had a significant effect on FIE (Table 3). In this analysis, the variable N-source encompassed manure and various forms of synthetic N fertilizer, including enhanced efficiency fertilizers. The variable 'nitrification and urease inhibitor' included the categories 'DCD', 'ECC', 'nitrapyrin' and 'none'. Although not statistically significant at the 0.05 probability level, FIE tended to be slightly higher when N was applied before or at planting versus after planting ($p = 0.07$). There were no significant differences in FIE when tillage versus no-till was practiced, when the corn was part of a continuous corn cropping system versus corn soybean rotation, or when fertilizer N was broadcasted versus banded. In addition, no significant effect of N-surplus or N-rate on FIE was observed; In other words, FIE remained fairly constant across an N-surplus or N-rate gradient.

**Table 3:** Statistical results from meta-analytic analyses testing the effect of agronomic management on fertilizer induced emissions. Qm/Qt expresses the portion of total heterogeneity across the observations that can be explained by differences in the categories defined for a particular type of agronomic management. The grey shaded variables had no significant effect on FIE ($p < 0.05$).

| **Agronomic management** | **$Q_m/Q_t$ (%)** | **p-value** |
|---|---|---|
| N-source | 44 | 0.0002 |
| Nitrification inhibitor | 16 | 0.0002 |
| Split vs. single N application | 4.3 | 0.0072 |
| N-timing | 3.0 | 0.07 |
| N-surplus | 26 | 0.21 |
| Tillage | 0.8 | 0.23 |
| Rotation | 0.5 | 0.33 |
| N-placement | 0.2 | 0.53 |
| N-rate | 0.5 | 0.73 |

When side-by-side comparisons were considered, meta-analyses indicated that manure N caused between 17 and 68% more $N_2O$ emissions compared to synthetic N (Figure 3). Furthermore, $N_2O$ emissions were between 18 and 56% higher in fields where no urease or nitrification inhibitors were applied compared to their counterparts that

received DCD + NBPT. In contrast, we observed no significant effects of rotation, tillage or polymer-coated urea on $N_2O$ emissions. Note that some studies included side-by-side comparisons, but did not include a control treatment necessary for the calculation of FIE, or vice versa. Therefore, the data included in side-by-side comparisons overlaps with, but is not identical to, the data used in meta-analytic moderator analysis with FIE as the dependent variable. Reoccurring significant effects of N-source (more specifically manure vs. synthetic N) and NBPT + DCD in side-by-side comparisons and moderator analysis of FIE strengthens confidence in the validity of these results.

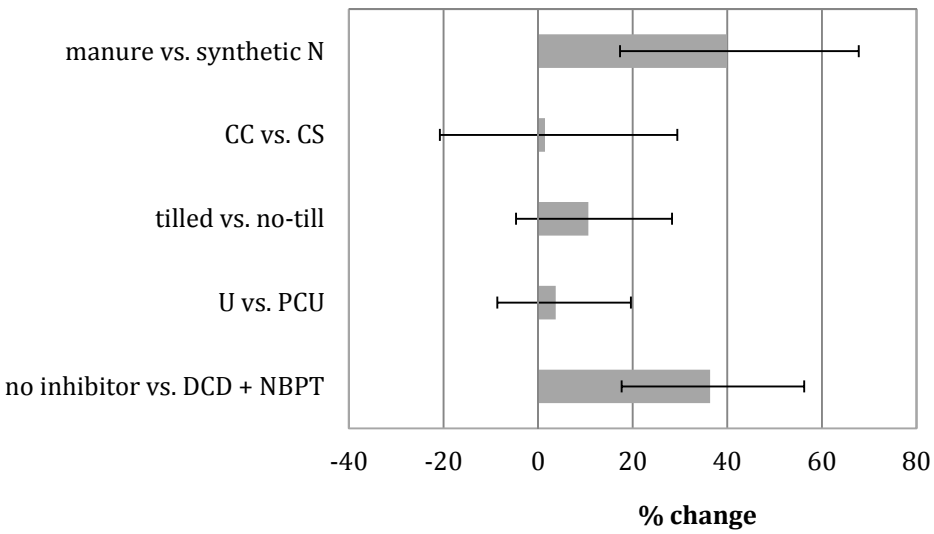


**Figure 3:** Results from meta-analysis of side-by-side comparisons of $N_2O$ emissions following various management practices. Error bars denote 95%-confidence intervals.

Among all ancillary variables recorded, 'site' was highly significant ($p = 0.0002$) and explained 59% of the total heterogeneity between the observations (Table 4). This implies that the combination of environmental and management characteristics unique to each field site has a major effect on FIE. This can be expected, given the complexity of controls on microbial processes that cause $N_2O$ emissions, and the necessity of favorable soil moisture conditions, pH, and high availability of carbon and nitrogen to coincide for $N_2O$ pulses to occur under field conditions. The categorical variable 'region' also had a significant effect on FIE, explaining 40% of the total heterogeneity between observations. This strongly suggests that a regional approach is preferable over a national or global approach for quantifying $N_2O$ emissions from corn cropping systems. Note, however, that our database had a limited number of studies per region, which potentially caused site-specific effects to partially confound results for 'region' in our analysis.

The variables 'irrigation (yes/no)', 'aridity class', 'mean annual precipitation' and 'aridity index' all significantly affected FIE, while the effect of precipitation (or precipitation + irrigation) during the measurement period was not significant (Table 34). This suggests that, across major corn producing regions in the USA and Canada, broad differences in climate overrode effects of year-to-year weather variability on FIE when all data are analyzed together. Nevertheless, various studies have found significant year-to-year variability in $N_2O$ emissions from a particular field site, which has mostly been

attributed to weather variability (Rochette *et al.*, 2008a; Lee *et al.*, 2009). Our results therefore suggest that a national or international approach for quantifying $N_2O$ emissions is likely not sensitive enough to capture variability in $N_2O$ emissions due to year-to-year weather variability. Soil property-related ancillary variables that had a significant effect on FIE were 'Soil order', 'Percent soil organic carbon' and 'Percent sand'. The variables 'pH' and 'Percent clay' had a marginal effect on FIE, with *p*-values equal to 0.06 and 0.09, respectively. Given that a relatively large number of observations were included in each soil order category, soil order lends itself as an appropriate grouping variable to subset the data for subsequent assessment of the consistency of effects of agronomic management practices on FIE, in addition to a per region assessment.

**Table 4:** Statistical results from meta-analytic moderator analysis testing effects of ancillary variables other than agronomic management on FIE. $Q_m/Q_t$ expresses the portion of total heterogeneity across the observations that can be explained by differences in the categories defined for a particular type of agronomic management. The grey shaded variables had no significant effect on FIE ($p < 0.05$).

| Continuous variables | | | Categorical variables | | |
|---|---|---|---|---|---|
| **Variable** | **$Q_m/Q_t$ (%)** | **p-value** | **Variable** | **$Q_m/Q_t$ (%)** | **p-value** |
| Mean annual precipitation | 36.9 | 0.006 | Site | 59.3 | 0.0002 |
| Aridity index | 36.8 | 0.006 | Region | 39.5 | 0.0002 |
| Percent soil organic carbon | 25.5 | 0.045 | Soil order | 24.0 | 0.0002 |
| Percent sand | 21.4 | 0.046 | Irrigation | 21.6 | 0.0002 |
| pH | 18.8 | 0.06 | Aridity class | 19.5 | 0.0002 |
| Percent clay | 15.4 | 0.09 | Texture group [#] | 1.8 | 0.30 |
| Minimum temperature[*] | 5.3 | 0.28 | Measurement period (year vs. season) | 0.2 | 0.52 |
| Potential evapotranspiration | 5.3 | 0.30 | | | |
| Bulk density | 14.8 | 0.32 | | | |
| Longitude | 3.7 | 0.36 | | | |
| Maximum temperature[*] | 3.6 | 0.37 | | | |
| Crop yield | 3.6 | 0.42 | | | |
| Precipitation[*] | 5.2 | 0.44 | | | |
| Nitrate exposure | 4.3 | 0.50 | | | |
| Water-filled pore space | 1.5 | 0.60 | | | |
| Measurement period (days) | 0.2 | 0.82 | | | |
| Mean annual temperature | 0.1 | 0.86 | | | |
| Precipitation + irrigation[*] | 0.0 | 0.94 | | | |
| Latitude | 0.0 | 0.99 | | | |

[*]Average minimum and maximum temperatures and cumulative precipitation were determined for the measurement period associated with each observation. For the effect of temperature, only observations with growing-season $N_2O$ emissions were considered. For the effect of precipitation, only rainfed systems were included, whereas all observations were included for assessing the effect of precipitation + irrigation. [#] Texture group refers to the categories 'coarse', 'medium' and 'fine'.

### *3.3 Effect of N-rate and N-surplus on $N_2O$ emissions*

As expected, there was a general trend of increasing $N_2O$ emissions with increasing N-rate (Figure 4a). This is in agreement with other studies (Bouwman *et al.*, 2002; Hoben *et al.*, 2011) and with the IPCC (2006) guidelines, where predicted $N_2O$ emissions from soils are scaled relative to the total amount of N-inputs in the system. Much more debated is the magnitude of the response of $N_2O$ emissions to changes in N-rate, and whether the response adheres to a linear or exponential model. The linear model is used in the IPCC (2006) guidelines for quantifying $N_2O$ emissions from cropland, and based on a meta-analysis by Bouwman *et al*. (2002) who summarized $N_2O$ emissions from various climate zones and cropping systems. Exponential responses of $N_2O$ to increasing N rate as observed in other studies have been attributed to excess N availability when N-rate exceeds crop N demand (McSwiney and Robertson, 2005; Hoben *et al.*, 2011). Because crop N-demand can vary from system to system, it has been suggested that the response of $N_2O$ to N-surplus would be more predictable and consistent compared to the response of $N_2O$ to N-rate (Van Groenigen *et al.*, 2010). Furthermore, Kim *et al.* (2012) proposed that $N_2O$ emissions increase linearly with increasing N-rate until plant N demand is met. In this phase, soil conditions are N-limited. Once N-rate exceeds plant N demand, $N_2O$ emissions are expected to increase exponentially in their model, until N-uptake by soil microorganisms is at its maximum. At that point, a steady-state is reached, and $N_2O$ emissions are hypothesized to be limited by soil C availability (Kim *et al.*, 2012).

In our study, the exponential model across all observations did not deviate much from the linear model for N-rates lower than 200 kg $ha^{-1}$. Within an N-rate range of 0 to 200 kg N $ha^{-1}$, the slope of the models equaled 0.017 (see Supplementary materials C.48 and Figure 4), implying that, on average, 1.7% of applied N was lost as $N_2O$. This is higher than the average emission factor of 1% proposed by the IPCC (2006) to quantify $N_2O$ emissions from soil, but within the proposed range of 0.3 – 3% (IPCC, 2006). Note, however, that our regression is based on observations for $N_2O$ emissions over a range of N-rates, but most data included in the database are not part of an N-rate trial within a field. Furthermore, the behavior of controlling factors other than N-rate that might affect $N_2O$ emissions is not uniform across the N-rate gradient. Therefore, the $N_2O$ response curve to N-rate observed in our study might deviate somewhat from the expected $N_2O$ response to reduced N-rate on a given corn field, when all other variables are unchanged.

Both the linear and the exponential model were statistically significant when regressing cumulative $N_2O$ with N-rate across all data in our database (Table 5), but the exponential model had a slightly better fit than the linear model ($R^2$ = 0.12 versus 0.06). Notably, the model fit was relatively poor for both models. In addition, N-rate had no significant effect on FIE (see Table 3), suggesting that every incremental increase in N-rate had the same effect on $N_2O$ emissions, regardless of the position along the N-rate gradient. Under this scenario, a linear model should underpin the $N_2O$ response curve to N-rate. In our study, the more favorable $R^2$ value for the exponential compared to the linear model might be forged by a small number of control treatments where variability around $N_2O$ emissions is minimal, limited data availability in the lower N-rate ranges (< 100 kg N $ha^{-1}$), and a large number of data with great variability in the higher N-rate range (> 100 kg N $ha^{-1}$). Considering only the N-rate range between 100 and 200 kg N $ha^{-1}$, no apparent trend between $N_2O$ emissions and N-rate was readily observed (Figure 4a,

Supplementary materials C.44). $N_2O$ increased drastically as N-rates exceeded 200 kg N $ha^{-1}$, suggesting that the exponential response only takes effect when systems are really overloaded with N. Yields increased with increasing N-rate, but yield variability was very large along the N-rate gradient (see Supplementary materials C.44), limiting our ability to relate $N_2O$ responses to yield responses. Boundary line analysis showed that the response of $N_2O$ to N-rate tended to taper off at approximately 180 kg N $ha^{-1}$ (see Supplementary materials C.72). A similar trend has been observed when regressing $N_2O$ in function of soil $NO_3^-$ concentration in cropland in Germany (Schmidt *et al.*, 2000). The boundary line analysis suggests that, when all other controls on $N_2O$ are non-limiting, there might be a saturation point beyond which $N_2O$ emissions no longer increase, and where excessive N finds other loss pathways to leave the system.

In general, our results tend to follow the model proposed by Kim et al. (2012), where linear, exponential and steady-state responses of $N_2O$ to N-rate are controlled by optimal crop N-uptake and optimal N-uptake by microorganisms. Differences between studies in factors such as agronomic management, climate and soil type likely confounded regressions between $N_2O$ versus N-rate and yield versus N-rate in our analysis. Furthermore, optimal uptake of N by plants and microorganisms likely varies from field to field. For example, where corn yields are below 9.5 Mg ha-1 due to limiting factors other than N availability, N-rates greater than 180 kg N $ha^{-1}$ are likely too much; Meanwhile, modern corn production systems may take up over 220 kg N $ha^{-1}$ (grain + above-ground plant residue) in achieving yields above 12 to 14 Mg $ha^{-1}$ (Snyder, 2012). Therefore, one of the biggest challenges of quantifying $N_2O$ emissions from cropland might lie in characterizing optimal plant and microbial N-uptake rates for a particular system.

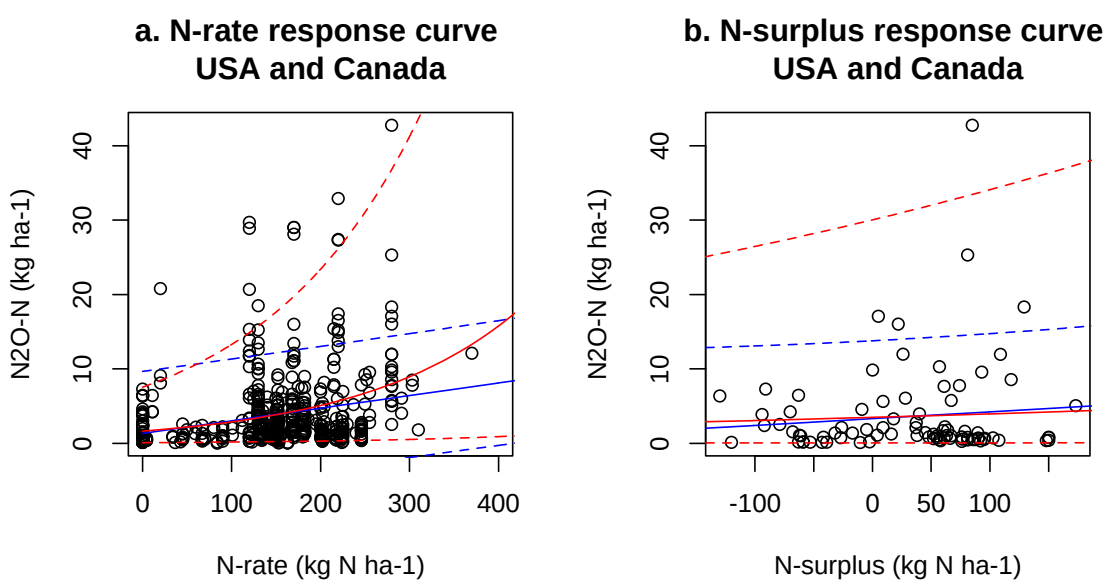


**Figure 4:** Response curves of cumulative $N_2O$ emissions to (a) N-rate and (b) N-surplus across all observations included in the database. Open circles represent individual observations. Blue and red solid lines represent the best linear and exponential model fit to the data. Blue and red dashed lines indicated 95%-confidence intervals for the linear and exponential model, respectively.

Regressions between $N_2O$ emissions and N-rate had a marginally better fit for the USA Land Resource Regions compared to the models fitting all data included in the database (Table 5). The $N_2O$ response curve to N-rate fitted the exponential model better compared to linear model in LRR G and N, whereas the opposite was observed for LRR L. In LRR M, similar $R^2$ values were observed for the exponential compared to the linear model. In contrast to trends observed between $N_2O$ emissions and N-rate in LRRs in the USA, regressions between $N_2O$ emissions and N-rate were not significant in the Canadian ecozones: Atlantic Maritimes and MixedWood Plain. This is likely a result of data bias; for example, conditions other than N-rate favoring $N_2O$ emissions (e.g. high clay content and soil moisture levels) might coincidentally have been predominantly associated with observations at low N-rates. In other words, the lack of a significant regression between $N_2O$ and N-rate for corn cropping systems in the Atlantic Maritimes and MixedWood Plain does not imply that reducing N-rate on a given field in those regions would not reduce $N_2O$ emissions. Nevertheless, the lack of a significant regression between $N_2O$ and N-rate and the wide range of $N_2O$ emissions observed at any given N-rate in those ecozones suggest that there is likely potential for management practices other than N-rate (e.g. reduced tillage, timing to better match N application with N-demand) to reduce $N_2O$ emissions from corn cropland. While slopes of regression models differed between regions (see supplementary materials C.48), potential data bias prohibits derivation of regional emission factors directly from the regression models presented in this study. Instead, we propose more strategized data collection and/or process-based modeling efforts to generate robust, preferably region-specific, emission factors.

**Table 5:** R-squared values and p-values associated with linear and exponential model fits of the response of $N_2O$ to N-rate in diverse regions. '# obs.' is the number of observations and '# sites' is the number of field sites contributing to the data within each region.

| **Region** | ***Linear model*** | | ***Exponential model*** | | **# obs.** | **# sites** |
|---|---|---|---|---|---|---|
| | $R^2$ | p-value | $R^2$ | p-value | | |
| USA and Canada | 0.06 | <0.0001 | 0.12 | <0.0001 | 548 | 33 |
| LRR G | 0.30 | <0.0001 | 0.52 | <0.0001 | 96 | 3 |
| LRR L | 0.36 | <0.0001 | 0.15 | 0.001 | 74 | 5 |
| LRR M | 0.20 | <0.0001 | 0.19 | 0.000 | 119 | 8 |
| LRR N | 0.10 | 0.123 | 0.17 | 0.045 | 23 | 2 |
| Atlantic Maritimes | 0.03 | 0.243 | 0.05 | 0.114 | 53 | 4 |
| MixedWood Plain | 0.02 | 0.099 | 0.02 | 0.145 | 128 | 6 |

As indicated earlier, it has been suggested that N-surplus would be a better predictor of $N_2O$ emissions compared to N-rate (Van Groenigen *et al.*, 2010; Grassini and Cassman, 2012), because it better reflects the N that is available for microbial N transformations and $N_2O$ production. In our study, there was no significant linear or exponential relationship between $N_2O$ and N-surplus when all data were considered (Figure 4b and Table 6). Likewise, the $N_2O$ emissions response curves to N-surplus based on observations from Alfisols and Inceptisols did not fit a linear nor exponential model (Supplementary Materials C.51). In contrast, there was a reasonably good exponential fit

between $N_2O$ and N-surplus for observations from LRR G, LRR M and the ecozone MixedWood plain ($p < 0.05$; $R^2 > 0.25$). This implies that N-surplus can be a good predictor of $N_2O$ emissions at the regional level, after variability due to difference in environmental characteristics is partially removed. It should be noted that in the study by Van Groenigen et al. (2010), N-surplus was calculated as the difference between N applied and aboveground N-uptake, whereas data limitation led to the use of the difference between applied N and N removed by harvest (i.e., grain N) in our study. Given that variation in harvest index is likely small relative to yield variation (Lorenz *et al.*, 2010), the use of grain N instead of aboveground N-uptake for the calculation of N-surplus to assess relationships between $N_2O$ emissions and N available for soil microbial processes is justified for the purposes of this study. However, because grain N removal may not be related to nitrate intensity as much as aboveground N-uptake (Zebarth *et al.*, 2012), we recommend measurements of aboveground N-uptake and its use in calculations of N-surplus for future studies.

**Table 6:** R-squared values and p-values associated with linear and exponential model fits of the response of $N_2O$ to N-surplus in diverse regions. '# obs.' is the number of observations and '# sites' is the number of field sites contributing to the data within each region.

| **Region** | ***Linear model*** | | ***Exponential model*** | | **# obs.** | **# sites** |
|---|---|---|---|---|---|---|
| | $R^2$ | p-value | $R^2$ | p-value | | |
| USA and Canada | 0.01 | 0.355 | 0.00 | 0.558 | 87 | 5 |
| LRR G | 0.11 | 0.045 | 0.31 | <0.0001 | 37 | 1 |
| LRR M | 0.18 | 0.037 | 0.31 | 0.005 | 23 | 1 |
| MixedWood Plain | 0.17 | 0.086 | 0.25 | 0.034 | 17 | 2 |

### *3.4 The effect of N-placement on FIE*

In our study, no overall significant differences in FIE were observed between the banded and broadcast fertilizer N applications (Figure 5). For both N-placement categories, great variation in FIE was observed. Furthermore, no consistent and reliable trends in FIE from experiments with banded versus broadcast N were observed at the regional or soil order level (See supplementary materials C.8-11). It has been suggested that banding of fertilizers with a high ammonium portion could decrease $N_2O$ emissions compared to broadcasting N, due to an inhibitory effect of very high, localized soil $NH_4^+$ concentrations on nitrification (Pfab *et al.*, 2012). Conversely, banding fertilizer N could alter soil pH and favor $NO_2^-$ accumulation at the application site, resulting in increased $N_2O$ emissions compared to broadcasting fertilizer N (Breitenbeck and Bremner, 1986; Engel *et al.*, 2010). More side-by-side comparisons of banded versus broadcast N for a variety of N-sources would be informative, but current results from this meta-analysis suggest that the distribution of applied N on the soil surface across the seedbed has little effect on $N_2O$ emissions from corn cropland in major corn producing regions in the USA and Canada.

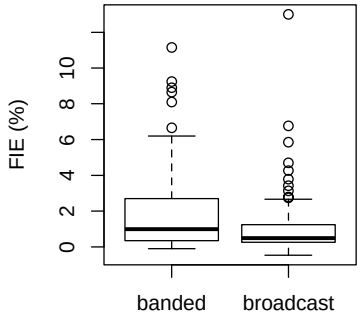


**Figure 5:** Boxplots illustrating effect of N-placement on fertilizer-induced emissions (FIE), considering all available data. Open circles represent outliers. The category banded had 143 observations from 8 different field sites; the category broadcast had 92 observations from 9 different field sites.

In addition to the distribution of applied N across the soil surface, fertilizer incorporation into the soil or the depth of fertilizer N-placement might affect $N_2O$ emissions. This is of great importance, because incorporation of especially urea-containing N sources by tillage, rain, and/or irrigation within a few days after N application is considered a best management practices that is adopted by many farmers. Furthermore, interactive effects of N-placement depth and tillage type or N-source on $N_2O$ emissions have been suggested (Venterea and Stanenas, 2008). However, data limitation prohibited testing for such interactions in our study.

### *3.5 The effect of N-timing on FIE*

It could be expected that delaying fertilizer N application to better match plant N demand could reduce direct (and indirect) $N_2O$ emissions, by avoiding early season loss of N through leaching or denitrification (Drury *et al.*, 2012). On the other hand, a tendency for higher $N_2O$ emissions immediately following sidedress N-application compared to preplant N-application has been attributed to increased $N_2O$ production under higher soil temperatures later in the growing season in Canadian corn cropping systems (Ma *et al.*, 2010). In our study, we observed slightly greater (but statistically non-significant) FIE when applying N before or at planting compared to after planting (Figure 6). Greater $N_2O$ emissions with fertilizer N application before or at planting compared to after planting were observed for LRR M, LRR G, Alfisol and Mollisol data subsets, but not for LRR L (Supplementary Materials C.12-15). Studies included in each data subset might have biased the observed trends. For example, data representing N application after planting in LRR M originates from a study with very high $N_2O$ emissions on a claypan soil in Missouri (Paniagua, 2006), while the data for N application before or at planting in this region were from a study on a silt loam soil in Minnesota (Venterea *et al.*, 2011). Even though bias by other variables cannot be ruled out, our results warrant continued research with respect to the effect of N-timing on $N_2O$ emissions in corn cropping systems of major corn producing regions in the USA and Canada.

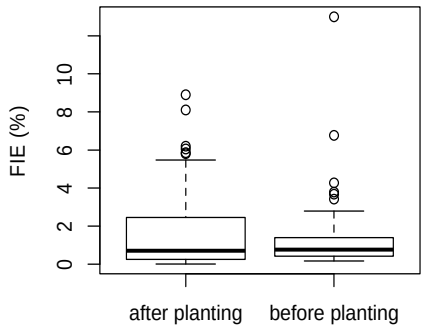


**Figure 6:** Boxplots illustrating effect of N-timing on fertilizer-induced emissions (FIE), considering all available data. Open circles represent outliers. The category after planting had 114 observations from 8 different field sites; the category before or at planting (referred to as before planting) had 74 observations from 7 different field sites.

It has been suggested that annual cumulative $N_2O$ emissions might be higher when N is applied in fall compared to spring (Burton *et al.*, 2008). Fall N application can be an attractive management practice, because it simplifies the logistics of farm operations and secures N-inputs for the subsequent growing season in situations where fields risk inaccessibility in spring before planting due to late snow cover and/or waterlogging. In the Cornbelt, USDA-ARMS data indicates that up to 50% of corn cropland received N in fall in 2010 (see Supplementary Materials C.60). This percentage could be even higher in case the USDA-ARMS data did not take into account fall application of diammonium phosphate, monoammonium phosphate, or ammonium polyphosphate, which are sometimes perceived as just phosphorus fertilizers. In our meta-analysis, there was not sufficient data to test whether $N_2O$ emissions are generally greater in systems that receive N applications in fall compared to spring.

Averaged across all data, FIE were significantly higher for observations with split compared to single N application in our study (Figure 7). However, the variable split versus single N application only explained 4.3% of the total heterogeneity in the data (Table 3). Furthermore, the variable split versus single N application had no significant effect on FIE at the regional or soil order level (Figure 8). Note that in LRR L, the cumulative effect size for split application constitutes $N_2O$ emissions reported by McSwiney and Robertson (2005), whereas single N application averages results presented by Hoben et al. (2011). Consequently, the comparison between split and single N application is based on a comparison of two studies that did not only differ in the number of N applications, but also differed in the choice of N-source and N-placement. We conclude that differences between FIE following split versus single N applications observed in our study are unlikely true effects. In other studies, decreased $N_2O$ emissions by increasing the number of N-applications to better match plant N demand have been attributed to lower soil mineral N accumulation during growth stages when plant N uptake is low (e.g., Kennedy et al. In Review; Burton et al. 2008). Alternatively, it could be hypothesized that increasing the number of N applications could increase cumulative $N_2O$ emissions, by increasing the number of N application-induced $N_2O$ pulses. Side-by-side comparisons of single versus split N-application could provide more insight into the greenhouse gas benefit of matching N fertilizer application with plant N demand in corn cropping systems in major corn producing regions in the USA and Canada. Furthermore,

it should be noted that currently available USDA-ARMS data does not provide information on adoption of split N application in corn cropland.

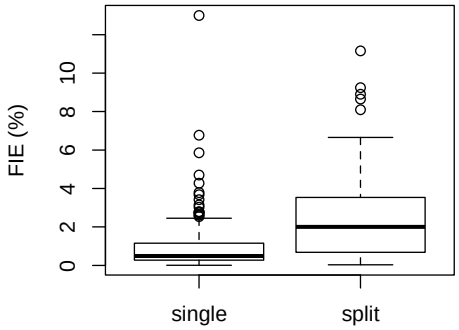


**Figure 7:** Boxplots illustrating effect of split versus single N application on fertilizer-induced emissions (FIE), considering all available data. Open circles represent outliers. The category split had 102 observations from 7 different field sites; the category with single N application had 150 observations from 11 different field sites.

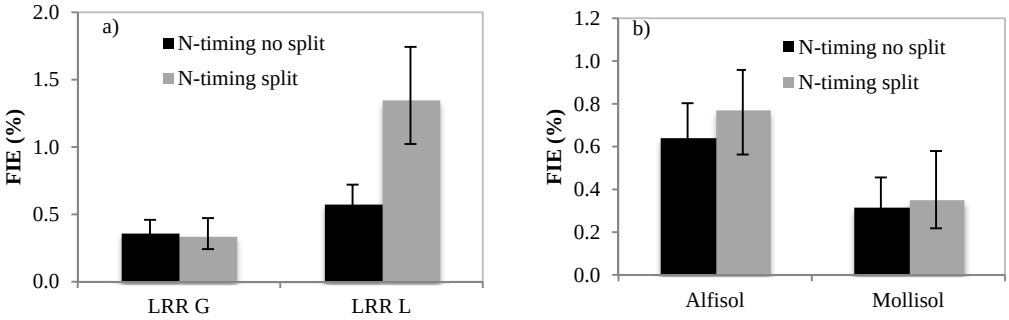


**Figure 8:** Results from meta-analytic moderator analysis testing the effect of split versus single N application on fertilizer-induced emissions (FIE) per region (a) and per soil order (b).

### *3.6 Effects of N-source on $N_2O$ emissions and FIE*

Among N management practices, N-source had the strongest effect on FIE. In general, manure showed the greatest FIE, and enhanced efficiency fertilizers the lowest (Figure 9). Mean, un-weighted FIE tended to decrease in the order: solid manure ≥ liquid manure ≥ anhydrous ammonia ≥ urea ammonium nitrate ≥ ammonium nitrate ≥ urea ≥ polymer coated urea ≥ urea ammonium nitrate plus DCD and NBPT ≥ urea plus DCD and NBPT.

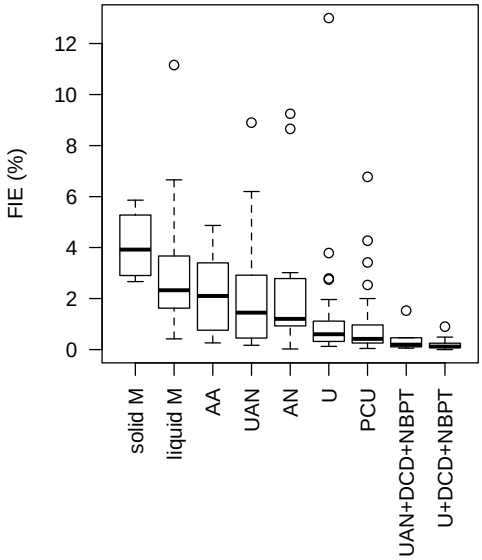


**Figure 9:** Boxplots illustrating effect of N-source on fertilizer-induced emissions (FIE), considering all available data. Open circles represent outliers. Solid M = solid manure (4/1), liquid M = liquid manure (36/1 ), AA = Anhydrous Ammonia (12/2), UAN = urea ammonium nitrate (36/4), AN = ammonium nitrate (16/5), U = Urea (79/11), PCU = polymer coated urea (22/4), UAN + DCD + NBPT (6/2), U + DCD + NBPT (14/3). Data included in parenthesis is: (number of observations/number of sites).

### 3.6.1 Effects of manure application and management on $N_2O$ emissions

The high FIE associated with manure compared to other fertilizer sources is based on data from only 2 field sites, one where liquid manure and one where solid manure was applied. Interestingly, results observed for FIE were validated by side-by-side comparisons, where, on average, significantly higher $N_2O$ emissions were observed after manure compared to synthetic N application based on 73 comparisons from 9 different experimental sites (Figure 3). In practice, manure is often applied at higher N-rates compared to synthetic fertilizer N, as growers anticipate that manure mineralization might not be synchronized with crop N demand. In our study, manure N-rates and synthetic N rates were the same for 51 out of 73 comparisons, while manure N-rate was higher than synthetic N-rate in the other comparisons. Hence, the stimulating effect of manure on $N_2O$ emissions is unlikely an artifact of differences in N-rates. Our results indicate that manure typically causes larger $N_2O$ emissions compared to synthetic N in corn cropping systems in the major corn producing regions in the USA and Canada. These enhanced $N_2O$ emissions after manure compared to synthetic N application might be caused by manure-induced changes in readily available carbon, soil structure and/or microbial communities (Rochette *et al.*, 2008a; Adviento-Borbe *et al.*, 2010).

USDA-ARMS data indicate that manure application is relatively limited in the Corn Belt, Northern Plains and Appalachia, where less than 15 percent of corn acres typically receive manure N (Supplementary materials C.61-64). In contrast, over 30 percent of corn acres received manure amendments in the Lake States in 2010. In the Lake States, manure N was applied either in fall or spring before planting, mostly in liquid form. Broadcasting with or without incorporation appears to be common, but

adoption of injecting or knifing manure into the soil has increased in the last decennium. While our study indicates that manure causes greater $N_2O$ emissions compared to synthetic N, there was not sufficient data to test whether timing and application method significantly affects $N_2O$ emissions induced by manure application. Optimizing manure management to minimize $N_2O$ emissions is of particular importance, since manure is a waste product and any type of manure waste management, whether manure is amended to the soil or not, will likely be associated with greenhouse gas emissions. Furthermore, it should be acknowledged that the use of manure instead of synthetic fertilizer N might have some benefits with respect to carbon sequestration and provision of micronutrients essential for soil biogeochemical processes and plant growth.

### 3.6.2 Nitrification inhibitors and slow release fertilizers

The lowest FIE were observed for UAN + DCD + NBPT and U + DCD + NBPT. Significantly lower FIE for U + DCD + NBPT compared to conventional U were consistent across regions and soil types (supplementary materials C.25-28). In addition, side-by-side comparisons showed significantly lower $N_2O$ emissions when DCD + NBPT was used compared to conventional synthetic fertilizers (Figure 3), reinforcing the effectiveness of DCD + NBPT to reduce $N_2O$ emissions from corn cropland in major corn producing regions in the USA and Canada. A meta-analysis by Akiyama et al. (2010) suggested that the nitrification inhibitor DCD reduces $N_2O$ emissions across a broad range of crop types and geographic regions, while the urease inhibitor NBPT had no significant effect on $N_2O$ emissions. In our study, there were no independent data available on the single effects of DCD and NBPT on $N_2O$ emissions. It should also be noted that limited information is available on long-term efficacy (i.e., effects of repeated application) and potential adverse side-effects of DCD and NBPT and/or their breakdown products on non-target soil biogeochemical processes or ground and surface water quality (Remde and Hund, 1994; Mohanty *et al.*, 2009). In addition, manufacturing of NBPT and DCD causes greenhouse gas emissions and generates industrial waste streams. Therefore, it is pertinent to investigate if the $N_2O$ mitigation potential of the commercially available enhanced efficiency fertilizers SuperU® and AgrotainPlus® is due to DCD alone, or if combined action of DCD and NBPT is essential to attain $N_2O$ emission reductions. Moreover, urease and nitrification inhibitors other than NBPT and DCD have been suggested, including nitrapyrin, ECC, DMPP (3,4-dimethyl pyrazole phosphate), thiosulfate, neem and hydroquinone. Our literature synthesis suggests that the nitrification inhibitors nitrapyrin and ECC do not reduce $N_2O$ emissions (See supplementary materials C.30). However, this was based on data from only one study and field site for each of these components. No data on the effect of DMPP, thiosulfate, neem and hydroguinone on $N_2O$ emissions from corn cropland in our focus area were available.

With respect to slow release fertilizers, the polymer coated urea ESN® had no significant effect on FIE and $N_2O$ emissions relative to conventional urea in our study (Figure 3 and Figure 9). In contrast, polymer coated fertilizers showed a significant $N_2O$ mitigation potential across various crops and soil types, except for Andosols, in the abovementioned meta-analysis by Akiyama et al. (2010). Potentially, soil characteristics and environmental conditions observed in our focus area promoted a hydrolysis pattern of the particular slow release fertilizer formulation ESN® (used in studies included in this

meta-analysis) that was not well synchronized with corn N-uptake patterns, enabling hydrolyzed N to become available for $N_2O$ production. For example, the $N_2O$ mitigation potential of a PCU fertilizer manufactured by Shandong Kingenta Ecological Engineering Co. Ltd. (Linshu, China) was greater than that of the more rapidly hydrolyzing ESN® in a potato cropping system in Minnesota (Hyatt *et al.*, 2010). Furthermore, interactions between the efficacy of PCU and tillage type have been observed (Halvorson and Alluvione, 2010). Hence, PCU fertilizers likely have potential to reduce $N_2O$ emissions from corn cropping systems in the USA and Canada, but limited data availability in our study prohibited the identification of conditions under which PCUs are most successful.

In the Corn Belt, there was a sharp increase in the uptake of nitrogen inhibitors (i.e., enhanced efficiency fertilizers) in 2010 compared to previous survey years (USDA-ARMS, see supplementary materials C.65). Likely, marketing of enhanced efficiency fertilizers will increase uptake further in coming years. It should be noted, however, that data on urease inhibitors, nitrification inhibitors and slow release fertilizers (such as PCU) are aggregated in currently available USDA-ARMS data, while this study indicates a potential important difference between the effect of urease inhibitors plus nitrification inhibitors and slow release fertilizers on $N_2O$ emissions. Consequently, disaggregated data on the use of nitrification inhibitors and slow release fertilizers would be more informative to evaluate the $N_2O$ mitigation potential of nitrification and/or urease inhibitors across the landscape.

### 3.6.1 Formulation of synthetic fertilizer N

In our study, AA and $NO_3^-$-containing fertilizers tended to have higher FIE compared to urea (Supplementary Materials C.20-24). However, differences between urea and UAN were inconsistent across regions and soil orders, not enough data were available to assess differences in FIE between AA and U on the region or soil order level, and the number of side-by-side comparisons of AA, $NO_3^-$-containing fertilizers, $NH_4^+$ based fertilizers and urea was insufficient for meta-analysis. It has been suggested that AA causes greater $N_2O$ emissions compared to broadcast urea, because AA is typically applied by injection, creating soil microsites with high alkalinity and high N availability where $NO_2^-$ accumulation and hydrolysis of soil C are favored (Venterea *et al.*, 2010). When it comes to $NO_3^-$ versus $NH_4^+$-based fertilizers, it can be readily hypothesized that $NO_3^-$ based fertilizers will induce greater $N_2O$ emissions in conditions that favor denitrification, while $N_2O$ emissions will more likely peak after application of $NH_4^+$-based fertilizers under conditions that favor nitrification (Breitenbeck *et al.*, 1980). Furthermore, urea-N only becomes available for plant N-uptake and $N_2O$-producing microbial processes after hydrolysis, a process that is pH and temperature dependent (Harrison and Webb, 2001). Given these intrinsic properties of different synthetic fertilizer types, it is no surprise that effects of N-source on $N_2O$ emissions have been shown to depend on tillage type, N application method and timing, soil characteristics, climate, and weather variability (Hénault *et al.*, 1998; Tenuta and Beauchamp, 2003; Venterea *et al.*, 2005). Therefore, guidelines regarding the selection of synthetic fertilizer N source to mitigate $N_2O$ emissions in corn cropland in major corn producing regions in the USA and Canada should preferably be region-specific. Note that USDA-ARMS data on the use of different synthetic fertilizer N sources were not publicly available.

### *3.7 Tillage*

We observed no significant overall effect of tillage type on FIE in our study (Figure 10). At the regional and soil order level, no till tended to show lower $N_2O$ emissions than tilled systems, but this effect was likely caused by data bias and unbalanced design of the data set (supplementary materials C.33-36). Meta-analysis of 64 side-by-side comparisons from 10 experimental sites confirmed the lack of effect of tillage type on $N_2O$ emissions (Figure 3). Other studies have found that effects of tillage type on $N_2O$ emissions depend on duration of the tillage practice, climate, and N-placement (Six et al. 2004; Van Kessel *et al.* In Review). In our meta-analysis, data availability prohibited testing for interactions between tillage type and duration of the tillage practice, climate or N-placement on $N_2O$ emissions in our focus area. USDA-ARMS data suggest increasing adoption of no-till in the Northern Plains and mulch till in the Corn Belt (Supplementary materials C.66).

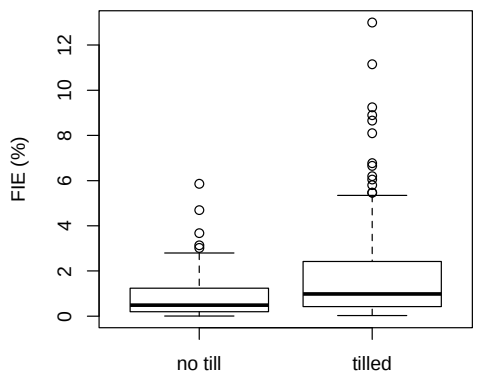


Figure 10: Boxplots illustrating effect of tillage type on fertilizer-induced emissions (FIE), considering all available data. Open circles represent outliers. There were 69 observations from 6 sites for no till, and 183 observations from 14 sites for tilled systems.

### *3.8 Rotation*

As different crops require particular management practices and their residues have different qualities, it can be hypothesized that $N_2O$ emissions during a growing season will not only depend on the current crop, but will also be affected by the imprint the previous crop left on the system. Corn crop residues typically have a greater biomass compared to soybean crop residues, leading to enhanced dissolved organic carbon levels that can fuel denitrification in the next cropping cycle (Venterea *et al.*, 2010). Furthermore, high rates of mineral N applied during a corn year can cause carry-over of residual N into the next year, which can once again trigger $N_2O$ emissions (Drury *et al.*, 2008). In addition, fertilizer N, when properly managed can also contribute to increases in soil organic matter (Ladha *et al.*, 2011). Soybean-corn rotations receive lower total mineral N inputs and less biomass enters the system in the form of crop residue before the corn year. However, the low carbon (C) to N ratio of soybean crop residues causes N contained in the residues to be easily mineralized, upon which increased N availability can stimulate $N_2O$ emissions in the following corn cropping cycle (Mosier *et al.*, 2006; Venterea *et al.*, 2010).

When corn follows soybean cultivation, agronomists and extension specialists typically recommend lower N-rates than when corn follows corn cultivation, because it is expected that the soybean crop residue will provide a N-credit of 34 to 45 kg N $ha^{-1}$ for the following crop (Bundy *et al.*, 1993; Rehm *et al.*, 2006). In contrast, a net soil N deficit due to greater aboveground soybean N-uptake than N supply by biological N fixation can appear at high soybean seed yields (Salvagiotti *et al.*, 2008). Hence, N requirements for soybean corn-rotations may vary with productivity of the system, and differences in N requirements between soybean-corn rotations and continuous corn systems likely exist. Therefore, the selection of N-rates for comparing the performance of continuous corn versus corn-soybean rotations complicates and likely confounds interpretation of the applicability of our results under management practices commonly observed in the landscape.

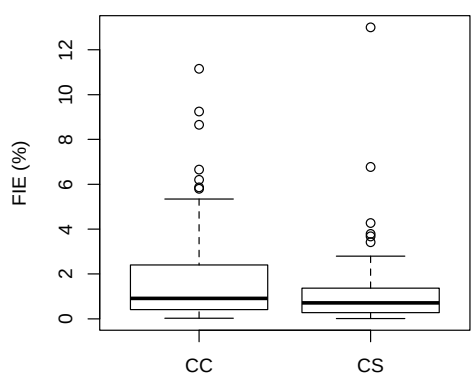


Figure 11: Boxplots illustrating effect of rotation on fertilizer-induced emissions (FIE), considering all available data. Open circles represent outliers. There were 154 observations from 8 sites for continuous corn cropping systems (CC), and 77 observations from 8 sites for corn-soybean rotations (CS).

Crop rotation had no effect on FIE in our study (Table 3, Figure 11). Our meta-analysis of side-by-side comparisons (17 comparisons, 5 sites) also indicated no significant effect of rotation on $N_2O$ emissions (Figure 3), while yields tended to be higher for corn following soybean compared to corn following corn (Figure 12). For 4 out of 17 side-by-side comparisons included in our meta-analysis (2 out of 5 studies), a N-credit from the soybean crop was taken into account, and N-rates were higher for the continuous corn systems compared to the corn years of the corn-soybean rotations. The N-rate was fixed for the other side-by-side comparisons. Possibly, fertilization and precipitation-induced $N_2O$ pulses overrode the contribution of any effects of differences in crop residues to the cumulative $N_2O$ emission (Omonode *et al.*, 2011). The effect of crop rotation on $N_2O$ emissions is of particular importance for the Corn Belt, where continuous corn cropping systems have gained popularity in the last decennium (See supplementary materials C.68).

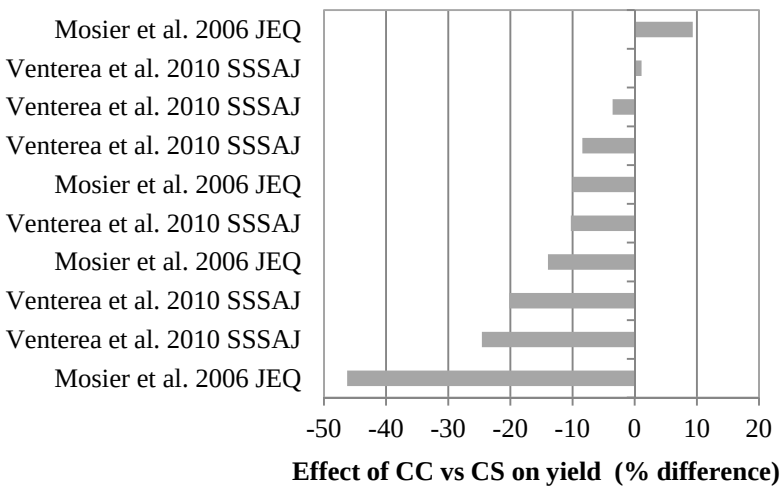


Figure 12: Effect of continuous corn (CC) versus corn-soybean rotations (CS) on corn crop yield for individual side-by-side comparisons from the two studies for which yield data was available. The N-rate was fixed in those two studies (Mosier et al. 2006; Venterea et al. 2010).

### *3.9 FIE from irrigated versus rainfed systems*

We found significantly lower FIE in irrigated systems compared to rainfed corn cropping systems in our study (Figure 13). In contrast, Liebig *et al.* (2005) found that irrigated cropland had the greatest $N_2O$ emissions, followed by non-irrigated cropland and rangeland systems, when summarizing data on $N_2O$ emissions observed in a variety of agroecosystems in northwestern USA and Western Canada. Dryland annual cropping systems included in the study by Liebig *et al.* (2005) were situated in Colorado, Alberta and Alaska; data for irrigated systems were from Colorado and Alberta. The overlapping geographic area for the data from dryland versus irrigated cropping systems indicates that the comparison by Liebig *et al.* (2005) relates to the effect of agricultural intensification on $N_2O$ emissions in regions where water is the limiting factor to crop growth. In our study, $N_2O$ emissions from highly productive corn cropping systems in regions where

rainfall is abundant during the growing season are compared to $N_2O$ emissions in corn cropping systems that require irrigation to sustain competitively high corn yields.

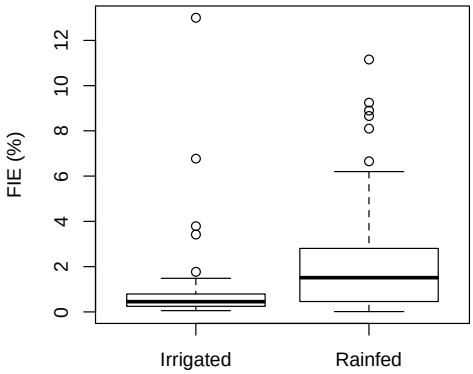


Figure 13: Boxplots illustrating effect of irrigation on fertilizer-induced emissions (FIE), considering all available data. Open circles represent outliers. There were 90 observations from 5 sites for irrigated cropland, and 162 observations from 13 sites for rainfed cropping systems.

It could be expected that irrigation-induced $N_2O$ fluxes are similar to fluxes triggered by precipitation in rainfed cropping systems (Rochette *et al.*, 2008b). However, $N_2O$ emissions were lower in irrigated compared to rainfed systems in our study, despite similar cumulative water inputs during the growing season and a tendency for higher average soil moisture contents in irrigated systems (Figure 14). Interestingly, irrigated systems in our study had significantly lower soil organic C contents compared to rainfed systems (Figure 14). Consequently, C availability might have limited $N_2O$ emissions in irrigated systems. Low soil organic C contents likely result from the semi-arid climate typically observed in regions with irrigated agriculture, where low precipitation has limited biomass production and soil C accumulation long before ecosystem conversion to cropland.

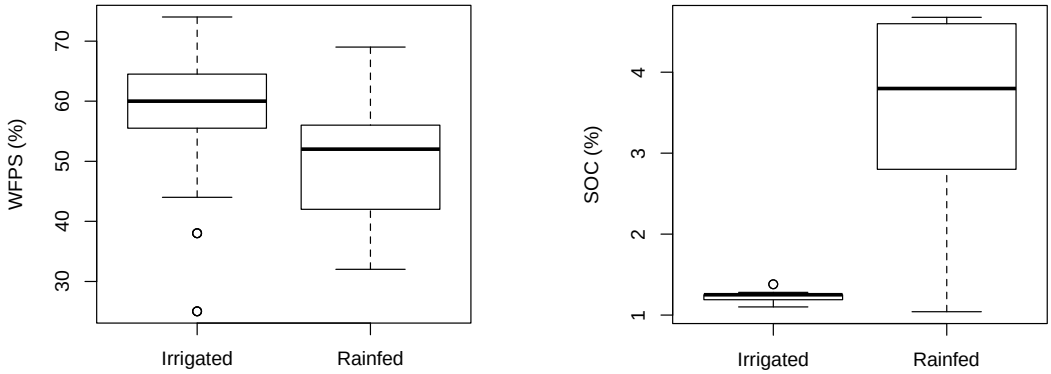


Figure 14: Boxplots illustrating effect of irrigation on water-filled pore space (WFPS, left) and soil organic carbon content (SOC, right), considering all available data. Open circles represent outliers.

### *3.10 Major data gaps and research needs*

A recurring theme in this report is the limited data availability. In order to bridge the lack of side-by-side comparisons for many management practices, we assessed potential effects of alternative management practices by comparing observations across studies, after normalizing $N_2O$ emissions for differences in background emissions and N-rate (i.e., we used the variable FIE). Variability in FIE was large and very few significant effects of optimizing N-placement, N-timing and N-source, diversifying rotation or de-intensifying tillage on FIE were found. Nevertheless, individual studies have shown significant effects of alternative agronomic management practices on $N_2O$ emissions, and potential mechanisms have been proposed to explain the observed responses. This questions the sensitivity of FIE to identify the $N_2O$ mitigation potential of alternative management practices, especially at geographic scales that are relevant to extension workers and growers.

One shortcoming of the variable FIE might be the intention, practical realization, and eventual meaning of the unfertilized control treatment. Control treatments were instated to differentiate $N_2O$ emissions associated with N fertilization from $N_2O$ emissions associated with environmental characteristics. Consequently, $N_2O$ emissions from unfertilized control treatments are often referred to as background emissions. Nevertheless, unfertilized control treatments represent, for a great part, the fertilization and cropping history of previous years (Mosier *et al.*, 1996). This implies that unfertilized controls include human-induced emissions, which should be accounted for. For this reason, Bouwman *et al.* (1996) advocated basing the determination of $N_2O$ emissions from cropland on a linear regression between $N_2O$ and N-rate, rather than FIE as defined in this study and elsewhere. Furthermore, the significant imprint of historical agronomic management on unfertilized controls makes them transient as a reference point, and accuracy of corrections for effects of inherent environmental characteristics such as climate and soil type on $N_2O$ emissions is largely uncertain. To advance our insight in promising mitigation strategies for $N_2O$ emissions reductions from corn cropland, we recommend more long-term experiments, where effects of historic N and crop management practices on the control treatments have faded, and where long-term effects of alternative management practices can be assessed. Also more side-by-side comparisons of common and alternative management practices across agronomically realistic and economically viable N-rates (e.g. ±15% of recommended rate) are desirable, preferably laid out as factorial designs to test interactions between the 4R's, tillage type and/or rotation on $N_2O$ emissions on a regional scale.

In addition to the need for more regional $N_2O$ data from various treatment combinations relative to common practice, it is important to note that annual $N_2O$ emissions estimates from corn cropping systems in our focus area were scarce, despite the notion that high $N_2O$ pulses might occur at snow smelt. The effect of management practices and regional variables on the magnitude of snowmelt $N_2O$ emissions relative to growing season $N_2O$ emissions in our focus area is largely unknown. Therefore, we strongly recommend that future studies capture $N_2O$ emissions in corn cropland during both the non-growing season and the growing season.

While this meta-analysis focuses on direct $N_2O$ emissions, any management decision to reduce $N_2O$ emissions from the agroecosystem should be accompanied by an

evaluation of potential effects on indirect $N_2O$ emissions associated with N lost through leaching, runoff, and volatilization. It should be noted that $N_2O$-N losses most frequently ranged between 0 and 4 kg N $ha^{-1}$ $yr^{-1}$ in this study, while partial N-balances suggest typical surplus N inputs of 20-30 kg N $ha^{-1}$ $yr^{-1}$ in our focus area (Fixen, 2010), much of which is likely lost through leaching. Moreover, $NH_3$ volatilization, nitric oxide emissions, and leaching can not only cause indirect $N_2O$ emissions, but are also associated with other important air and water quality issues. Ideally, management recommendations should be based on an integrated approach, preferably taking into consideration all potential upstream and downstream environmental pollutants, as well as the quality and economic value of the crop.

Finally, it should be noted that the list of management practices evaluated for effects on $N_2O$ emissions in this study is far from exhaustive. Precision agriculture and organic agriculture are two examples of agroecosystem management geared towards improving efficiency or decreasing resource intensity and the potential for harmful environmental consequences that were not evaluated in this study due to data limitation.

## 4 Conclusions

This study illustrates current data-availability and gaps in our understanding of effects of agronomic management on $N_2O$ emissions from corn cropping systems in major corn producing regions in the USA and Canada. Outcomes from this study can inform the planning of future data collection and modeling efforts. The following specific conclusions could be drawn:

- Large variability around $N_2O$ emissions and the significant effect of region on fertilizer-induced emissions indicate that $N_2O$ quantification approaches and guidelines for reducing $N_2O$ emissions are best developed at the regional scale. USDA-defined land resource regions were proposed to have appropriate geographic resolution in our study.
- The response of $N_2O$ to N-rate varied by region and was either linear, exponential or not significant. Furthermore, N-surplus was not necessarily a better predictor of $N_2O$ emissions in corn cropping systems compared to N-rate. However, the fitting of regressions between $N_2O$ and N-rate or $N_2O$ and N-surplus in our meta-analysis was likely confounded by differences in factors such as agronomic management, climate and/or soil type between studies, causing increased uncertainty around our results.
- The use of the nitrification inhibitor DCD in combination with the urease inhibitor NBPT resulted in consistent reductions in $N_2O$ emissions across regions and soil orders.
- Our results suggest that manure N-application causes greater $N_2O$ emissions compared to synthetic N-application. Life cycle analyses of the use of manure versus synthetic fertilizer N and the potential of optimizing manure source, timing and placement to minimize $N_2O$ emissions after land application could be further explored. This is particularly relevant for the Lake States, where up to 30% of corn acres typically receive manure inputs.

- The assessment of effects of N-timing, N-placement, synthetic fertilizer formulation (4R: right source, at the right rate, at the right time, and right place), tillage and rotation was inconclusive due to data limitations. Side-by-side comparisons for common versus alternative agronomic management are recommended, preferably in a factorial experimental design where interactions between various management practices, including N-rate responses within an agronomically viable range, can be elucidated.

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## Supplementary materials

## A Supplementary information on data collection and analysis

### *A.1 Data sources and categorization*

The collection of data on $N_2O$ emissions from corn cropping systems in major corn producing regions of the USA and Canada encompassed an exhaustive survey of the peer-reviewed literature using ISI-Web of Science and Google Scholar (Google Inc., Mountain View, CA, USA) with the keywords "$N_2O$" or "nitrous oxide" and "corn" or "maize". In addition, publication lists of well-known researchers in the field and reference lists in $N_2O$ review papers were consulted. In the USA, the geographic area of interest extended from North Dakota to Eastern Colorado in the west and from Ohio to Northern Tennessee in the East. Studies from Canada were situated in the southeast of the country. $N_2O$ emissions from continuous corn cropping systems as well the corn years of multiple-year crop rotations, with or without cover crops, were considered. In addition, both irrigated and rain-fed systems were eligible. The type of rotation and the presence of irrigation were included as ancillary variables in the database. Each data entry represents one observation, with an observation defined as the mean of several replicates for a particular treatment-year combination within a given study. For each observation, a suite of ancillary variables was collected, relating to agronomic management and environmental characteristics.

Note that the dataset developed in this study is unbalanced, because the combination of categories for the diverse variables is not represented by an equal number of observations. The data set is also biased, as the range of values for continues variables and the categories considered by categorical variables are constrained by data availability. Finally, the dataset has many missing value, because most studies do not report information on all variables included in the data set. In addition, the data set includes observations with cumulative $N_2O$ emissions for the growing season and cumulative $N_2O$ emissions over an entire year. No extrapolation was made for growing season $N_2O$ emissions to encompass a full year, as it was assumed that the majority of the annual $N_2O$ emissions occurred during the growing season in those studies. While it is well-known that non-growing season emissions can contribute significantly in certain situations (e.g., a large $N_2O$ flux is often observed during snow smelt), our approach was validated within the scope of this meta-analysis, as the measurement period (season versus year) had no significant effect on fertilizer induced emissions in our study. In general, limitations of the data set's design were carefully taken into consideration for both data analysis and interpretation of the results.

#### A.1.1 Categories for N-management practices (4 R's)

As the study primarily intended to assess effects of attributes of IPNI's 4R nutrient stewardship (i.e. the right fertilizer source at the right rate, time and place) on $N_2O$ emissions, information on N-management was carefully collected and categorized. For each observation, *N-rate* was recorded. Where data on yields and grain N-concentrations were available, N-surplus was calculated as the difference between N

applied and N removed by harvest. With respect to *N-timing*, we defined two variables: (1) number of N applications, and (2) the timing of N application relative to planting. The first variable has two categories, i.e. 'split' and 'single'. In general, 'split' includes observations where N was applied in two doses or more, whereas 'single' includes the observations where all fertilizer N was applied at once. For several observations, a small amount of starter fertilizer N was applied at planting, while the bulk amount of fertilizer N input was applied at a later growth stage. Such observations were categorized as 'split' only if the starter N fertilization accounted for more than 10% of the total fertilizer N input. For the variable pertaining to the timing of N application relative to planting date, only observations from the category 'single' N application were considered. Within N-timing relative to planting, there were two categories, i.e. 'before or at planting' and 'after planting'. In the 'before or at planting' category, N was applied up to 25 days before planting. In the 'after planting' category, N was applied several days to 50 days after planting. The categorization resulted from a trade-off between the number of observations per category and the biological meaning of each category, taking into account the general notion that plant N uptake will only start several days after seeding. Note that observations where N was applied in Fall are excluded from the 'before or at planting' category. Mechanisms underlying $N_2O$ emissions after Fall N application might be very different from those after Spring N application, prohibiting the inclusion of observations with Fall N application in the 'before or at planting' category, and there were not enough observations for Fall N-application to distinguish a separate category. For the variable *N-placement*, the categories 'banded' and 'broadcast' were considered. The category 'broadcast' included all observations where N was distributed relatively uniformly across the field, with or without incorporation of the fertilizer. The category 'banded' included observations where N was injected, knifed in, or applied as a sidedress next to the corn row, where N can be applied at depth or on the surface. No variable pertaining to the depth of N application was distinguished, because individual studies provided insufficient information on the depth of N placement and the occurrence of fertilizer incorporation. The observations encompassed the use of various *N-sources*. N-sources for which there were a considerable number of observations were included as categories of the variable N-source. These N-sources are: solid manure (solid M), liquid manure (liquid M), anhydrous ammonia (AA), urea ammonium nitrate (UAN), ammonium nitrate (AN), urea (U), polymer-coated urea (PCU), urea ammonium nitrate plus the nitrification inhibitor dicyandiamide (DCD) and the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) (UAN + DCD + NBPT), and urea impregnated with the nitrification inhibitor dicyandiamide (DCD) and the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) (U + DCD + NBPT). Furthermore, a variable for nitrification inhibitor was distinguished, including the categories 'ECC', which stands for encapsulated calcium carbide, 'nitrapyrin', 'DCD' and 'none'. Note that all studies using PCU applied the commercially available formulation ESN®; studies with UAN + DCD + NBPT used the trademarked product Agrotain Plus®; and studies with U + DCD + NBPT used the trademarked product SuperU®.

### A.1.2 Collection and categorization of other ancillary variables

As noted earlier, the agricultural management practices 'rotation' and 'irrigation' where included as ancillary variables in the database. For data analysis, rotation included the categories continuous corn cropping system ('CC') and corn-soybean rotation ('CS'). The variable 'irrigation' included the categories 'irrigated' and 'rainfed'. In addition, 'tillage type' was considered as a variable, where we distinguished between the categories 'no till' and 'tilled'. The category 'tilled' includes observations with conventional tillage as well as observations where tillage occurred at various degrees of reduced intensity.

Geographic information for each observation was recorded, including: country, state or province, region, latitude, and longitude. The variable 'Region' is meant to group observations from locations with similar agricultural and ecological characteristics, and goes beyond administrative boundaries such as state and province boundaries. Categories for the variable 'Region' followed Land Resource Regions (LRR) for observations in the USA and Ecozones for observations in Canada. Land Resource Regions (LRR) are defined by USDA as geographically associated Major Land Resource Areas (MLRA) which approximate broad agricultural markets. MLRAs confine areas with similar physiography, geology, climate, hydrology, soil types, biological resources and land use, as detailed in the U.S. Department of Agriculture Handbook 296 (2006). Canada's ecozones result from a collaborative project undertaken by a number of federal agencies in cooperation with provincial and territorial governments, all under the auspices of the Ecological Stratification Working Group. Canada is divided into 15 separate terrestrial ecozones, which are areas representative of large and very generalized ecological units characterized by interactive and adjusting abiotic and biotic factors, as detailed in the Canadian Biodiversity Web Site[1]. A brief description of the regions relevant to this study can be found in Table A.1.

**Table A.1:** Description of land resource regions (LRRs) and Ecozones relevant to this study

| Brief description | MAP in. (mm) | MAT °F (°C) | FFT days |
|---|---|---|---|
| *Ecozones* | | | |
| **Atlantic Maritimes:** Geologically, this region is a mix of sedimentary and igneous bedrock. Agriculture is limited to the coastal lowlands, overlying sedimentary bedrock, where fertile soil is available and the climate is milder. Agriculture is an important part of the economy in this ecozone. | 35-59 (900-1500) | 23-57 ((-5)-14) | Not available |
| **MixedWood Plain:** Characterized by plains and gently rolling hills, several major waterways and lakes. Deposits from ancient water bodies and glaciers make the soil the most productive in Canada. Carbonate-rich Paleozoic bedrock characterizes the geology of the Mixedwood Plains. The ecozone has relatively mild winters and warm summers, but generally highly changeable weather, as the ecozone is in one of the major storm tracks of North America. | Not available | 23-63 ((-5)-17) | Not available |
| *Land Resource Regions (LRR)* | | | |

[1] http://canadianbiodiversity.mcgill.ca/english/ecozones/ecozones.htm

| | | | |
|---|---|---|---|
| **F: Northern Great Plains Spring Wheat Region:** Much of this region has been topographically smoothed by continental glaciation and is blanketed by undulating till and level to gently rolling lacustrine deposits. Fertile soils and dominantly smooth topography in this region favor agricultural uses, but relatively low precipitation and a short growing season severely limit the choice of crops that can be grown. The soils in this region are dominantly Mollisols. The main crop is spring wheat, which is grown by dryfarming methods. | 14-21 (355-535) | 39-45 (4-7) | 130-170 |
| **G: Western Great Plains Range and Irrigated Region:** This region forms the western edge of the Great Plains. It is an elevated piedmont plain dissected by numerous rivers flowing to the east. The amount of precipitation in this region typically is low because much of the region is on the leeward side of mountains. The soils in this region are dominantly Entisols and Mollisols. Dry-farmed winter wheat and other small grains are grown either for cash or for feed. Irrigated crops are grown along many of the major streams. These crops primarily include corn, alfalfa, forage crops, and sugar beets. | 13-22 (330-560) | 44-51 (7-11) | 135-185 |
| **K: Lake States Forest and Forage Region:** This region is in the Central Lowland areas south and west of the western Great Lakes. It has numerous lakes and wetlands. Winters are cold, and significant amounts of snow can accumulate. Most of the precipitation falls in spring and summer. The soils in this region are dominantly Histosols, Alfisols, Spodosols, and Entisols. Important crops include corn, wheat, alfalfa, oats, barley, and soybeans. | 26-34 (660-865) | 39-44 (4-7) | 120-175 |
| **L: Lake States Fruit, Truck Crop, and Dairy Region:** Typically, the land surface is a nearly level to gently sloping glaciated plain. The precipitation is fairly evenly distributed throughout the year.The soils in this region are dominantly Alfisols, Entisols, or Spodosols. Canning crops, corn, soft winter wheat, beans, and sugar beets are among the leading crops. | 30-41 (760-1,040) | 43-49 (6-10) | 145-205 |
| **M: Central Feed Grains and Livestock Region:** Typically, the land surface is a nearly level to gently sloping, dissected glaciated plain. Most of the precipitation occurs during the growing season. The soils in this region are dominantly Alfisols, Entisols, Inceptisols, or Mollisols. The soils and climate favor agriculture. This region produces most of the corn, soybeans, and feed grains produced in the U.S. | 32-39 (815-990) | 47-53 (8-12) | 170 to 210 |

| | | | |
|---|---|---|---|
| **N: East and Central Farming and Forest Region:** Diversity of topography and climate gives rise to a wide range of natural ecosystems and limits the amount of land available for production agriculture. The climate ranges from hot and humid with modest snowfall in the western part of the region to more than 100 inches (2,540 mm) of annual snowfall in spruce forests in the eastern part. The soils in this region are dominantly Alfisols, Entisols, Inceptisols, or Ultisols. The array of crops grown is diverse and includes cotton, soybeans, corn, and wheat. | 40-59 (1,015-1,500) | 52-59 (11-15) | 180 to 235 |
| **P: South Atlantic and Gulf Slope Cash Crops, Forest, and Livestock Region:** This region consists of generally smooth Atlantic and Gulf Coast marine terraces and the hilly piedmont area. Abundant moisture and a long growing season favor agricultural production in this region. If crops are to be grown, artificial drainage typically is needed to lower the water table on the lower marine terraces. The climate is hot and humid. The soils in this region are dominantly Alfisols, Entisols, Inceptisols, Ultisols, or Vertisols.The diverse array of crops includes cotton, soybeans, peanuts, corn, rice, sugarcane, and wheat. | 44-63 (1,120-1,600) | 59-66 (15-19) | 225 to 290 |

The following climate characteristics were collected for each observation: mean annual temperature (MAT), mean annual precipitation (MAP), potential evapotranspiration (PET), Aridity Index, and Aridity Class. For each observation, we extracted 50-yr average (1950-2000) MAT and MAP data from the global climate database 'worldclim' (www.worldclim.org). For studies that reported MAT and MAP, the reported MAT and MAP corresponded well with the data collected from worldclim. For consistency purposes, the worldclim MAT and MAP data were used in our analyses. Data on PET, Aridity Index and Aridity Class were obtained from the Global Aridity and PET Database from the Consultative Group on International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI, http://www.cgiar-csi.org/). PET is a measure of the ability of the atmosphere to remove water through evapo-transpiration processes. The CGIAR-CSI Global Aridity Index used in this study is defined as the ratio of mean annual precipitation to mean annual potential evapo-transpiration. For the Aridity class, the following classification was used: < 0.03: Hyper Arid; 0.03 - 0.2 Arid; 0.2 – 0.5: Semi-Arid; 0.5 – 0.65: Dry Sub-Humid; > 0.65: Humid. Note that Aridity Index values increase for more humid conditions, and decrease with more arid conditions. Weather data was collected in addition to climate data, in order to assess the role of interannual variation in temperature and precipitation on $N_2O$ emissions. The average air temperature and cumulative precipitation during the measurement period was extracted from the DAYMET database (http://daymet.ornl.gov/), using the specific measurement start and end dates for each observation. For studies that reported temperatures and precipitation during the measurement period, there were no significant differences between the data reported in the studies and the data obtained from the DAYMET database. For observations from irrigated systems, the total amount of irrigation water applied was added to the cumulative precipitation during the measurement period in our

analyses.

Data on a suite of soil characteristics was collected for each observation, including soil classification, soil texture, % sand, % clay, pH, soil organic carbon (SOC), bulk density, average water-filled pore space (WFPS), and nitrate ($NO_3^-$) exposure. Average WFPS and $NO_3^-$ exposure were calculated as weighted averages during the measurement period, based on WFPS and $NO_3^-$ concentration time series and the number of days between individual measurements. Because the number of observations within each soil texture class was very limited, we defined a simplified grouping for soil texture: fine (> 30% clay), medium (< 30 clay and < 45% sand) and coarse (> 45% sand), as observed in the top 10-15 cm of the soil profile. Likewise, the variable soil order was introduced to simplify soil classification. The soil orders Alfisol, Mollisol and Inceptisol were observed in the data.

### A.1.3 USDA-ARMS data on adoption of agronomic management practices

Data from the United States Department of Agriculture's Annual Agricultural Resource Management Survey (USDA-ARMS) is available online at http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/tailored-reports.aspx). Data on organic corn production was obtained from the USDA Economic Research Service (USDA-ERS) available at http://www.ers.usda.gov/data-products/organic-production.aspx.

For placement of synthetic N, the following categories were available: 'No N-broadcast', 'all N-broadcast with incorporation', 'all N-broadcast without incorporation', 'mixed N application method with incorporation', 'mixed N application method without incorporation'. The USDA-ARMS data on N-placement is categorized separately for manure N, using the categories 'broadcast without incorporation', 'broadcast or sprayed with incorporation', and 'Injected or knifed in'. Note the categories 'banded' and 'broadcast' in our meta-analysis include observations with synthetic as well as manure N application, but the majority of observations used synthetic N. Therefore, the USDA category for synthetic N 'No N-broadcast' corresponds best with the category 'banded' in our meta-analysis, whereas the categories 'all N-broadcast with incorporation and all N-broadcast without incorporation' combined correspond best with the category 'broadcast' in our meta-analysis. In practice, soil incorporation could be achieved through tillage, rainfall or irrigation. However, the USDA classification 'with incorporation' likely only targets incorporation by tillage. For timing of synthetic N, data on the categories 'in fall before planting', 'in spring before planting', 'at planting' and 'after planting' were available. The USDA-ARMS data categorized N timing of manure application as follows: 'fall before planting' and 'spring before planting'. Since survey subjects might select more than one of these categories to answer questions on N-timing, relating trends in the USDA-ARMS survey data with results from our meta-analysis should be done with caution. It should also be noted that the USDA-ARMS categorization for N-timing does not allow distinguishing between split and single N application. Furthermore, it is not clear if the USDA-ARMS category 'in fall before planting' includes fall application of diammonium phosphate, monoammonium phosphate, or ammonium polyphosphate, or of those fertilizer sources are only counted as phosphorus fertilization. With respect to the

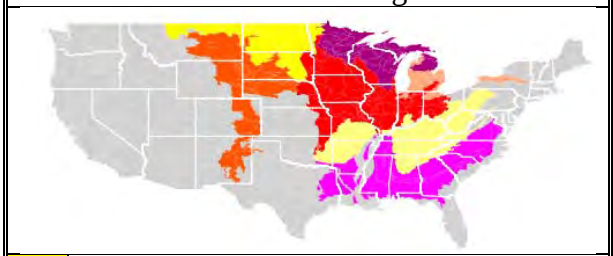
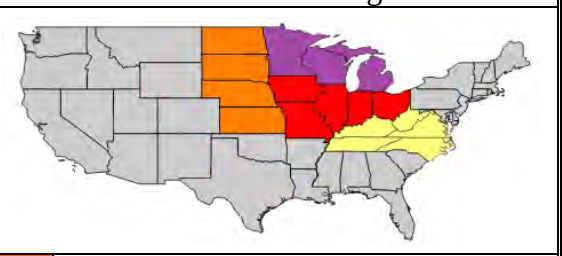
separation of synthetic versus manure N, there was not sufficient data available to assess interactions between manure versus synthetic N as N-source and N-timing or N-placement on $N_2O$ emissions in our meta-analysis.

The USDA-ARMS data relating to N-source included information on the use of manure, the type of manure, and the use of nitrogen inhibitors. No data is publicly available on the use of diverse synthetic N-sources (e.g. urea versus nitrate-based synthetic fertilizer N). Manure type includes the categories 'Slurry liquid', 'Lagoon liquid' and 'Semi-dry or dry manure'. Slurry liquid manure is from in-ground tanks, basins, or pits or from above-ground tanks, silos, or other manure tanks, while lagoon liquid manure is from lagoons or holding ponds. In contrast, semi-dry or dry manure is from barns, sheds, or embankment. Nitrogen inhibitors are defined as products that slow down the breakdown of N on the field and include nitrification inhibitors, urease inhibitors and chemical coated fertilizers. No disaggregated data on nitrogen inhibitors is publicly available.

Other agronomic management practices considered in the USDA-ARMS database are tillage type, rotation, precision agriculture, irrigation and organic corn production. Tillage type includes the categories 'no till', 'ridge till', 'mulch till' and 'reduced till'. No till refers to the absence of tillage. For ridge till, sweeps or disk blades cut the top of preformed ridges and deposit the residue between the rows. Mulch till implies tillage with an implement with a single disk followed by two or more ranks of chisel shanks. Reduced tillage refers to tillage practices that leave 15-30% of the crop residue on the soil surface. With respect to crop rotation, data could be disaggregated based on the previous crop. For our study, we focused on 'corn' versus 'soybean' as the previous crop to reflect continuous corn and corn-soybean rotations, respectively. For precision agriculture, we considered the data category 'precision agriculture used', which embodies the use of yield monitors for monitoring crop moisture, conducting experiments, creating yield maps, the use of soil property maps based on soil tests, electrical conductivity or other soil properties, the use of aerial or satellite imagery and the use of variable rate technology (VRT) for fertilizer applications, seeding or pesticide application. In addition, we focused on the use of VRT for N application in particular.

Disaggregated USDA-ARMS data on crop production practices were available per farm production region, but not per land resource region (LRR). Farm production regions are clusters of states with similar farm production characteristics. Farm production regions roughly overlap with LRRs (Figure A.1), but the clustering of similar agronomic properties is constrained by state boundaries. Consequently, LRRs represent a biophysically and agronomically more appropriate grouping of agricultural regions, while farm production regions are more practical for grouping data that have been collected at the state-level. Therefore, it is most appropriate to use LRR in our meta-analysis, even though USDA-ARMS data on agronomic management practices are only available per farm production region for placing the results from the meta-analysis in a broader context.

**Figure A.1:** USDA-defined Land Resource Regions and Farm Production Regions relevant to this study.

| Land Resource Regions | | Farm Production Regions | |
|---|---|---|---|
|  | |  | |
| | F – Northern Great Plains Spring Wheat Region | | Northern Plains |
| | G – Western Great Plains Range and Irrigated Region | | Lake States |
| | K – Northern Lake States Forest and Forage Region | | Corn Belt |
| | L – Lake States Fruit, Truck Crop, and Dairy Region | | Appalachia |
| | M – Central Feed Grains and Livestock Region | | |
| | N – East and Central Farming and Forest Region | | |
| | P – South Atlantic and Gulf Slope Cash Crops, Forest, and Livestock Region | | |

## *A.2 Data analysis of $N_2O$ emissions*

### A.2.1 Supplementary information related to the meta-analyses

For side-by-side comparisons, the pooled variance of ln*R* ($v_{\ln R}$) was calculated as follows:

$$v_{lnR} = \left(\frac{SE_A}{X_A}\right)^2 + \left(\frac{SE_B}{X_B}\right)^2$$

Where $SE_A$ and $SE_B$ are the standard error around $X_A$ and $X_B$, respectively. Not all studies reported standard errors around the cumulative $N_2O$ emissions. For observations where *SE* was missing, we conservatively estimated *SE* based on the cumulative $N_2O$ emission for that observation, the number of replicates (*n*), and 150% of average coefficient of variation ($CV_{avg}$) for observations where *SE* was reported:

$$SE = \frac{150 \times CV_{avg} \times X}{100 \times \sqrt{n}}$$

Various meta-analytic models were fitted to ln*R*: (1) a fixed effects meta-analytic model, with weights equal to $w_i = 1/(v_{lnR,i})$, and parametrically generated 95% confidence intervals; (2) a random effects meta-analytic model, with weights equal to $w_i = 1/(v_{lnR,i} + \hat{\tau}^2)$, where $\hat{\tau}^2$ denotes the estimate of the total heterogeneity $\tau^2$, and non-parametrically constructed 95% confidence intervals using bootstrapping; and (3) a random effects meta-analytic model, with weights equal to $w_i = 1/(n_{study} + \hat{\tau}^2)$ where $n_{study}$ is the number of observations per study, and non-parametrically generated 95% confidence intervals using bootstrapping. For each study, all comparisons between

treatment *A* and *B* were separately included in our meta-analysis. Hence, multifactorial studies and studies that reported results for multiple years contributed more than 1 comparison to the analysis.

For the calculation of FIE, $N_{Control}$ is the N-rate in the control treatment. For most studies, $N_{control}$ equaled 0, except for the studies by Venterea *et al.* (2011), Gagnon *et al.* (2011) and Fujinuma *et al.* (2011). In the study by Venterea *et al.* (2011), the control treatment received 4.5 kg N $ha^{-1}$ as starter fertilizer, while the total N-rate in non-control treatments amounted to 150.5 kg N $ha^{-1}$. In the study by Gagnon *et al.* (2011), the control treatment received 20 kg N $ha^{-1}$ as starter fertilizer versus a total N-rate between 120 and 220 kg N $ha^{-1}$ in non-control treatments. In the study by Fujinuma *et al.* (2011), the control treatment received 5.6 kg N $ha^{-1}$ as starter fertilizer, but 31-37 kg N $ha^{-1}$ was involuntary applied through the application of $NO_3^-$-rich irrigation water. Total amount of N applied to non-control (i.e. N fertilized) treatments ranged between 217 and 223 kg N $ha^{-1}$.

For each study, FIE were for all treatment-year combinations where separately included in our meta-analysis. Hence, multifactorial studies and studies that reported results for multiple years contributed more than 1 comparison to the analysis.

In our moderator analysis, we used random effects models meta-analytic models for continuous moderator variables and mixed effects meta-analytic models for categorical variables. We controlled for bias from studies with more observations compared to studies with a small number of observations by using the number of observations per study as weights. Confidence intervals were constructed non-parametrically using bootstrapping.

### A.2.2 Technical details on boundary line approach

We followed guidelines provided by (Schmidt *et al.*, 2000) to construct boundary lines in a standardized manner. First, we split the data into groups of equal size. The number of groups was based on the range of values observed for the independent variable. In the case of N-rate, for example, values ranged between 0 and 522 kg N $ha^{-1}$, and 14 groups using 40 kg N $ha^{-1}$ increments were defined. Second, boundary points were determined for each group as the $99^{th}$ percentile of values observed for the dependent variable (i.e., $N_2O$ or FIE in our study) within each group. In addition, breakpoints associated with the boundary point for each group were determined as the average value for the independent variable (e.g., N-rate) within this group. Third, boundary lines were fitted as smoothing lines through boundary points with their accompanying breakpoints. Line fitting was performed using the function '*loess.smooth*' in the statistical package R.

## B Full dataset

The full database is available in the attached file 'Supplementary Materials B.xlsx'.

## C Exhaustive compilation of results

Visuals for results from all analyses carried out in the context of this project are available in the file 'supplementary materials C.ppsx'.

## D Reference list for studies included in the database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## E List of relevant publications that did not meet criteria for inclusion on the database

This section includes an annotated bibliography with studies relevant to $N_2O$ emissions from corn cropping systems in major corn cropping regions of the USA and Canada, that were not included in the database. Reason for exclusion from the database include the following: $N_2O$ emissions were measured in a controlled laboratory or greenhouse experiment; the study is based on modeling and does not show measured data; sampling frequency was insufficient or did not cover a full growing season; or no disaggregated data per treatment combination were available.

- Adler, P.R., Grosso, S.J.D., Parton, W.J., 2007. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications 17, 675-691.

  Modeling exercise to assess greenhouse gas benefit of biofuel production in Pennsylvania. Considering upstream and downstream greenhouse gas emissions, $N_2O$ was estimated to be the largest greenhouse gas source of biofuel cropping systems. Compared with the life cycle of gasoline and diesel, ethanol and biodiesel from corn rotations reduced GHG emissions by 40%.
- Amos, B., Arkebauer, T.J., Doran, J.W., 2005. Soil surface fluxes of greenhouse gases in an irrigated maize-based agroecosystem. Soil Science Society of America Journal 69, 387-395.

Greenhouse gas emissions from irrigated corn cropping system at intensive and best management practices fertility regimes. Fertility regime had minimal effects on $CO_2$ and $CH_4$. The intensive fertility regime showed higher $N_2O$ fluxes on 3 sampling occuasions during one of the 2 study years.

- Breitenbeck, G., Blackmer, A., Bremner, J., 1980. Effects of different nitrogen fertilizers on emission of nitrous oxide from soil. Geophysical Research Letters 7, 85-88.

  Greater $N_2O$ emissions after application of ammonium sulfate or urea compared to calcium nitrate to bare soil demonstrated that nitrifiers can play an important role in $N_2O$ production.
- Breitenbeck, G., Bremner, J., 1986a. Effects of rate and depth of fertilizer application on emission of nitrous oxide from soil fertilized with anhydrous ammonia. Biology and fertility of soils 2, 201-204.

  In bare soil, anhydrous ammonia application at 30 cm depth lead to greater $N_2O$ emissions compared to application at 10 or 20 cm depth.
- Breitenbeck, G., Bremner, J., 1986b. Effects of various nitrogen fertilizers on emission of nitrous oxide from soils. Biology and fertility of soils 2, 195-199.

  Anhydrous ammonia caused greater $N_2O$ emissions compared to aquous ammonia and urea when applied to bare soil.
- Bremner, J., Blackmer, A.M., 1978. Nitrous oxide emission from soils during nitrification of fertilizer nitrogen. Science 199, 295.

  Demonstrates potential for the nitrification inhibitor nitrapyrin to reduce $N_2O$ emissions from soil.
- Chantigny, M.H., Prévost, D., Angers, D.A., Simard, R.R., Chalifour, F.P., 1998. Nitrous oxide production in soils cropped to corn with varying N fertilization. Canadian Journal of Soil Science 78, 589-596.

  Effect of ammonium nitrate application rate on $N_2O$ emissions in a sandy loam and a sandy clay soil cores cropped with an early-maturing corn. Results suggest that limiting N fertilizer to 120 kg ha–1, under early-maturing corn production, may prevent excessive gaseous N losses due to denitrification
- Del Grosso, S., Halvorson, A., Parton, W., 2008. Testing DAYCENT model simulations of corn yields and nitrous oxide emissions in irrigated tillage systems in Colorado. Journal of Environmental Quality 37, 1383-1389.

  The process-based biogeochemical model DAYCENT was used to estimate national-scale nitrous oxide emissions from cropped soils in the United States. DAYCENT predicts decreasing $N_2O$ emissions factors ($N_2O$ as a fraction of total N inputs, including N from fertilizer + N from fixation + N from aboveground crop residue) with coarser soil texture, higher mean annual precipitation, and greater N-rate for major US crops.
- Del Grosso, S.J., Parton, W.J., Mosier, A.R., Walsh, M.K., Ojima, D.S., Thornton, P., 2006. DAYCENT national-scale simulations of nitrous oxide emissions from cropped soils in the United States. Journal of Environmental Quality 35, 1451-1460.

  DAYCENT was used to simulate $N_2O$ emissions from irrigated corn cropland in Colorado. DAYCENT $N_2O$ emissions matched the measured data

in that simulated emissions increased as N fertilization rates increased and emissions from no-till (NT) tended to be lower on average than conventional-till (CT). However, the model overestimated $N_2O$ emissions.

- Duxbury, J., McConnaughey, P., 1986. Effect of fertilizer source on denitrification and nitrous oxide emissions in a maize-field. Soil Science Society of America Journal 50, 644-648.

  Nitrous oxide emissions were greater when urea fertilizer was used compared to calcium nitrate or no fertilizer N addition. $C_2H_2$ inhibition indicated greater reduction rates of $N_2O$ to $N_2$ in the control and calcium nitrate treatment compared to the urea treatment. Nitrification accounted for approximately half of the $N_2O$ emissions in the urea treatment, whereas $N_2O$ predominantly came for denitrification in the control and calcium nitrate treatment.
- Elmi, A., Mehdi, B., Madramootoo, C., Dam, R., Smith, D., 2009. Long-term effect of conventional and no-tillage production systems on nitrous oxide fluxes from corn (Zea mays L.) field in Southwestern Quebec. American Journal of Environmental Sciences 5, 238-246.

  Tillage type (reduced tillage, no till, conventional tillage) had no effect on $N_2O$ fluxes, $N_2O$ concentrations in the soil profile, and denitrification.
- Elmi, A.A., Madramootoo, C., Hamel, C., Liu, A., 2003. Denitrification and nitrous oxide to nitrous oxide plus dinitrogen ratios in the soil profile under three tillage systems. Biology and Fertility of Soils 38, 340-348.

  Effect of tillage on $N_2O$ emissions. There were no significant differences between no-till and conventionally tilled systems on $N_2O$ emissions.
- Ginting, D., Eghball, B., 2005. Nitrous Oxide Emission from No-Till Irrigated Corn. Soil Science Society of America Journal 69, 915-924.

  Temporal fluctuations and wheel traffic effects on $N_2O$ emissions in an irrigated corn cropping system. There was no significant diurnal pattern in $N_2O$ emissions, and there was no significant difference in $N_2O$ emissions between the wheel-tracked row and the non-wheel-tracked row.
- Grace, P.R., Philip Robertson, G., Millar, N., Colunga-Garcia, M., Basso, B., Gage, S.H., Hoben, J., 2011. The contribution of maize cropping in the Midwest USA to global warming: A regional estimate. Agricultural Systems 104, 292-296.

  Modeling exercise to estimate greenhouse gas emissions from corn cropping systems between 1964 and 2005. The authors found that nitrous oxide production from N fertilizer inputs represented 59% of greenhouse gas emissions, soil C decline (0–30 cm) represented 11% of total emissions, and the remaining 30% (517 Mt) was attributed to the combustion of fuel associated with farm operations. 1.75% of N applied between 1964 and 2005 was emitted as $N_2O$.
- Grassini, P., Cassman, K.G., 2012. High-yield maize with large net energy yield and small global warming intensity. Proceedings of the National Academy of Sciences 109, 1074-1079.

  Modeling exercises indicated that high input irrigated corn cropping systems in Nebraska can have a lower greenhouse gas emission intensity compared to lower input systems if nitrogen and energy use efficiencies are optimized.

- Hernandez-Ramirez, G., Brouder, S.M., Smith, D.R., Van Scoyoc, G.E., Michalski, G., 2009. Nitrous Oxide Production in an Eastern Corn Belt Soil: Sources and Redox Range. Soil Sci. Soc. Am. J. 73, 1182-1191.

    Effect of long term manure and urea ammonium nitrate application on potential $N_2O$ emissions at different soil moisture contents suggest that indicate that soils receiving repeated manure application that are subject to intensive, recurrent soil rewetting events may be prone to higher $N_2O$ emissions.
- Hilton, B., Fixen, P., Woodard, H., 1994. Effects of tillage, nitrogen placement, and wheel compaction on denitrification rates in the corn cycle of a corn-oats rotation. Journal of plant nutrition 17, 1341-1357.

    Effect of tillage, nitrogen placement, and wheel compaction on denitrification rates in the corn cycle of a corn oats rotation. No till resulted in greater denitrification N-loss compared to tilled systems. Denitrification rates were greater in wheel-tracked areas compared to non-wheel-tracked areas.
- Jacinthe, P.A., Dick, W., Owens, L., 2002. Overwinter soil denitrification activity and mineral nitrogen pools as affected by management practices. Biology and Fertility of Soils 36, 1-9.

    Compared to denitrifier enzyme activity (DEA) at soil core sampling in fall, freeze thaw cycles reduced DEA in the upper 5 cm by 78-84 % in soil from systems that had been chisel plowed, whereas DEA was only decreased by 40-45% by freeze-thaw cycles in the upper 5 cm of soils from systems that received manure. Enhanced soil mineral N concentrations by freeze-thaw cycles were not affected tillage or manure application.
- Jarecki, M.K., Parkin, T.B., Chan, A.S.K., Hatfield, J.L., Jones, R., 2008. Greenhouse gas emissions from two soils receiving nitrogen fertilizer and swine manure slurry. Journal of Environmental Quality 37, 1432-1438.

    Interaction between soil texture and N-source on $N_2O$. In the sandy loam soil, $N_2O$ emissions decreased in the order: urea ammonium nitrate > manure > control. In the clay soil, $N_2O$ emissions after manure application were greater compared to the other two N-source treatments.
- Kaharabata, S., Drury, C., Priesack, E., Desjardins, R., McKenney, D., Tan, C., Reynolds, D., 2003. Comparing measured and Expert-N predicted $N_2O$ emissions from conventional till and no till corn treatments. Nutrient Cycling in Agroecosystems 66, 107-118.

    Testing of the biogeochemical model Expert-N to estimate $N_2O$ emissions from conventional till versus no-till corn cropping systems with or without a clover cover crop. Cover crop and tillage type had no effect on measured cumulative $N_2O$ emissions. Expert-N underestimated $N_2O$ emissions.
- Linn, D., Doran, J., 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Science Society of America Journal 48, 1267-1272.

    Soils from no-till systems caused greater $N_2O$ emissions compared to soils from tilled soils, likely because no-till soils had a greater water-filled pore space.

- Liu, X., Mosier, A., Halvorson, A., Zhang, F., 2005. Tillage and nitrogen application effects on nitrous and nitric oxide emissions from irrigated corn fields. Plant and soil 276, 235-249.

  $N_2O$ emissions were not affected by tillage type in irrigated corn cropping systems in Colorado, whereas NO emissions were significantly lower under no-till compared to conventional till. Furthermore, $N_2O$ and NO emissions during the fallow season were higher in the conventional tilled soil compared to the no-till system. ($N_2O$ data was also reported in Mosier et al. 2006 and included as such in the database)
- Liu, X.J., Mosier, A.R., Halvorson, A.D., Zhang, F.S., 2006. The impact of nitrogen placement and tillage on NO, $N_2O$, $CH_4$ and $CO_2$ fluxes from a clay loam soil. Plant and soil 280, 177-188.

  Effect of tillage and urea ammonium nitrate placement depth on $N_2O$ and NO emissions in irrigated corn cropping systems in Colorado. N placement at 10 or 15 cm depth resulted in lower $N_2O$ and NO fluxes compared to N placement at 0 or 5 cm depth. No till resulted in lower NO and higher $N_2O$ emissions compared to conventional till, regardless of N placement depth.
- Loecke, T.D., Robertson, G.P., 2009. Soil resource heterogeneity in terms of litter aggregation promotes nitrous oxide fluxes and slows decomposition. Soil biology and biochemistry 41, 228-235.

  Effect of litter aggregation on $N_2O$ emissions. Patchy clover litter caused higher $N_2O$ emissions than uniformly distributed litter in controlled experiments with and without growing corn plants. This suggests that litter manipulation has potential as a greenhouse gas mitigation strategy.
- Ma, B.L., Wu, T.Y., Tremblay, N., Deen, W., Morrison, M.J., McLaughlin, N.B., Gregorich, E.G., Stewart, G., 2010. Nitrous oxide fluxes from corn fields: on-farm assessment of the amount and timing of nitrogen fertilizer. Global Change Biology 16, 156-170.

  During 28-days following fertilizer application, side-dress N application caused higher $N_2O$ emissions than pre-plant N-application
- MacKenzie, A., Fan, M., Cadrin, F., 1997. Nitrous oxide emission as affected by tillage, corn-soybean-alfalfa rotations and nitrogen fertilization. Canadian Journal of Soil Science 77, 145-152.

  Effect of N-rate, rotation and tillage type on $N_2O$ emissions. Emission of $N_2O$ was higher with no till than with conventional tillage, and with corn than with soybean or alfalfa.
- MacKenzie, A., Fan, M., Cadrin, F., 1998. Nitrous oxide emission in three years as affected by tillage, corn-soybean-alfalfa rotations, and nitrogen fertilization. Journal of Environmental Quality 27, 698-703.

  Effect of N-rate, rotation and tillage type on $N_2O$ emissions. No till showed higher $N_2O$ emissions compared to conventional till. $N_2O$ increased with increasing N-rate. $N_2O$ emissions were between 1 and 1.6% of N applied.
- Mkhabela, M., Madani, A., Gordon, R., Burton, D., Cudmore, D., Elmi, A., Hart, W., 2008. Gaseous and leaching nitrogen losses from no-tillage and conventional tillage systems following surface application of cattle manure. Soil and Tillage Research 98, 187-199.

Effect of no-tillage and conventional tillage systems on gaseous N losses, $N_2O$:$N_2O$ + $N_2$ ratios and $NO_3^-$-N leaching following surface application of cattle manure. No till had higher NH3 losses than conventional tillage, denitrification rates and $N_2O$ emissions were higher in no-till compared to conventional tillage, $N_2O$:$N_2O$ + $N_2$ ratios were lower in no till, suggesting more complete reduction of $N_2O$ to $N_2$ under no till, and $NO_3^-$-N leaching was higher ( $p < 0.05$) in convential tillage compared to no-till.

- Mosier, A., Guenzi, W., Schweizer, E., 1986. Soil losses of dinitrogen and nitrous oxide from irrigated crops in northeastern Colorado. Soil Science Society of America Journal 50, 344-348.

  Loss of $N_2O$ plus $N_2$ was assessed after applying the equivalent of 200 kg N ha-1 15N-enriched ammonium sulfate to microplots in a corn cropping system in Colorado. 2.5% of applied N was lost as $N_2O$ + $N_2$, of which 70% was lost as $N_2O$. The authors indicate that the role of denitrification as a N loss mechanism had been historically overemphasized for soils in this area.
- Mosier, A., Halvorson, A., Peterson, G., Robertson, G., Sherrod, L., 2005. Measurement of net global warming potential in three agroecosystems. Nutrient Cycling in Agroecosystems 72, 67-76.

  Comparison of the global warming potential of a dryland cropping system in Colorada, a rainfed system in Colorado and a rainfed system in Michigan. $N_2O$ contributed 40-44% of the global warming potential in the rainfed systems. In the irrigated cropping system, energy used for irrigation contributed substantially to the global warming potential.
- Nash, P.R., Motavalli, P., Nelson, K.A., 2012. Nitrous Oxide Emissions from Claypan soils due to Nitrogen Fertilizer Source and Tillage/Fertilizer Placement. Soil Science Society of America Journal doi:10.2136/sssaj2011.0296.

  Effects of tillage/fertilizer placement (i.e., no-till/surface broadcast versus strip-till/deep banded) and N fertilizer source [i.e., non-coated urea (NCU), polymer-coated urea (PCU), non-treated control] on soil $N_2O$ emissions during the corn growing season in a poorly drained claypan soil in Northeast Missouri. N-source had no significant effect, while $N_2O$ emissions were 28% lower in the strip-till/deep banded compared to the no-till/surface broadcast treatments.
- Omonode, R.A., Smith, D.R., Gál, A., Vyn, T.J., 2011. Soil Nitrous Oxide Emissions in Corn following Three Decades of Tillage and Rotation Treatments. Soil Science Society of America Journal 75, 152-163.

  Effect of long-term tillage and rotation practices on $N_2O$ emissions. $N_2O$ emissions were 40% and 57% lower under no-till compared to chisel and moldboard tillage, but the differences were not statistically significant. $N_2O$ emissions were greater in corn fields that were part of a corn-soybean rotation compared to corn fields in continuous corn systems.
- Ostrom, N., Sutka, R., Ostrom, P., Grandy, A., Huizinga, K., Gandhi, H., von Fischer, J., Robertson, G., 2010. Isotopologue data reveal bacterial denitrification as the primary source of $N_2O$ during a high flux event following cultivation of a native temperate grassland. Soil Biology & Biochemistry 42, 499-506.

In this study, high $N_2O$ fluxes predominantly from denitrification were observed in the third year of cultivation of a previously uncultivated grassland

- Parkin, T., Kaspar, T., Singer, J., 2006. Cover crop effects on the fate of N following soil application of swine manure. Plant and soil 289, 141-152.
  Effect of cover crop on N losses after manure application. The rye cover crop reduced N-leaching and $N_2O$ emissions. (greenhouse/laboratory experiment)
- Parkin, T.B., 2008. Effect of sampling frequency on estimates of cumulative nitrous oxide emissions. Journal of Environmental Quality 37, 1390-1395.
  Effect of sampling frequency on $N_2O$ emissions between fertilizer bands and over the fertilizer band. The variance of potential fluxes associated with the between-band positions was less than the over-band position, indicating that the underlying temporal variability impacts the efficacy of a given sampling protocol.
- Pattey, E., Blackburn, L.G., Strachan, I.B., Desjardins, R., Dow, D., 2008. Spring thaw and growing season $N_2O$ emissions from a field planted with edible peas and a cover crop. Canadian Journal of Soil Science 88, 241-249.
  $N_2O$ emissions during snowmelt following corn cultivation were 0.7 kg N ha-1. This was comparable to $N_2O$ emissions during snowmelt following a pea cover crop the following year (i.e. 0.8 kg N ha-1)
- Qian, J.H., Doran, J.W., Weier, K.L., Mosier, A.R., Peterson, T.A., Power, J.F., 1997. Soil denitrification and nitrous oxide losses under corn irrigated with high-nitrate groundwater.
  Denitrification in irrigated corn cropping system in Nebraska affected by soil moisture content and plant growth.
- Robertson, G.P., Paul, E.A., Harwood, R.R., 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science 289, 1922-1925.
  $N_2O$ emissions from corn-soybean-wheat rotations measured between 1991 and 1999 were not significantly different between a conventional, no-till, low input and organic management system. No-till showed potential to mitigate greenhouse gas emissions from cropland due to increase soil organic carbon accruel.
- Rochette, P., Simard, R.R., Ziadi, N., Nolin, M.C., Cambouris, A.N., 2004. Atmosphere composition and $N_2O$ emissions in soils of contrasting textures fertilized with anhydrous ammonia. Canadian Journal of Soil Science 84, 339-352.
  Effect of soil texture on $N_2O$ emissions were minimal and inconsistent. There was important temporal variability.
- Rogovska, N., Laird, D., Cruse, R., Fleming, P., Parkin, T., Meek, D., 2011. Impact of biochar on manure carbon stabilization and greenhouse gas emissions. Soil Science Society of America Journal 75, 871-879.
  Effect of biochar and manure application on $CO_2$ and $N_2O$ emissions. Biochar showed potential to reduce $N_2O$ emissions in their experiment (laboratory experiment)

- Sey, B., Whalen, J., Gregorich, E., Rochette, P., Cue, R., 2008a. Carbon dioxide and nitrous oxide content in soils under corn and soybean. Soil Science Society of America Journal 72, 931-938.

  Effect of soil aggregates on $N_2O$ emissions. $N_2O$ was predominantly derived from denitriification in microaggregates incubated at 80% WFPS, whereas nitrification mostly drove $N_2O$ emissions when macroaggregates and bulk soil were incubated at 80% WFPS (laboratory experiment)
- Sey, B.K., Manceur, A.M., Whalen, J.K., Gregorich, E.G., Rochette, P., 2008b. Small-scale heterogeneity in carbon dioxide, nitrous oxide and methane production from aggregates of a cultivated sandy-loam soil. Soil biology and biochemistry 40, 2468-2473.

  Effect of tillage (conventional tillage versus no-till) and N-source (manure versus synthetic fertilizer) on $N_2O$ in the depth profile. $N_2O$ in the depth profile was not affected by tillage or N-source. Soil moisture was more important as a control on $N_2O$ in the depth profile compared to soil temperature and agronomic management.
- Sey, B.K., Manceur, A.M., Whalen, J.K., Gregorich, E.G., Rochette, P., 2010. Root-derived respiration and nitrous oxide production as affected by crop phenology and nitrogen fertilization. Plant and soil 326, 369-379.

  Effect of corn crop phenology on root-respiration and $N_2O$ emissions. A peak in $N_2O$ production was observed with corn at the milk stage, suggesting that the corn rhizosphere supported microbial communities that produced $N_2O$. (greenhouse/laboratory experiment)
- Singurindy, O., Molodovskaya, M., Richards, B.K., Steenhuis, T.S., 2009. Nitrous oxide emission at low temperatures from manure-amended soils under corn (*Zea mays* L.). Agriculture, Ecosystems & Environment 132, 74-81.

  Effect of tillage and manure application on $N_2O$ emissions during freeze-thaw cycles. Total winter $N_2O$ emissions from manured soils were greater from the field areas that were tilled earlier in the fall, particularly in the first few freeze–thaw cycles, during which the maximum $N_2O$ fluxes occurred.
- Smith, D.R., Hernandez-Ramirez, G., Armstrong, S.D., Bucholtz, D.L., Stott, D.E., 2011. Fertilizer and Tillage Management Impacts on Non-Carbon-Dioxide Greenhouse Gas Emissions. Soil Science Society of America Journal 75, 1070-1082.

  Effects of different management practices on GHG emissions. $N_2O$ emissions from corn fields decreased in the order: no-till + cover crop ≥ conventional tillage ≥ no-till, split N application ≥ no-till ≥ precision till
- Tan, I., van Es, H.M., Duxbury, J.M., Melkonian, J.J., Schindelbeck, R.R., Geohring, L.D., Hively, W.D., Moebius, B.N., 2009. Single-event nitrous oxide losses under maize production as affected by soil type, tillage, rotation, and fertilization. Soil and Tillage Research 102, 19-26.

  Effect of soil type, tillage, rotation and fertilization on $N_2O$ emissions during simulated rainfall in spring. Results suggest that untilled soil and sod-based crop rotations increase latespring $N_2O$ losses under maize production, especially with early fertilization

- Thelen, K., Fronning, B., Kravchenko, A., Min, D., Robertson, G., 2010. Integrating livestock manure with a corn-soybean bioenergy cropping system improves short-term carbon sequestration rates and net global warming potential. biomass and bioenergy 34, 960-966.

  Effect of livestock manure amendments on global warming potential of corn cropping system with complete removal of crop residues. Livestock manure application remediated greenhouse gas emissions in this renewable fuel cropping system.
- Venterea, R.T., Stanenas, A.J., 2008. Profile analysis and modeling of reduced tillage effects on soil nitrous oxide flux. Journal of Environmental Quality 37, 1360-1367.

  Measurement of biological, physical and chemical properties over a depth profile in combination with simulation modeling suggest interactive effects of tillage type and N-placement on $N_2O$ emissions. $N_2O$ fluxes from reduced and no-till systems can likely be minimized by subsurface fertilizer placement and by using a chemical form of fertilizer that does not promote substantial $NO_2^-$ accumulation
- Wagner-Riddle, C., Thurtell, G., 1998. Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. Nutrient Cycling in Agroecosystems 52, 151-163.

  $N_2O$ during winter and spring thaw was assessed following various crops and management practices. Results indicated that fallowing, manure application and alfalfa incorporation in the fall lead to high spring emissions, while the presence of plants (as in the case of alfalfa or grass) can result in negligible emissions during thaw
- Weeks, E.P., McMahon, P.B., 2007. Nitrous oxide fluxes from cultivated areas and rangeland: US High Plains. Vadose Zone Journal 6, 496-510

  Concentration profiles of $N_2O$ in the vadose zone were used to estimate soil-to-atmosphere $N_2O$ fluxes from various ecosystems. Results indicate that $N_2O$ emissions are substantially reduced following conversion of irrigated corn cropland to Conservation Reserve grassland.