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Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis

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Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis

A.D. Basche, F.E. Miguez, T.C. Kaspar, and M.J. Castellano

Abstract: There are many environmental benefits to incorporating cover crops into crop rotations, such as their potential to decrease soil erosion, reduce nitrate (NO_3) leaching, and increase soil organic matter. Some of these benefits impact other agroecosystem processes, such as greenhouse gas emissions. In particular, there is not a consensus in the literature regarding the effect of cover crops on nitrous oxide (N_2O) emissions. Compared to site-specific studies, meta-analysis can provide a more general investigation into these effects. Twenty-six peer-reviewed articles including 106 observations of cover crop effects on N_2O emissions from the soil surface were analyzed according to their response ratio, the natural log of the N_2O flux with a cover crop divided by the N_2O flux without a cover crop (LRR). Forty percent of the observations had negative LRRs, indicating a cover crop treatment which decreased N_2O, while 60% had positive LRRs indicating a cover crop treatment which increased N_2O. There was a significant interaction between N rate and the type of cover crop where legumes had higher LRRs at lower N rates than nonlegume species. When cover crop residues were incorporated into the soil, LRRs were significantly higher than those where residue was not incorporated. Geographies with higher total precipitation and variability in precipitation tended to produce higher LRRs. Finally, data points measured during cover crop decomposition had large positive LRRs and were larger than those measured when the cover crop was alive. In contrast, those data points measuring for a full year had LRRs close to zero, indicating that there was a balance between periods when cover crops increased N_2O and periods when cover crops decreased emissions. Therefore, N_2O measurements over the entire year may be needed to determine the net effect of cover crops on N_2O. The data included in this meta-analysis indicate some overarching crop management practices that reduce direct N_2O emissions from the soil surface, such as no soil incorporation of residues and use of nonlegume cover crop species. However, our results demonstrate that cover crops do not always reduce direct N_2O emissions from the soil surface in the short term and that more work is needed to understand the full global warming potential of cover crop management.

Key words: cover crops—global warming potential—meta-analysis—nitrous oxide

Agricultural soils account for 69% of nitrous oxide (N_2O) emissions in the United States (USEPA 2013). This occurs because nitrogen (N) is an essential nutrient for agricultural production; N is added to soil as N fertilizer and manure, released from soil organic matter, and has high reactivity and mobility in terrestrial ecosystems (Robertson and Vitousek 2009). Fertilizer N recovery efficiency for major cereal production is less than 50% and even as low as 20% (Cassman et al. 2002), which potentially makes large quantities of N available for the biological processes that release N_2O. Nitrous oxide, which has 300 times the radiative forcing per mass unit compared to carbon dioxide (CO_2), has been calculated to be the largest contributor to global warming potential from agricultural cropping systems (USEPA 2013; IPCC 2007; Robertson et al. 2000). Therefore, small reductions in N_2O emissions from agricultural soils can have an overall large impact on global warming potential. The challenge is to find agricultural management practices with consistent reductions in N_2O emissions across locations, cropping systems, and years given the high spatial and temporal variability of emissions (Venterea et al. 2012).

Emissions of N_2O from terrestrial ecosystems are a function of available mineral N, soil water content, the availability of electron donors (such as labile carbon [C]), and soil physical properties (Davidson et al. 2000; Firestone and Davidson 1989; Venterea et al. 2012). Cover crops may impact aspects of all these processes in ways that could potentially increase or decrease N_2O emissions as is outlined in table 1. For example, a growing cover crop can decrease soil mineral N by incorporating it into its biomass, while a legume cover crop may increase soil mineral N via N fixation (Kaspar and Singer 2011). While alive, cover crops can decrease soil water through transpiration. After termination, the mulching effect of cover crop residues on the soil surface may increase soil water and the potential for denitrification depending upon timing of precipitation (Dabney 1998). Additionally, decomposing cover crop residues can temporarily immobilize soil N and then later increase soil pools of labile C and inorganic N (Kaspar and Singer 2011; Steenwerth and Belina 2008), which will also impact dynamics of N_2O emissions.

There are many well-researched benefits to incorporating cover crops into crop rotations, such as their potential to decrease soil erosion, reduce nitrate (NO_3) leaching, increase soil organic matter, reduce pest and weed pressure, and provide additional soil N for cash crops (Kaspar and Singer 2011; Doran and Smith 1991). However, the net impact of cover crops on N_2O is not well understood (Cavigelli et al. 2012; Cavigelli and Parkin 2012). Although cover crops may temporarily decrease soil NO_3 pools and leaching losses, C can be the substrate limiting N_2O emissions in some agroecosystems. In these situations, a cover crop's contribution to the labile C pool can enhance N_2O emissions from the soil surface (Mitchell et al. 2013).

Meta-analysis is an approach that can be used to improve understanding of the fac-

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Table 1

Drivers of nitrous oxide (N_2O) loss and potential influential factors investigated in the meta-analysis. A full description of database variables appears in table 3.

Denitrification driver	Database factor
Mineral nitrogen (N)	C:N residue ratio
	Type of cover crop
	Incorporation of residue
	N fertilizer rate
	Tillage
Reactive carbon (C)	Soil organic C
	Biomass input from cover crop
	Type of cover crop
	Incorporation of residue
	Tillage
Soil water	Biomass input from cover crop
	Precipitation
	Drainage
Soil physical properties	Bulk density
	Soil texture

tors affecting N_2O emissions through the systematic review and quantitative summary of effect size from individual studies. Many studies investigating cover crops and N_2O are conducted on short time scales (≤2 years) under specific management and climate conditions which may make it difficult to detect differences. Meta-analysis allows these studies to be pooled and the factors affecting N_2O emissions investigated. The effect of other conservation practices on N_2O emissions have been similarly evaluated using meta-analytic methods (Six et al. 2004; Van Kessel et al. 2013), but none to our knowledge that have used meta-analysis to examine the existing literature on cover crop effects on N_2O.

The objectives of this study were to use a meta-analysis approach to (1) examine the relative impact of cover crops on N_2O emissions and (2) determine what management and environmental factors contribute to variability in cover crop effects on N_2O emissions. There were several factors that we hypothesized would have a large contribution to this variability. First, we hypothesized that the type of cover crop (legume versus nonlegume) would have different effects on N_2O emissions; namely legumes would have a greater potential to increase N_2O emissions versus nonlegumes. Second, we hypothesized that precipitation and cover crop biomass would impact N_2O emissions because denitrification also requires anaerobic conditions and C. Finally, we hypothesized that the timing of measurements was influential in how cover crops impact N_2O, namely that the period immediately following cover crop termination and the subsequent decomposition would have the largest N_2O emissions because of N and C release from residues.

Materials and Methods

Database Development. For the purposes of this study, we defined a cover crop as a plant not intended to be harvested, that is grown during a fallow period between harvest and planting of two cash crops. This included treatments labeled as cover crops, green manures, or catch crops. A literature review utilizing electronic databases Google Scholar and Web of Science was conducted with the following search string: "nitrous oxide emissions *or* greenhouse gas emissions *and* cover crops *or* green manures *or* catch crops." This combination of key terms resulted in approximately five thousand papers. To reduce the number of papers included in the meta-analysis, the following criteria were applied:

1. Studies in which the cover crop is not harvested and is grown between the harvest and planting of cash crops.
2. Studies reporting N_2O measurements.
3. Studies with a control treatment varying only in the inclusion of a cover crop and keeping all other management practices such as tillage and N additions equal.
4. Studies that provided enough information (standard errors, standard deviations, coefficients of variation, etc.) about experimental error either in the published paper or in information that was provided by the authors when contacted to allow for an estimate of within study variance.
5. Studies published before December of 2012.

On the basis of these criteria, 26 peer-reviewed studies representing 19 field experiments (83 observations), 2 growth chamber studies (9 observations), and 5 modeling experiments with validation data (14 observations) were selected for inclusion in a database (table 2) (n = 106 observations).

We omitted studies measuring emissions from cover crop treatments where the cover crop was not grown in the soil on which the measurements were taken (Bhattacharyya et al. 2012; Petersen et al. 2013). We also omitted papers analyzing emissions of varied cropping rotations if they did not have a true control treatment aligning with the cover crop treatment, as these would not allow for a proper comparison (Liebig et al. 2010; Gomes et al. 2009). If an experimental design matched our criteria, but the publication did not include enough detail to perform required calculations, authors were contacted when possible to obtain this information.

Data Analysis. Environmental and management factors were included in the database to examine factors that might be correlated with variabilility among observations. The full list of these factors is summarized in table 3 and describes categorical vs. numeric variables and the number of observations included in each analysis. For some of the factors, information that was not directly available in the studies was derived from other sources and is described below.

Precipitation. Unless the rainfall data was explicitly reported by the experiments, National Oceanic and Atmospheric Administration's (NOAA) Global Historical Climatology Network-Daily database was utilized (Menne et al. 2012) from the closest available stations over the specific range of dates when N_2O was sampled.

Soil Properties. Reported values for soil texture (percent of sand, silt, and clay), pH, organic C, and drainage class categorization were directly included in the database. If these values were not reported, the Web Soil Survey (Soil Survey Staff 2012) or literature for experiments conducted on the same fields was utilized. Drainage for non-US sites was determined either via contacting individual authors or by soil classification. Soil classification was determined by the referenced literature, and all sites were converted to one of the World Reference Base Group and US Soil Classification Group equivalents using Krasilnikov et al. (2009).

Table 2
Summary of studies included in the meta-analysis.

Cash crop(s)	Cover crop(s)	Location	Reference
Oats	Nonlegume and legume	Scotland, UK	Baggs et al. 2000
Corn	Nonlegume and legume	Maryland, USA	Rosecrance et al. 2000*
Rice–wheat	Legume	Ludhiana, India	Aulakh et al. 2001
Rice	Legume	Jiangxi, China	Xiong et al. 2002
Wheat–corn	Nonlegume and legume	England, UK	Baggs et al. 2003
Corn	Nonlegume	England, UK	Sarkodie-Addo et al. 2003
Corn	Legume	Nyabeda, Kenya	Millar et al. 2004
Barley	Nonlegume	Foulum, Denmark	Olesen et al. 2004†
Soybean	Nonlegume	Iowa, USA	Parkin et al. 2006*
Corn–soybean	Nonlegume	Iowa, USA	Parkin and Kaspar 2006
Corn–soybean	Nonlegume	Illinois, USA	Tonitto et al. 2007†
Corn–soybean	Nonlegume and legume	Iowa, USA	Farahbakhshazad et al. 2008†
Corn–soybean	Nonlegume	Michigan, USA	Fronning et al. 2008
Grapes	Nonlegume	California, USA	Steenwerth and Belina 2008
Rice	Nonlegume and legume	Kanto Plains, Japan	Zhaorigetu et al. 2008
Corn–pasture–alfalfa	Nonlegume	Pennsylvania, USA	Chianese et al. 2009†
Corn–soybean	Nonlegume	Iowa, USA	Jarecki et al. 2009
Corn silage	Legume	Turin, Italy	Alluvione et al. 2010
Corn–tomato, Tomato–cotton, Tomato–safflower–corn–wheat	Nonlegume and legume Legume	California, USA	De Gryze et al. 2010†
Tomato	Legume	California, USA	Kallenbach et. al 2010
Corn	Nonlegume	Michigan, USA	McSwiney et al. 2010
Tomato	Nonlegume	California, USA	Barrios-Masias et al. 2011
Corn	Nonlegume	New York, USA	Dietzel et al. 2011
Barley	Nonlegume	Foulum, Denmark	Petersen et al. 2011
Corn–soybean	Nonlegume	Indiana, USA	Smith et al. 2011
Tomato	Nonlegume	California, USA	Smukler et al. 2012

*Growth chamber experiment.

†Model simulation experiment.

Period of Nitrous Oxide Measurement. The included experiments varied in the length of time and time of year over which N_2O emissions were measured. Thus, we divided the observations based on the time periods into the following categories: full year, cover crop growth, cover crop decomposition, and cash crop growth.

These divisions allowed for an analysis of how cover crops influence N_2O fluxes at different times of the year. For full year, the included observations measured throughout the entire span of at least one entire year. For cover crop growth, the period coincided with the time that the cover crop was alive and growing. In many studies, this aligned with the winter season. For cover crop decomposition, the period coincided with the time of cover crop termination and potential incorporation into the soil. Depending upon the design of the experiments, this period lasted between two weeks at minimum and two months at maximum. This period often aligned with the spring season as well as fertilization events. For cash crop growth, the period coincided with the growth of the main cash crop. This period often aligned with the summer and fall seasons.

The dependent variable was the ratio between the N_2O flux with a cover crop treatment to N_2O flux without a cover crop:

$$RR = \frac{N_2O \text{ emissions cover crop treatment}}{N_2O \text{ emissions no cover crop treatment}} \,. \quad (1)$$

Response ratios (RR) were calculated for all combinations of cover crop and no cover crop (control) treatments within studies where these treatment pairs varied solely in the inculsion of a cover crop. Thus, the number of observations obtained from each study for the meta-analysis varied according to the study's experimental design. Within studies, different cover crop treatments (factorial experiments investigating for example tillage and cover crops), measurement periods (N_2O emissions reported by season or by individual years), or different species of cover crops were all counted as individual observations, and response ratios were determined for each of them.

Then equation 1 was natural log transformed (Hedges et al. 1999) to normalize the data as follows:

$$LRR = \ln RR. \quad (2)$$

The log ratio ensure that changes in the numerator and denominator are affected equally.

Within study error (V_i) was calculated following the method of Hedges et al. (1999), using reported estimates of variances and

Table 3

Description of database factors included to analyze variability in the cover crop effects on nitrous oxide (N_2O).

Factor	Description of categorical factors and range for numerical factors	Number of observations
Tillage	No-till, conventional tillage	74
Carbon (C):Nitrogen (N) residue ratio	9 to 48	57
Soil bulk density	1.2 to 2.65	67
pH	5.5 to 8.1	89
Type of cover crop	Legume, nonlegume, and biculture	106
N rate (kg ha^{-1})	0 to 303	103
Soil incorporation of residues	Yes, no	84
Kill date	Days between cover crop termination and cash crop planting (1 to 25)	71
Percentage of Sand	8 to 80	106
Percentage of Silt	11 to 73	106
Percentage of Clay	5 to 45	106
Percentage of organic C 0 to 30 cm	0.38 to 2.1	97
Cover crop biomass (kg ha^{-1})	280 to 14,400	65
Total precipitation (mm)	11 to 906	77
Standard deviation precipitation (mm)	0.5 to 40	77
Drainage	Well-drained, poorly-drained	69
Period of measurement	Full year, cover crop growth, cover crop decomposition, cash crop growth	80
Experiment type	Field, model, growth chamber	106

converting to standard deviations based on experimental replications:

$$V_i = \frac{SDcc^2}{ncc \times ycc^2} + \frac{SDncc^2}{nncc \times yncc^2}\,, \qquad (3)$$

where SD*cc* is the standard deviation of the cover crop treatment, n*cc* is the replications of the cover crop treatment, y*cc* is the mean N_2O emissions of the cover crop treatment, and *ncc* represents the N_2O emissions of the control or no cover crop treament. Equation 3 assumes that reported means are normally distributed.

The first step of the analysis was to determine if there was homogeneity among the LRR values from all the studies in the dataset (Hedges and Olkin 1985; Miguez and Bollero 2005). This tested the assumption that all of the LRR values came from the same population. If the test was significant, the effect of cover crops varied among observations, and other factors were affecting the response. If the test was not significant, then we could conclude that the cover crops had a similar effect across observations.

An inverse variance weighting factor (W_i) was used in this step to weigh each of the 106 LRR values, where studies with larger variances were weighted less heavily in the analysis. This is one way by which we can account for the assumed unequal variances among studies (Hedges et al. 1999). The inverse variance weighing factor is calculated as

$$W_i = 1/V_i\,. \qquad (4)$$

In the next step of the analysis, mixed model regression analyses were conducted to individually examine the relative effects of each of the 18 environmental and management factors on LRR (the natural log of response ratio) while accounting for the variation between studies (St-Pierre 2001) with the weighting factor (equation 4). The database's environmental and management factors were treated as fixed effects while study and intercept were treated as random effects. The statistical model used was

$$L_{ij} = \beta_o + s_i + \beta_1 A_{ij} + b_i A_{ij} + e_{ij}. \qquad (5)$$

where L_{ij} is natural log of the response ratio of i^th^ study, receiving j^th^ level of fixed factor A (factors in the analysis [table 3]). β_o is the overall intercept across all studies, si is the random effect due to the i^th^ level of study (i = 1,…,26), β_1 is the fixed regression coefficient of L_i on A across all studies, b_i is random effect of study i on the regression coefficient β_1, and e_{ij} is the residual error. This general model was first used to test each of the 18 factors individually. In these analyses, the N rate factor was found to have the largest effect on L_{ij}. Next, a second series of regression analyses were performed using models with the N rate factor plus one of the other 17 factors and its interaction with N rate. The statistical analysis was performed using the MIXED procedures of SAS (SAS Institute 2010).

For studies that simultaneously measured changes to NO_3 leaching, response ratios were generated to estimate the effect of the cover crop on these N fluxes. These response ratios represent the natural log of NO_3 leaching in the study's cover crop treatment divided by the measured value from the no cover crop treatment. When analyzed alongside the N_2O LRR values created in the same manner, these values provide a more complete understanding of a cover crop's role in these parts of the N cycling.

Finally, a sensitivity analysis was performed in order to test the robustness of the database and overall conclusions. We repeated the homogeneity test and mixed model regression analyses excluding all individual field and growth chamber studies one at a time as well as for a subset of the data excluding all of the modeling studies (Tudoreanu and Phillips 2004; Philibert et al. 2012). This provided an indication of whether the dominant factors were still significant as the database changed.

Results and Discussion

Overall. A test of homogeneity for the data set was significant (entire data set p = <0.0001, excluding modeling studies in sensitivity analysis $p = <0.0001$), indicating that the LRRs varied significantly among observations. This means that the effect of cover crops varied among the data points in our analysis and that other factors were affecting the response. Forty percent of the studies assessed in this analysis showed that cover crops decreased N_2O emissions (negative LRR) and 60% of the studies showed that cover crops increased N_2O emissions (positive LRR [figure 1]). To analyze these general trends, other factors that potentially affect N_2O emissions are discussed separately. Table 4 presents the results of the regression analysis of factors affecting the LRR including regression coefficients for the continuous variables. Positive coefficients indicate that LRR increases with increases the independent variable, while negative coefficients indicate that the LRR decreases with increases in the independent variable.

Nitrogen Rate. It is well documented that higher N rates increase N_2O emissions (Eichner 1990; Bouwman et al. 2002; Stehfast and Bouwman 2005). Our statistical analyses evaluating management and environmental factors revealed that N rate explained more of the LRR variability than other factors (table 4). In the sensitivity analysis, N rate was significant (at the $p < 0.0001$ level) when excluding the modeling experiments and in 100% of the regression analyses when excluding each of the 19 field and 2 growth chamber studies. As a result, interactions with N rate and other factors were investigated.

There was a significant interaction between the type of cover crop and N rate (figure 2). When no additional N is applied (zero N application rate), legumes exhibited higher LRRs than nonlegume species. This is consistent with the results of Gomes et al. (2009) who found that legume cover crop residues, which have C:N ratios less than 25, stimulated N mineralization rates in maize (*Zea mays* L.) systems with no additional N applications. Because a significant quantity of mineralized N is subsequently nitrified, this may enhance NO_3 substrate for N_2O production. In a laboratory incubation experiment, Huang et al. (2004) observed that low C:N crop residue ratios increased N_2O emissions. Consistent with the negative relationship between crop residue C:N ratios and N_2O emissions in the absence of additional N inputs, nonlegume cover crops showed a slight increase in LRRs as N fertilizer rate increased, reflecting the

Figure 1

Natural log of response ratios (LRR) for 106 observations in the dataset, where the response ratio represents the nitrous oxide (N_2O) flux with a cover crop divided by the N_2O flux without a cover crop.

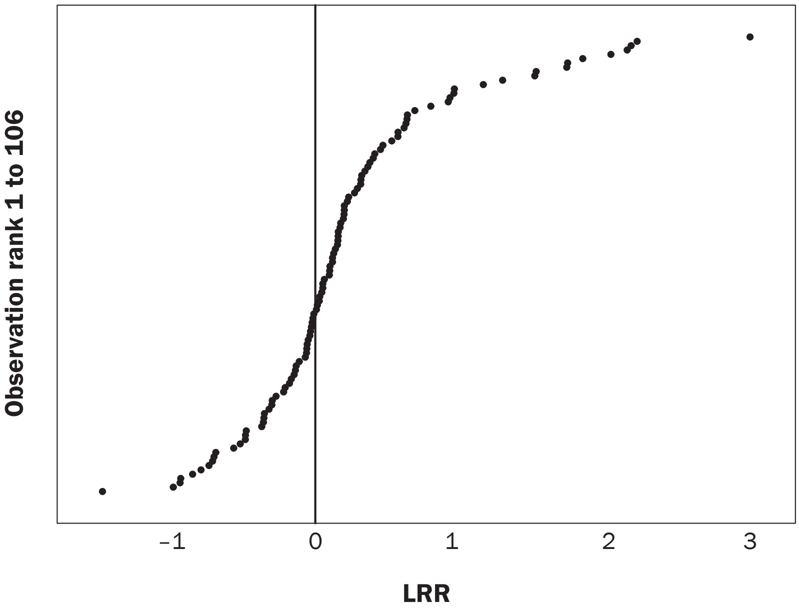


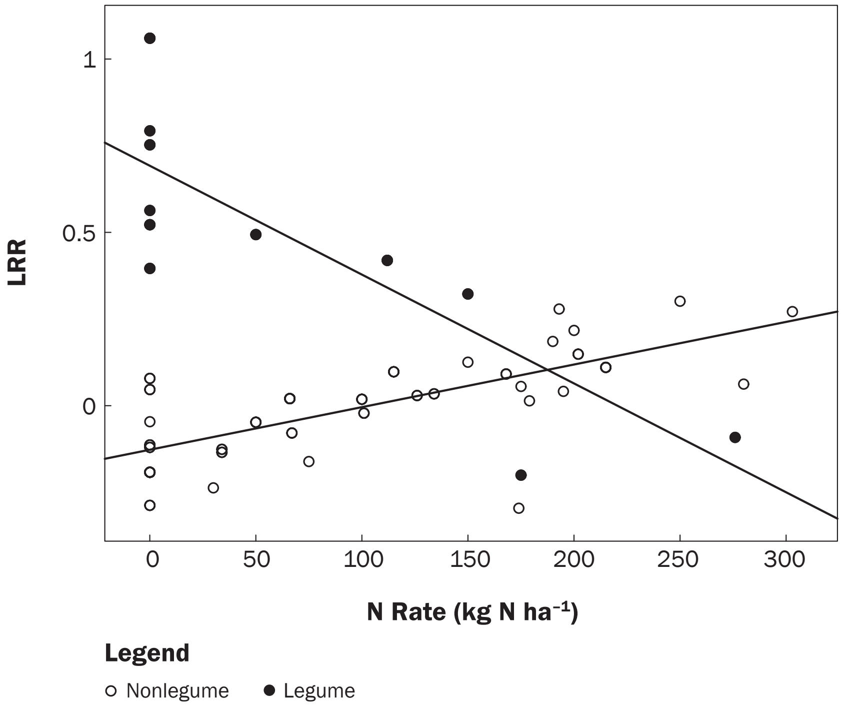
Table 4

***F* and *p* values for all environmental and management factors in the mixed model regression analysis. Regression coefficients are presented for the continuous variables analyzed. DF = degrees of freedom.**

Source	DF	Error DF	Regression coefficient	F value	Pr > F
Tillage	1	54		2.7	0.106
Carbon (C): nitrogen (N) residue ratio	1	43	−0.04	2.17	0.1483
Soil bulk density	1	51	0.97	2.7	0.1063
pH	1	65	0.68	15.57	0.0002
Type of cover crop	2	78		2.51	0.0878
N rate	1	77	0.00	364.58	<0.0001
Soil incorporation	1	64		5.84	0.0186
Kill date	1	53	−0.03	1.14	0.2901
Percentage of sand	1	79	0.36	0.36	0.5494
Percentage of silt	1	79	−0.24	0.12	0.7297
Percentage of clay	1	79	−1.23	0.65	0.4217
Percentage of organic carbon	1	74	−0.56	4.05	0.0478
Cover crop biomass	1	49	0.00	0.74	0.3947
Total precipitation	1	58	−0.00	8.49	0.0051
Standard deviation	1	58	0.11	10.66	0.0018
Precipitation drainage	1	54		0.03	0.8693
Period of measurement	3	57		54.94	<0.0001
Experiment type	2	80		0.73	0.4862

Figure 2

Response ratios (LRR) of legume versus grass cover crop species as a function of fertilizer nitrogen (N) rate. At the 0 N rate, legume cover crops have a higher response ratio than grass cover crop species. Across a range of N application rates, the response ratio for nonlegume cover crop species only increases slightly; for legumes the trend declines.



importance of both C and N for the denitrification process.

There was also a significant interaction between N rate and tillage system (figure 3). Mechanical soil disturbances have been observed to stimulate C mineralization and net N mineralization (House et al. 1984; Beare et al. 1994; Omonode et al. 2011) due to the disruption of soil aggregates which expose organic C to microbial decomposition. In no-till systems, LRRs slightly increased with increasing N rate. This may have occurred because increasing cover crop biomass on the soil surface with increasing N fertilizer rate could have mulched the soil surface keeping it slightly wetter. In conventionally tilled systems, lower N rates tended to result in positive LRRs. This suggests that at higher N rates in a conventionally tilled system, the cover crop may contribute to a reduction in N_2O emissions relative to the control treatment without cover crops.

Further, even negative LRRs (cover crop treatments reduced N_2O) may not reflect a large reduction in the overall magnitude of N_2O emissions, particularly with high N fertilization rates. Table 5 includes a subset of studies reporting N_2O in kg ha^{-1} (LRRs were generated using the reported units which varied by study and the length of measurement) to demonstrate the magnitude of changes with and without cover crops. Cover crops reduced N_2O emissions at high N rates (~1 to 2 kg [2.2 to 4.4 lb] N_2O difference in study 1 and 2) or by a neglibile amount at 0 N rates (study 3). In other studies, cover crops increased N_2O emissions by 2 to 4 kg ha^{-1} (1.8 to 3.6 lb ac^{-1})at higher N rates (study 4 and 5). Finally, study 6 indicated a large increase (~40 kg [88.1 lb] N_2O) in N_2O emissions at a 0 N rate, given the large N contribution from a legume cover crop and the anaerobic soil conditions in the cropping system. Further, this large release of N_2O occurred while the cover crop was decomposing, a period observed to have high N_2O emissions (figure 5).

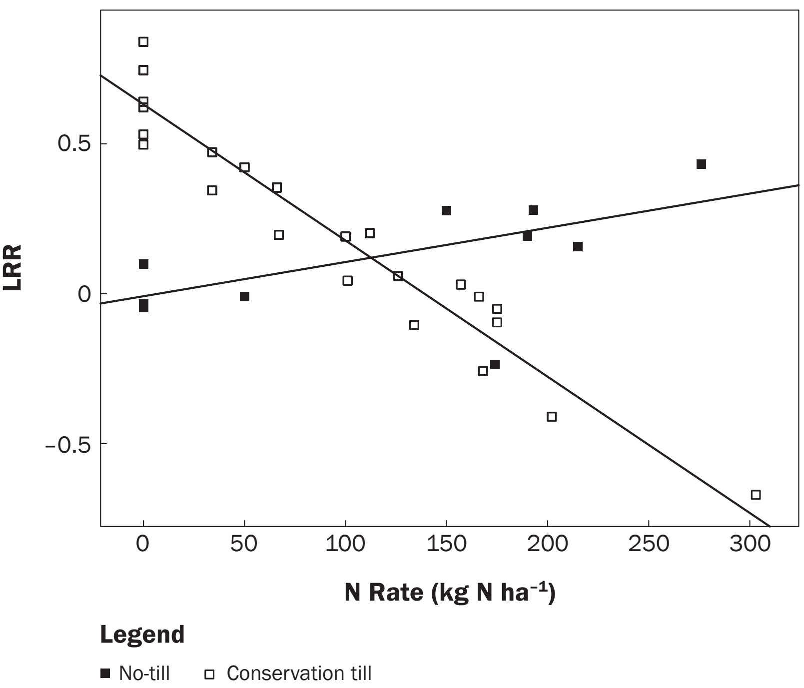
Type of Cover Crop. Cover crops were categorized into the following types: legume (such as clover, vetch [*Vicia villosa*], field bean, and pea varieties), nonlegume (such as cereal rye [*Secale cereal*], annual ryegrass [*Lolium multiflorum*], oats [*Avena sativa*], wheat [*Triticum aestivum*], and radish mustards), and biculture species (such as vetch and rye mixes). In general, legumes typically resulted in positive LRRs, while the LRRs for nonlegume and biculture species were close to zero (figure 4). Statistical analysis revealed that there was a significant difference at the $p < 0.10$ level in response ratios between the legume, cover crop type nonlegume and biculture groups. In the sensitivity analysis excluding the five modeling studies, type was found to be significant ($p = 0.002$), and we thus cannot reject our hypothesis that cover crop type influences cover crop impact on N_2O emissions. Because cover crops take up N that might otherwise be lost to leaching or because legume cover crops can fix N, cover crops may increase soil N availability during decomposition and, thus, may increase the available NO_3 substrate for denitrification and N_2O emissions within agricultural fields.

Period of Measurement. Based on the period of measurement, cover crops influenced N_2O dynamics differently throughout the year ($p < 0.0001$). The sensitivity analysis further revealed that period of measurement was significant (at the $p < 0.05$ level) in 95% of the statistical models when excluding individual studies. Data points based on measurements made across an entire year had an average response ratio close to zero compared to the other periods of measurement (figure 5). This may suggest that there is a net neutral effect of a cover crop on N_2O emissions when measured over longer timescales. Figure 5 illustrates that even if particular periods of the year see larger N_2O impacts of a cover crop, a full-year time scale may actually find a net neutral effect. More long-term field experiments measuring N_2O over the entire year are needed to better understand these dynamics.

Our analysis indicated that the highest LRRs were data points measuring during the cover crop decomposition period, consistent with our hypothesis. Rosecrance et al. (2000) observed the largest N_2O fluxes over the course of a growth chamber experiment in the five days after cover crop termination with rye, vetch, and a mixture of both (C:N of 21, 10, and 14 respectively). They concluded that additional C substrate plus available mineral N contributed to high N_2O emissions during this period. Aukulah et al. (2001) also found that N_2O production was highest in the initial four week period following legume cover crop soil incorporation in a flooded rice system. They attributed this

Figure 3

Response ratios (natural log of nitrous oxide [N_2O] flux with a cover crop divided by the N_2O flux without a cover crop [LRR]) of conventionally tilled and no-tilled systems as a function of nitrogen (N) application rate. Cover crops reduced response ratios at higher N rates in conventionally managed systems. No-till systems increased response ratios slightly (compared to conventional tillage) as N rates increased.



to the interaction between NO_3 and organic C availability, given that soil water content and temperature remained consistently favorable for denitrification. Sarkodie-Addo et al. (2003) measured NO_3, ammonium (NH_4), and N_2O for 55 days after incorporation of a wheat and winter rye cover crop with and without fertilizer. Fertilized plots had positive LRRs, and nonfertilized plots had negative LRRs. They reported that the decrease in N_2O emissions with cover crops in the nonfertilized plots could be a result of temporary N immobilization from the cover crop's C contribution. The results of the studies measuring N_2O during the cover crop decomposition period suggest that N_2O emissions are affected by the interaction of C input and N availability. Cover crop residues with low C:N ratios generally increased N_2O emissions (positive LRR [figure 6]) during the decomposition period. This is consistent with observations of Millar et al. (2004) that N_2O from systems with legume cover crops were positively correlated with residue N content. Further, the positive LRR observed during the growth of the cash crop may indicate that there is still some cover crop decomposition happening during this period.

Studies during the growth of the cover crop period had the lowest mean LRR of all the periods of measurement (figure 5). This could be a result of cover crop N uptake as well as the fact that this period often occurred during the winter when temperatures are lower. Temperature is important because microbial process rates including N mineralization, nitrification, and denitrification exponentially decline with decreasing temperature (Stanford et al. 1975). In a growth chamber study, in which temperature was controlled, Parkin et al. (2006) found that winter rye cultivated with manure treatments reduced available soil NO_3 as well as N_2O emissions compared with levels measured in the no cover crop treated pots. This suggests that crop N uptake creates a larger sink for the soil mineral-N pool than N_2O emissions or NO_3 leaching. Dietzel et al. (2011) measured N_2O emissions in a maize-winter rye cover crop system over two winter and spring seasons. The two years varied significantly in winter conditions which altered the soil water status by changing the frequency of freezing and thawing cycles. The warmer winter resulted in more negative LRRs than the colder winter when more freeze

Table 5

Magnitude of nitrous oxide (N_2O) changes with and without cover crops for subset of data base studies.

Study number	No cover crop N_2O emissions (kg N ha⁻¹)	Cover crop N_2O emissions (kg N ha⁻¹)	Cropping system and cover crop species	Measurement period	Nitrogen (N) application rate (kg ha⁻¹)	Reference
1	7.5	5.3	Corn in corn—soybean, 70% rye/ 30% oat	Full year	175	Jarecki et al. 2009
2	3.7	2.3	Soybean, winter rye	Winter (cover crop growth)	195	Parkin et al. 2006
3	1.5	1.4	Soybean in corn—soybean, annual ryegrass	Full year	0 N	Smith et al. 2011
4	11.3	15.4	Corn in corn—soybean, winter rye	Full year	215	Parkin and Kaspar 2006
5	3.8	5.1	Corn in corn—soybean, annual ryegrass	Full year	193	Smith et al. 2011
6	9.3	50.2	Rice—wheat, sesbania	Spring (cover crop decomposition)	0 N (176 from legume CC)	Aulakh et al. 2001

Figure 4

Mean response ratios (LRR; 95% confidence intervals also shown) for management factors included in the meta-analysis: the type of cover crop and soil incorporation of cover crop residues.

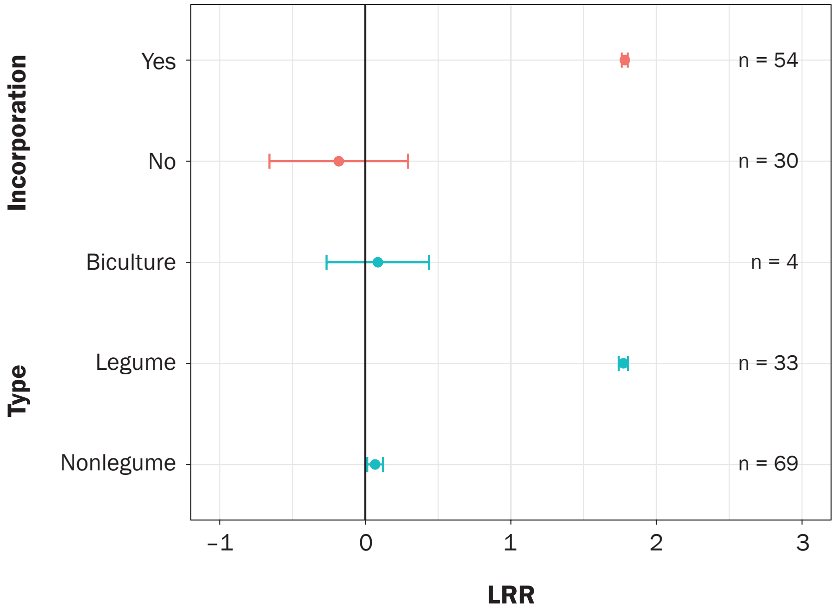
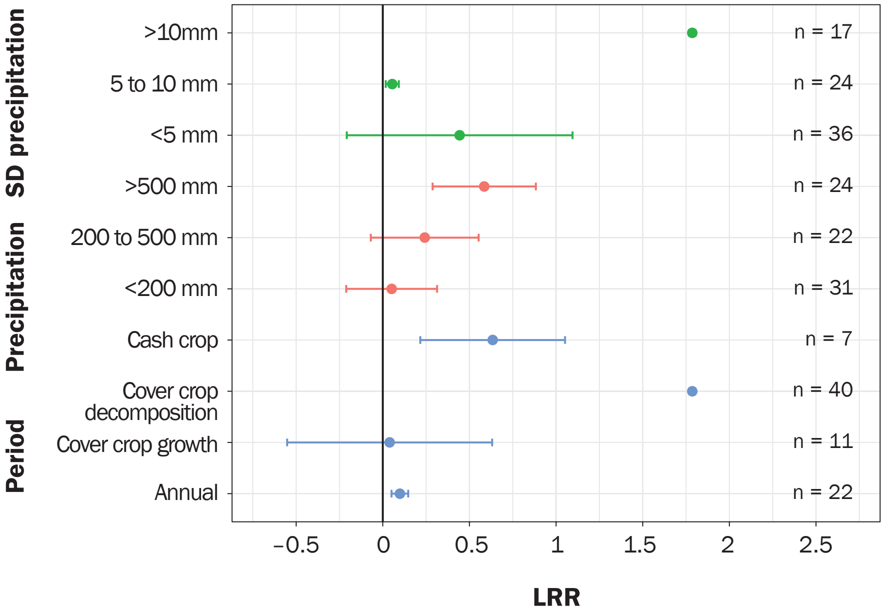


Figure 5

Mean response ratios (LRR; 95% confidence intervals also shown) for environmental factors included in the meta-analysis: the period of measurement, the total precipitation over the measurement period, and the standard deviation of precipitation over that period.



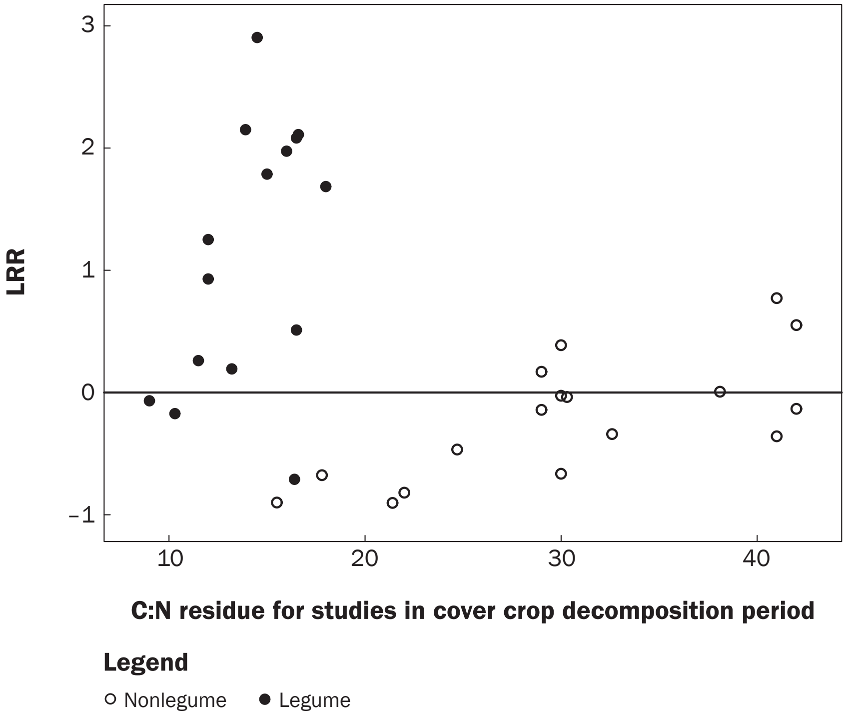
thaw cycles were present. In this study, the cover crop response ratio's dependence on weather variability may further illustrate the value of measuring over multiple seasons or years (larger time scales) to better understand annual cover crop N_2O dynamics.

Soil Incorporation. In our analysis, LRRs for studies that incorporated cover crop residues into the soil were significantly higher than those for studies that left the residues on the soil surface (p = 0.02 [figure 4]). Of the studies where incorporation was reported, 19 of the 20 highest positive response ratios in the database were cover crop treatments where residues had been incorporated into the soil. The sensitivity analysis also found that soil incorporation was significant ($p <$ 0.05) in 81% of the models when excluding individual studies. Incorporation of cover crop residues contributes to an increase in N_2O emissions through several potential effects. Incorporation of cover crop residues increases N mineralization rates of both soil organic matter and cover crop residues, and it contributes to greater NO_3 availability and denitrification (Firestone and Davidson 1989). Incorporation of cover crops residues also likely increases soil temperature and, thus, the potential for denitrification compared with soil covered with residues (Omonode et al. 2011). Lastly, anaerobic conditions for denitrification of cover crop N is more likely to occur if the residues are incorporated with tillage rather than left on the surface (Kaspar and Singer 2011). Thus, our analysis indicated that incorporating aboveground cover crop residues led to relative increases in N_2O emissions through a variety of mechanisms.

Precipitation. The episodic nature of N_2O emissions results in part from the requirement for denitrification for anaerobic soil conditions, which usually occur following large or intense precipitation events (Davidson et al. 2000). Cover crops may alter the soil water status and the potential for anaerobic conditions in several ways, including decreased soil evaporation, increased rainfall infiltration, and transpiration of stored soil water during cover crop growth (Unger and Vigil 1990). To evaluate the soil water status and potential for anaerobic condition of a study, we utilized total precipitation over the measurement period as well as the standard deviation of the rainfall as indicators for conditions favoring development of anaerobic soil conditions and denitrification. Similarly, the DeNitrification-DeComposition (DNDC) model (Li et al.

Figure 6

Response ratios (LRR) for observations measured during the cover crop decomposition period as a function of the residue carbon (C):nitrogen (N) ratio. Legume species and those species with lower C:N ratios frequently led to an increase in nitrous oxide (N_2O) emissions, as indicated by the positive response ratios.



1992) uses daily precipitation along with other variables as a predictor of the N_2O emissions. Other models like Agricultural Production Systems Simulator (APSIM) (Thorburn et al. 2010) use water filled pore space as a predictor of N_2O emissions.

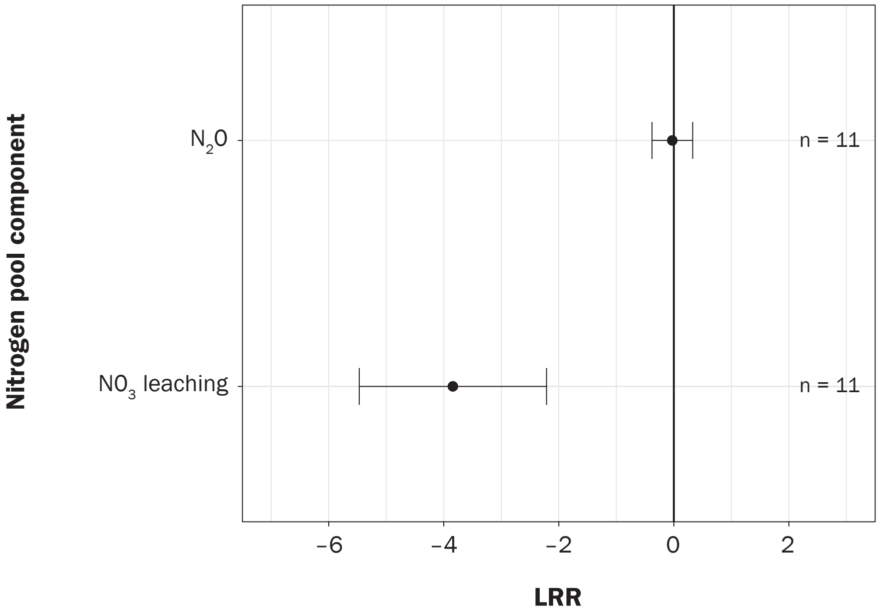
In the statistical model testing the effect of precipitation values on LRRs, total precipitation ($p = 0.005$) and the standard deviation of precipitation ($p = 0.002$) were significant (figure 5). As we hypothesized, precipitation is an important factor impacting the LRRs. Total precipitation, however, was significant at the $p < 0.1$ level in 86% of the statistical models excluding individual studies, while the standard deviation of precipitation was significant at the $p < 0.05$ level in 95% of the statistical models. Studies with legume cover crops had a more pronounced trend toward increased response ratios as the total precipitation and standard deviation of precipitation increased. All of the observations (20 points representing 7 different studies, where 77 total points were included in this part of the analysis) with a standard deviation of precipitation above 8.8 mm (0.34 in) had positive LRRs. This may indicate that regardless of other factors (such as cover crop type) above a threshold of rainfall variability, a cover cropped agroecosystem is more susceptible to N_2O emissions than one without a cover crop. Novoa and Tejeda (2006) noted that N_2O emissions from applied plant residues were predicted in part by rainfall. This could be a result of a cover crop residue maintaining higher soil moisture and providing labile C, along with the timing of high intensity rainfall events.

Soil Organic Carbon. Soil organic C (SOC) has a strong impact on N transformations including the denitrification process (Davidson et al. 2000). In addition, many models (APSIM, Daily Century Model [DAYCENT], DNDC, Environmental Policy Integrated Climate Model [EPIC], and ecosys) capable of simulating N_2O emissions include SOC as a predictor (Li et al. 1992; Adler et al. 2007; De Gryze et al. 2010; Thorburn et al. 2010). Cover crops are a source of C and therefore the amount and quality of additional biomass has the potential to alter N_2O emissions. Two factors were categorized and analyzed to evaluate the effect of SOC on LRRs: percentage organic C in the topsoil and total cover crop biomass. The percentage organic C of the topsoil was found to be significant in the statistical model testing its effect on the LRR ($p = 0.05$). With larger SOC values in the topsoil, the LRR showed a small decline. Bouwman et al. (2002) found significantly larger N_2O emissions in soils with 3% to 6% organic C versus those with 1% to 3%. However, the experiments included in this analysis had a much smaller range of SOC values (0.38% to 2.10% [table 3]), which may be one reason we did not observe as clear of a relationship between SOC and N_2O emissions. It is possible that at lower background levels of SOC, higher LRRs could be a result of a larger cover crop effect due to C limitation. Additionally, our analysis indicated that the total amount of cover crop biomass did not have a significant effect on LRRs, although there was a trend toward higher LRRs as biomass increased (data not shown). Contrary to our hypothesis that cover crop biomass would be an important factor controlling N_2O emissions we found inconclusive evidence of this. The sensitivity analysis found cover crop biomass significant at the $p < 0.10$ level in 62% of the regression analyses excluding individual studies. Robinson and Conroy (1999) found that when elevated CO_2 levels increased plant productivity, subsequent additional C substrate for microbes contributed to consumption of more soil O_2 than could be replaced by diffusion. This led to anerobic soil conditions and increased denitrification. This mechanism seems consistent with our analysis, given the relationships in the dataset with LRRs, SOC, cover crop biomass, and precipitation. It also underscores multiple interconnections between C and N cycling in agroecosystems.

Cover Crops and Global Warming Potential. Nitrate lost through leaching from agricultural fields is subject to denitrification and N_2O emissions off-site, which would not be reflected in the on-site measurements of N_2O emissions from the soil surface. Therefore, given the ability of cover crops to reduce NO_3 leaching, cover crops may contribute to an overall decrease in net global warming potential. Mosier et al. (1998) estimated indirect N_2O emissions resulting from leaching and runoff to be 2.5% of total leached N. They further calculated that indirect denitrification (e.g., from leaching and runoff) emissions constitute 25% of global N_2O emissions from agricultural soils.

Figure 7

The mean nitrate (NO_3) leaching response ratios (LRR; natural log of the NO_3 leaching with a cover crop divided by the NO_3 leaching without a cover crop) and 95% confidence intervals compared to the mean nitrous oxide (N_2O) response ratios from three studies measuring both. Ten of the 11 points were measured during the cover crop growth period. Although this represents only a small subset of the data base, it could further suggest that cover crop nitrogen uptake during growth decreases leaching losses and subsequent indirect N_2O emissions.



For studies measuring leaching losses in this meta-analysis, mean change in NO_3 loss with a cover crop was significantly lower than the slight increase to neutral effect on direct N_2O emissions (figure 7). This is consistent with the results of Tonitto et al. (2006) who found that on average nonlegume cover cropped systems reduced NO_3 leaching by 70% and legume cover cropped systems reduced NO_3 leaching by 40%. Even though indirect estimates of N_2O emissions are variable, this is an important impact to consider that would not be included in the LRR for direct emissions used in our analysis.

One modeling experiment (De Gryze et al. 2010) and two field experiments (Fronning et al. 2008; Smith et al. 2011) reported net global warming potentials (GWP) that were neutral or negative (indicating mitigative potential) when cover crops were present. In our database, only these three studies included full net GWPs, measuring change in SOC (or soil CO_2 respiration), N_2O, and CH_4. De Gryze et al. (2010) found that the net decrease in GWP was primarily a result of increased SOC storage in cover cropped systems. More multiyear field trials and modeling efforts are needed to better understand the long term effect of cover crops on the net GWP of agroecosystems.

Summary and Conclusions

This meta-analysis found that cover crops increased N_2O emissions from the soil surface in 60% of published observations while cover crops decreased N_2O emissions from the soil surface in 40% of observations. There are both environmental and management factors that modified the impact of cover crops on N_2O emissions, including fertilizer N rate, soil incorporation, and the period of measurement and rainfall. Legume cover crops had higher relative N_2O emissions at low N rates and lower emissions at high N rates, whereas N_2O emissions of nonlegume cover crops increased as N rate increased. In general, it seems that cover crops have a greater potential to reduce N_2O emissions when nonlegume species are utilized and cover crop residue is not incorporated into the soil. Our analysis also found that cover crops on average only lead to a small or negligible increase in N_2O emissions when measured for time periods of one year or greater. To understand the full global impact of cover crops on N_2O emissions, more field research with measurements over extended time periods is needed to examine the temporal component of N_2O emissions. Better accounting for cover crop reductions in indirect N_2O emissions from leached N should also be considered.

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