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REVIEW

Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis

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Abstract

No-tillage and reduced tillage (NT/RT) management practices are being promoted in agroecosystems to reduce erosion, sequester additional soil C and reduce production costs. The impact of NT/RT on N_2O emissions, however, has been variable with both increases and decreases in emissions reported. Herein, we quantitatively synthesize studies on the short- and long-term impact of NT/RT on N_2O emissions in humid and dry climatic zones with emissions expressed on both an area- and crop yield-scaled basis. A meta-analysis was conducted on 239 direct comparisons between conventional tillage (CT) and NT/RT. In contrast to earlier studies, averaged across all comparisons, NT/RT did not alter N_2O emissions compared with CT. However, NT/RT significantly reduced N_2O emissions in experiments >10 years, especially in dry climates. No significant correlation was found between soil texture and the effect of NT/RT on N_2O emissions. When fertilizer-N was placed at ≥ 5 cm depth, NT/RT significantly reduced area-scaled N_2O emissions, in particular under humid climatic conditions. Compared to CT under dry climatic conditions, yield-scaled N_2O increased significantly (57%) when NT/RT was implemented <10 years, but decreased significantly (27%) after ≥ 10 years of NT/RT. There was a significant decrease in yield-scaled N_2O emissions in humid climates when fertilizer-N was placed at ≥ 5 cm depth. Therefore, in humid climates, deep placement of fertilizer-N is recommended when implementing NT/RT. In addition, NT/RT practices need to be sustained for a prolonged time, particularly in dry climates, to become an effective mitigation strategy for reducing N_2O emissions.

Keywords: conservation tillage, mitigation, N-fertilizer, nitrous oxide, yield-scaled

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Introduction

The amount of fixed N in agroecosystems has increased in the past 100 years, mainly through the use of synthetic fertilizer nitrogen (N) following the discovery of the Haber-Bosch process and increased cultivation of N_2-fixing leguminous crops (Robertson & Vitousek, 2009). Whereas the increase in synthetic fertilizer-N use has boosted crop production to feed a growing world population, there have also been undesirable consequences, including increased emissions of nitrous oxide (N_2O).

Up to 10–12% of total anthropogenic greenhouse gas (GHG) emissions are derived from agricultural activities, 58% of which are derived from N_2O emissions and are mainly related to the application of nitrogenous fertilizers (Smith *et al.*, 2007). It is estimated that field-crop agriculture contributes more than 61% of total global anthropogenic N_2O emissions (Montzka *et al.*, 2011). These emissions are of concern because N_2O contributes to the depletion of the ozone layer (Crutzen, 1981) and N_2O is a potent GHG with a global warming potential (GWP) 12 times larger than CH_4 and 298 times larger than CO_2 based on a 100 year time horizon (IPCC, 2007). Whereas only a small portion (<3%) of applied fertilizer-N is generally emitted as N_2O, in cropping systems these emissions, both direct and indirect, are often a major contributor to the overall GHG budget (Roberston *et al.*, 2000; Beaulieu *et al.*, 2011).

Reduced (RT) or no tillage (NT) practices are widely implemented in cropping systems as a means to conserve water and reduce erosion and soil organic matter losses compared with conventional tillage (CT) (Six *et al.*, 2002). Although NT/RT has been promoted to increase soil organic C, reduce erosion, enhance soil fertility, and to reduce GHG emissions (Cole *et al.*, 1997;

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Ellert & Janzen, 1999; Schlesinger, 1999), its effect on N_2O emissions is highly variable (Rochette *et al.*, 2008; Gregorich *et al.*, 2008; Lemke *et al.*, 1998). Whereas some studies showed a decrease in N_2O emissions with NT/RT (e.g., Gregorich *et al.*, 2008; Mosier *et al.*, 2006), others reported higher emissions (e.g., Ball *et al.*, 1999; Burford *et al.*, 1981), no difference (Lemke *et al.*, 1998), or NT/RT effects depending on tillage type and placement of N fertilizer (Drury *et al.*, 2006; Venterea *et al.*, 2005).

Based on a literature review, Six *et al.* (2004) observed a tendency toward increased N_2O emissions during the first 10 years after conversion from CT to NT, but thereafter N_2O fluxes tended to decrease. However, this reduction in N_2O emissions following long-term NT was only significant in humid climates.

The variable response of N_2O emissions to tillage practices is not surprising as tillage can affect a number of biophysical factors that influence N_2O emissions in potentially contrasting ways (Snyder *et al.*, 2009). For example, NT tends to increase moisture content and bulk density, resulting in greater water-filled pore space (WFPS), which tends to promote N_2O emissions (Linn & Doran, 1984a). On the other hand, NT can improve soil structure and lower soil temperature, which in turn can reduce N_2O emissions relative to CT (Six *et al.*, 2002; Grandy *et al.*, 2006; Venterea & Stanenas, 2008; Venterea *et al.*, 2011). Other tillage effects have less predictable consequences for N_2O emissions such as shifts in soil pH (Dick, 1983) and microbial community composition (Minoshima *et al.*, 2007), and greater fungal disease pressure (Fernandez *et al.*, 2009). To further complicate matters, tillage affects not only the magnitude but also the vertical stratification of soil properties, including potential nitrification and denitrification enzyme activities, both of which tend to decline rapidly below the upper 5–10 cm of NT soils (Linn & Doran, 1984b; Groffman, 1985). Based on measured vertical distributions of several soil biophysical properties combined with process modeling, Venterea & Stanenas (2008) hypothesized that N fertilizer placement depth interacts with tillage to regulate N_2O emissions. Specifically, shallow N fertilizer placement with NT will increase N_2O emissions relative to CT whereas deep N fertilizer placement will have the reverse effect. This potential interaction between tillage and N fertilizer placement as a control over N_2O emissions has yet to be robustly examined across a larger number of studies.

The IPCC Tier 1 directive follows a linear relationship between N inputs and N_2O emissions. However, nonlinear relationships between these variables have also been reported (McSwiney & Robertson, 2005; Hoben *et al.*, 2011; Van Groenigen *et al.*, 2010), supporting the use of the more site-specific IPCC Tier 2 approach for estimating N_2O emissions based on N inputs (Millar *et al.*, 2010). Although several studies have measured both N_2O emissions and crop yields, there have been relatively few attempts to combine these measurements and report them together as yield-scaled N_2O emissions. When N_2O emissions are related to yield and the emissions are expressed on a yield-scaled basis, they will reflect GHG intensity. Reporting yield-scaled emissions may be particularly important for practices such as tillage which are likely to affect both yields and N_2O (Mosier *et al.*, 2006).

Our objective was to conduct a meta-analysis of peer-reviewed studies to evaluate the effects of NT/RT on N_2O emissions relative to CT, with emissions expressed on both an area- and yield-scaled basis. Using 239 direct comparisons of NT/RT relative to CT, we also examined how these effects vary with respect to (i) duration of the tillage practice (more or less than 10 years), (ii) climate regime (humid or dry), and (iii) placement of N fertilizer (shallow or deep).

Materials and methods

Data

We collected data on area-scaled N_2O emissions from studies in which CT was compared with NT or RT in side-by-side experiments. Using crop yield data from the same experiments, we also calculated yield-scaled N_2O emissions. Reduced tillage consisted of shallow cultivation or plowing, reduced number of tillage operations, lower depth of cultivation/harrowing but no plowing, use of chisel coulter drill, or zone tillage. An exhaustive literature survey of peer-reviewed publications was carried out using ISI-Web of Science and Google Scholar (Google Inc., Mountain View, CA, USA) for articles published before August 2011. The literature survey focused on N_2O emissions from cropping systems but excluded flooded systems such as rice paddies. Studies had to meet specific criteria to be included in the data set. First, N_2O fluxes must have been measured under field conditions for an entire season (i.e., period from planting to harvest). Second, crop yield data needed to be available, in some cases from other publications or via personal communication. Yield data were readjusted at 14.5% and 16.5% moisture content for maize (*Zea mays*) and wheat (*Triticum spp*), respectively. Third, means and the number of field replicates (i.e., plots per treatment combination) had to be reported for both CT and NT/RT systems. Because of the importance of N fertilizer application rate in regulating both crop yields and N_2O emissions, we only included comparisons where the N fertilizer application rate between tillage treatments differed by less than 15 kg N ha^{-1} yr^{-1} (only 5 of the 239 comparisons in our data set did not use identical N rates).

For each study, we noted whether CT was compared with either NT or RT, as well as the experimental duration (short or long, i.e. <10 years or ≥ 10 years). To determine the aridity index of the study area we followed the WorldClim database (Hijmans *et al*., 2005). Following the generalized climate classification scheme for Global-Aridity values (UNEP, 1997), study sites with an aridity index >0.65 were categorized as 'humid', whereas study areas with a lower index were categorized as 'dry'. Percentages of sand, silt and clay, were tabulated when available (235 of 239 comparisons). We used the soil texture data to calculate soil saturated hydraulic conductivity (K_{sat}) according to Saxton *et al*. (1986), which was then used as an integrated numeric indicator of soil drainage characteristics. Hydraulic conductivity is a key regulator of soil moisture content and is related to bulk density and structure, and therefore a potential indicator of the effect of soil texture on N_2O emissions. Information regarding depth of N fertilizer placement was included when available either in print or via communication with authors, but was not required for inclusion of the study in the overall analysis. Studies were categorized according to N placement depth in the NT/RT treatments (shallow or deep, i.e. <5 cm or ≥ 5 cm). In some cases, placement depth information was excluded because the study could not be clearly categorized, for example, when multiple N-fertilizer applications were made at different depths or when the exact application depth was in question or covered a range that included 5 cm. The studies and the number of comparisons within each study that were included in the analysis and associated information regarding location, crop, climate, duration, tillage treatment, and fertilizer placement are listed in Table 1.

Data analysis

For each study, all comparisons between CT and NT/RT treatments for net seasonal N_2O emissions, crop yield, and yield-scaled N_2O emissions were separately included in our meta-analysis. As such, multi-factorial studies (i.e., in which tillage treatments were combined with other treatments in a factorial design) and studies that reported results for multiple years contributed more than one comparison to our data set.

We used the natural log (ln*R*) of the response ratio as our effect size (Hedges *et al*., 1999):

$$\ln R = \ln(V_{NT/RT}/V_{CT}) \tag{1}$$

where V is the mean value in the NT/RT treatment or the CT treatment.

We performed meta-analyses using a nonparametric weighting function and generated confidence intervals (CIs) using bootstrapping. Effect sizes were weighted by replication. To avoid bias toward studies reporting results for multiple years, the weight of each effect size was divided by the number of years for which data were included from the corresponding study:

$$w_i = n/y \tag{2}$$

where w_i is the weight for the *i*th effect size, n is the number of field replicates, and y is the number of years for which comparisons were included in the data set from the study corresponding to the *i*th comparison. By favoring field experiments that are well replicated, our weighting approach assigns more weight to more accurate effect size estimates. Mean effect sizes were estimated as follows:

$$\overline{\ln R} = \sum(\ln R_i \times w_i)/\sum(w_i) \tag{3}$$

with $\ln R_i$ as the effect size for N_2O emissions, yield, or yield-scaled N_2O from the *i*th comparison, and w_i as before. We used METAWIN 2.1 to calculate mean effect sizes and to generate 95% bootstrapped CIs (4999 iterations) (Rosenberg *et al*., 2000). To ease interpretation, the results for the analyses on ln*R* were back-transformed and reported as percentage change under NT/RT relative to CT treatments ($[R - 1] \times 100$). Treatment effects were considered significant if the 95% CI did not overlap with zero. *P*-values for differences between categories of studies and for correlation with K_{sat} were calculated using resampling tests incorporated in METAWIN 2.1.

Results

Area-scaled N_2O emissions

Averaged across all 239 comparisons, NT/RT did not change area-scaled N_2O emissions compared with CT, and no significant tillage effects were found after separating data by tillage category (i.e., RT or NT) or by climate regime (Fig. 1a). Separation of data by duration of treatment indicated that long-term NT/RT tillage operations significantly reduced area-scaled N_2O emissions (by 14%) relative to CT (Fig. 2a). When separated by climate regime, the reduction in N_2O emissions with long-term NT/RT was significant in dry climates only (34%). In contrast, short-term NT/RT tillage operations in dry climates increased area-scaled N_2O emissions by 38% relative to CT (Fig. 2a). Within studies with deep N placement, NT/RT significantly reduced area-scaled N_2O emissions by 26% (Fig. 3a). When separated by climate regime, the effect of NT/RT was only significant for deep N placement in humid climates (27% reduction). Across all sites the relationship between K_{sat} and treatment effects on area-scaled N_2O emissions was not significant ($P = 0.42$). Likewise, K_{sat} showed no significant correlation with treatment effects on yield ($P = 0.49$) or yield-scaled emissions of N_2O ($P = 0.58$).

Crop yield

Averaged across all comparisons, NT/RT led to a significant decline in yield of 5% compared to CT (Fig. 1b). There was no significant difference in yield decline relative to CT between NT and RT operations (Fig. 1b). The yield decline with NT/RT was significantly greater in dry climates (11%) than that in humid climates (3%) (Fig. 1b), but did not depend on experimental duration (Fig. 2b). However, in humid climates, the decline in yield was only significant for long-term NT/RT

Table 1 Description of the location and climate the crops grown under different tillage and fertilizer placement practices as reported in the studies used in the meta-analysis

Reference	Country	Location	Number of comparisons	Crop	Climate	Conventional tillage vs.[*]	Fertilizer placement (cm)	Study duration (yr)
Abdalla *et al.* (2010)	Ireland	Carlow	6	barley	humid	RT	<5	<10
Almaraz *et al.* (2009a)	Canada	Quebec	2	maize	humid	NT	<5	<10
Almaraz *et al.* (2009b)	Canada	Quebec	2	soybean	humid	NT	na[†]	<10
Baggs *et al.* (2003)	UK	Wye	2	maize	humid	NT	<5	<10
Bhatia *et al.* (2010)	India	New Delhi	5	wheat	dry	NT	na	<10
Boeckx *et al.* (2011)	Belgium	Maulde	3	wheat/maize	humid	NT/RT	na	≥ 10
Chatskikh & Olesen, (2007)	Denmark	Foulum	2	barley	humid	NT/RT	na	<10
Chatskikh *et al.* (2008)	Denmark	Foulum	2	wheat	humid	NT/RT	na	<10
Chen *et al.* (2008)	China	Jiangsu	1	wheat	humid	RT	<5	<10
Drury *et al.* (2006)	Canada	Ontario	12	maize	humid	NT/RT	<5/ ≥ 5[‡]	<10
Drury *et al.* (2012)	Canada	Ontario	24	maize	humid	NT/RT	≥ 5	<10/ ≥ 10
Dusenberg *et al.* (2008)	USA	Montana	3	wheat	humid	NT	na	<10
Koga *et al.* (2004)	Mexico	Celaya	6	maize/wheat	dry	NT	<5	<10
Grageda-Cabrera *et al.* (2011)	Mexico	Celaya	4	wheat/maize	dry	NT	na	<10
Grandy *et al.* (2006)	USA	Michigan	7	maize/wheat	humid	NT	na	<10/ ≥ 10
Gregorich *et al.* (2008)	Canada	Ottawa	6	maize/soybean	humid	RT	<5	<10
Halverson *et al.* (2008)	USA	Colorado	4	maize	dry	NT	na	<10
Halverson *et al.* (2010)	USA	Colorado	6	maize	dry	NT	<5	<10
Heller *et al.* (2010)	Israel	Bet Dagan	6	maize	dry	NT	na	<10
Johnson *et al.* (2010)	USA	Minnesota	8	maize/soybean	humid	RT	<5	<10
Kessavalou *et al.* (1998)	USA	Nebraska	4	wheat	dry	NT/RT	na	≥ 10
Grageda-Cabrera *et al.* (2004)	Japan	Hokkaido	1	wheat	humid	RT	na	≥ 10
Lemke *et al.* (1999)	Canada	Alberta	12	wheat	dry	NT	<5	≥ 10
Regina & Alakukku, (2010)	Germany	Garte, Hohes	4	bean/wheat	humid	RT	<5	≥ 10
Malhi and Lemke, (2007)	Canada	Saskatchewan	8	barley /peas/wheat/ canola	humid	NT	<5	<10
Malhi *et al.* (2006)	Canada	Saskatchewan	8	wheat/canola	humid	NT	<5	<10
Parkin & Kaspar, (2006)	USA	Colorado	9	maize	dry	NT	≥ 5	<10
Omonode *et al.* (2011)	Denmark	Foulum	4	barley	humid	NT/RT	na	<10
Mutegi *et al.* (2010)	USA	Indiana	6	maize	humid	NT/RT	≥ 5	≥ 10
Mosier *et al.* (2006)	USA	Ames	4	maize	humid	NT	na	<10
Pelster *et al.* (2011)	Canada	Acadie	6	maize/soybean	humid	NT	≥ 5	≥ 10

Table 1 (continued)

Reference	Country	Location	Number of comparisons	Crop	Climate	Conventional tillage vs.*	Fertilizer placement (cm)	Study duration (yr)
Petersen *et al.* (2011)	Denmark	Foulum	2	radish	humid	NT/RT	≥ 5	<10
Ludwig *et al.* (2010)	Finland	southern (4 locations)	5	barley	humid	NT	<5	<10
Rochette *et al.* (2008)	Canada	Quebec	6	barley	humid	NT	<5	<10
Wang *et al.* (2011)	USA	Indiana	9	maize/soybean	humid	NT/RT	na	<10
Soon *et al.* (2011)	Canada	Saskatchewan, Alberta	14	canola/barley/ wheat	humid	NT	<5	<10
Ussiri *et al.* (2009)	USA	Ohio	2	maize	humid	NT	≥ 5	≥ 10
Venterea *et al.* (2005)	USA	Minnesota	6	maize	humid	NT/RT	<5/ ≥ 5‡	≥ 10
Venterea *et al.* (2011)	USA	Minnesota	12	maize	humid	NT	<5	≥ 10
Smith *et al.* (2011)	Australia	Queensland	4	wheat	humid	NT	≥ 5	≥ 10
Yao *et al.* (2010)	China	Jiangsu	2	wheat	humid	NT	<5	<10

*NT = no-till; RT = reduced till.

†Not available or not included because N placement practice cannot be clearly categorized.

‡Study included multiple tillage comparisons using different N placement treatments.

implementation (6%), whereas in dry climates the decline was only significant for short-term implementation (12%). For studies with deep fertilizer-N placement, NT/RT resulted in a yield decline of 10% compared to CT, while tillage had no significant effect on yield for studies with shallow N placement (Fig. 3b). In humid climates, the yield decline with NT/RT was limited to studies with deep N placement, whereas in dry climates, a significant yield decline with NT/RT was observed for both fertilizer placement categories.

Yield-scaled N_2O emissions

The pattern and magnitude of effects of NT/RT on yield-scaled N_2O emissions relative to CT were similar in most cases to their effects on area-scaled N_2O (Figs 1–3). Averaged across all comparisons, yield-scaled N_2O emissions with NT/RT were not different from CT (Fig. 1c). Under dry climate conditions, NT/RT caused a significant increase (35%) in yield-scaled N_2O emissions compared with CT (Fig. 1c). This effect was not significant for area-scaled emissions, but was magnified for yield-scaled emissions due to the significant yield decline observed in dry climates (Fig. 1b). The duration of NT/RT implementation had no effect on yield-scaled N_2O emissions in humid climates (Fig. 2c). However, short-term NT/RT in dry climates significantly increased yield-scaled N_2O emissions (57%) compared to CT (Fig. 2c). In contrast, long-term NT/RT in dry climates significantly decreased yield-scaled N_2O emissions (27%) compared to CT (Fig. 2c). For studies with deep fertilizer-N placement, NT/RT had significantly lower yield-scaled N_2O emissions compared with CT across all comparisons (18%), and in humid climates (20%; Fig. 3c).

Discussion

Area-scaled N_2O emissions

Our meta-analysis showed that, averaged across all comparisons, implementation of NT/RT had no significant effect on N_2O emissions (Fig. 1a). The absence of a significant effect may reflect that the different microbiological processes producing N_2O are often controlled by opposing physical and/or chemical factors. It is well established that N_2O is produced during denitrification, which requires anaerobic conditions in soil aggregates, as well as during nitrification which is a strictly aerobic process (Bremner, 1997; Firestone & Davidson, 1989). Moreover, when soil moisture conditions are sub-optimal for heterotrophic denitrification, a third source of soil N_2O emission is through the nitrifier denitrification process which can be a more significant

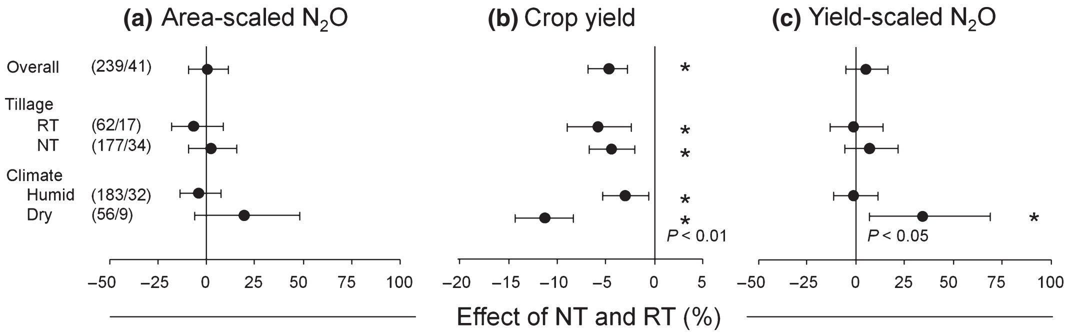

Fig. 1 Percent change in (a) area-scaled N_2O emissions, (b) crop yield, and (c) yield-scaled N_2O emissions in no-till (NT) and reduced tillage (RT) treatments compared with conventional tillage across all comparisons and for each climate regime. Numbers in parentheses indicate the number of comparisons, followed by the number of studies from which the comparisons were derived. Error bars are 95% confidence intervals (CI). Significant effects of NT/RT are denoted by * (where error bars do not overlap zero). *P*-values are for differences in effect sizes between categories.

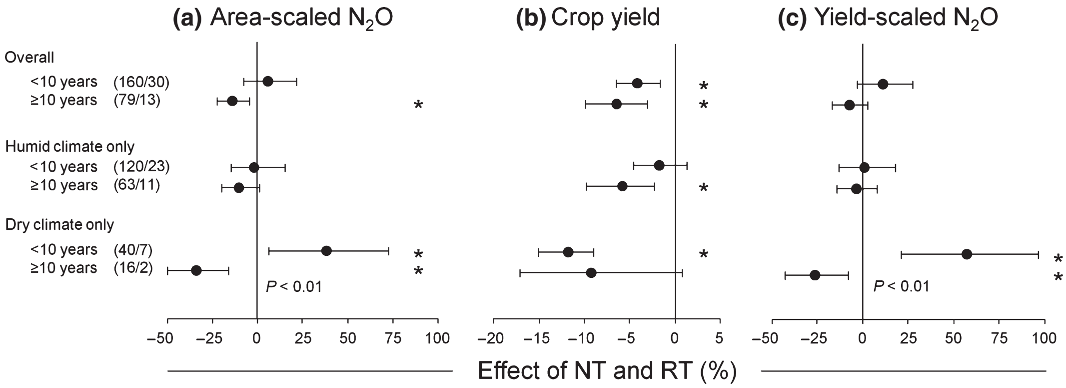

Fig. 2 Percent change in (a) area-scaled N_2O emissions, (b) crop yield, and (c) yield-scaled N_2O emissions in no-till (NT) and reduced tillage (RT) treatments compared with conventional tillage segregated by experiment duration and climate regime. Numbers in parentheses indicate the number of comparisons, followed by the number of studies from which the comparisons were derived. Error bars are 95% confidence intervals (CI). Significant effects of NT or RT are denoted by * (where error bars do not overlap zero). *P*-values are for differences in effect sizes between categories.

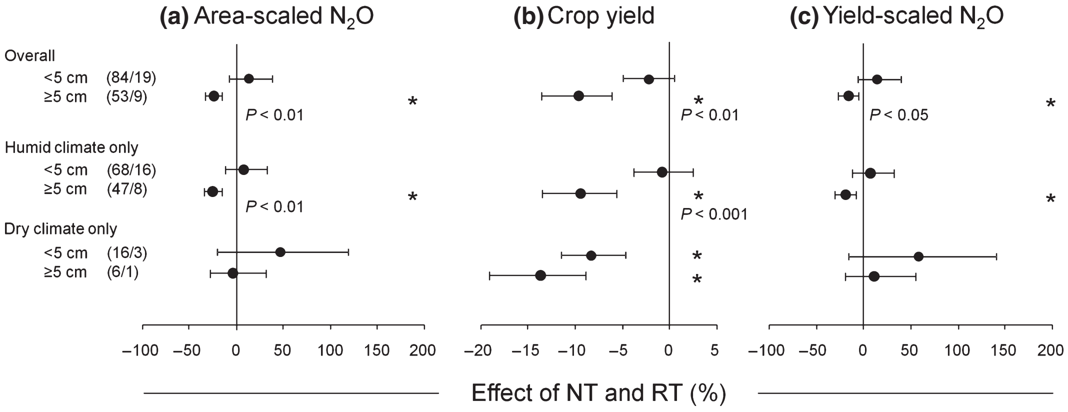

Fig. 3 Percent change in (a) area-scaled N_2O emissions, (b) crop yield, and (c) yield-scaled N_2O emissions in no-till (NT) and reduced tillage (RT) treatments compared with conventional tillage segregated by N fertilizer placement depth experiment and climate regime. Numbers in parentheses indicate the number of comparisons, followed by the number of studies from which the comparisons were derived. Error bars are 95% confidence intervals (CI). Significant effects of NT or RT are denoted by * (where error bars do not overlap zero). *P* values are for differences in effect sizes between categories.

contributor to total N_2O emissions than denitrification (Kool *et al.*, 2011). In addition to the oxygen status of the soil controlling the pathway of N_2O production, substrate (i.e., inorganic N and soluble C) availability and temperature are additional chemical and physical factors which can exert a major impact on the rate of N_2O production and the ratio of N_2O/N_2 produced (Eichner, 1990; Firestone & Davidson, 1989). Furthermore, species of crops grown have also been reported to control seasonal N_2O emissions (Kaiser *et al.*, 1998).

Although there was no significant overall effect of NT/RT on N_2O emissions, when separated by climatic regime and/or duration of implementation differences did emerge. Whereas in humid climates CT and NT/RT showed similar N_2O emissions, in dry climates area-scaled N_2O emissions following short-term NT/RT implementation increased significantly compared to CT whereas long-term implementation, resulted in a significant decrease (Fig. 2a). It is possible that in humid climates, the increase in soil moisture content often observed under NT/RT (Groffman, 1985; Palma *et al.*, 1997; Cox *et al.*, 1990) was insufficient to significantly increase denitrification-derived N_2O emissions whereas in dry climates, the increased soil moisture content and WFPS relative to CT was sufficient to enhance heterotrophic denitrification and/or nitrifier denitrification (Linn & Doran, 1984a). This explanation is consistent with results of Venterea *et al.* (2006) who found that both WFPS and soil respiration were greater in a NT than a CT soil in a growing season with 40% less rainfall than normal, although in a normally wet year, these variables did not differ between tillage systems. However, this does not explain why increased N_2O emissions in dry climates was found only with short-term NT/RT adoption, whereas with longer term adoption the reverse effect was found. Averaged across both climatic regimes, there was a significant decrease of 14% in N_2O emissions for long-term NT/RT implementation compared to CT (Fig. 2a). Six *et al.* (2004) reported an increase in N_2O emissions in the first 10 years of NT/RT, followed by a decrease in N_2O emissions, similar to the pattern observed here for dry climate comparisons (Fig. 2a).

There may be several reasons for the decrease in N_2O emissions in long-term NT/RT systems. Six *et al.* (2004) argued that following long-term adoption of NT/RT, increased soil organic matter content (West & Post, 2002; Mann, 1986; Ogle *et al.*, 2005) can improve soil structure and therefore decrease the tendency for the formation of anaerobic microsites conducive to N_2O production (Malhi *et al.*, 2006; Ussiri *et al.*, 2009). Thus, with longer term adoption these factors may have counteracted the WFPS effects described above.

The absence of a significant correlation between K_{sat} and treatment effects on N_2O fluxes is in contrast with earlier findings. Rochette (2008) concluded that, in general, NT leads to an increase in N_2O emissions in poorly aerated soils, e.g., clay soils, although not increasing N_2O emissions in soils with good to medium aeration, i.e., sand or loamy soils. There are a number of differences between the two studies which may have led to different conclusions. First, the available soil texture data were used in different ways. We combined sand, silt, and clay content to arrive at an integrated and continuous (i.e., non-categorical) indicator of soil texture/drainage characteristics and used regression analysis to evaluate relationships between this factor and N_2O emissions as influenced by tillage. Rochette (2008) on the other hand used soil drainage and precipitation information to distinguish three categories of studies: 'good', 'medium', and 'poor' soil aeration. Moreover, Rochette (2008) used a more conventional statistical approach to compare the ratio of mean N_2O emissions under NT and CT. Both these differences in methodology between studies could have caused contrasting conclusions.

Yield and N_2O

The decline in crop yield with NT/RT which was almost universal across sites is a potential cause for concern. The observed yield decline was most pronounced in dry climates: on average 11% less than that in CT systems. However, the data set (28 studies) used for the current meta-analysis was less comprehensive than previous analyses aimed at detecting tillage impacts on yield, because only studies that reported both N_2O emissions and yield were included here. However, previous meta-analyses have reported similar yield declines under NT/RT. Alvarez & Steinbach (2009) performed a meta-analysis of tillage studies (35) conducted in Argentina and observed a decline of cereal grain yields under NT/RT. Their analysis suggested that the yield decline could be overcome by increasing N fertilizer application rates, and thus the decline was caused by N deficiency. Van der Putten *et al.* (2010) conducted a meta-analysis (47 studies from Europe) assessing how soil tillage affected crop performance and reported an overall yield reduction under NT of 8.5%. More recently Ogle *et al.* (2012) conducted a meta-analysis (74 studies) on tillage and crop productivity and observed that productivity in the United States was reduced with NT/RT in cooler and/or wetter climates whereas yields increased in the drier climate zones. They reported that the lower yields of maize and spring wheat following adoption of NT were influenced by lower rates of N fertilization, suggesting again that there was N deficiency under NT/RT.

Six *et al.* (2004) also observed a tendency for yield decline in recently established RT systems and attributed it to N deficiency issues. Following establishment of RT management there is generally an increase in soil moisture content and WFPS (Blevins *et al.*, 1971; Cox *et al.*, 1990), which could result in increased denitrification-driven N_2 (and N_2O) losses, thereby reducing mineral N and contributing to plant N deficiency and yield decline (Vetsch & Randall, 2000). However, the increase in denitrification-derived gaseous N losses may be a temporary phenomenon (Six *et al.*, 2004), consistent with our meta-analysis results showing that after ≥ 10 years of NT/RT the N_2O emissions declined relative to CT (Fig. 2a).

However, with long-term NT/RT implementation yields remained low and did not recover to the yield observed under CT (Fig. 2b). In particular, the yield decline became pronounced in dry climates, with an average loss of 12% for short-term and 9% for long-term implementation of NT/RT. It is possible that in NT/RT systems, reduction of available N pools was sustained for ≥ 10 years after the adaption of NT/RT, or perhaps that disease pressures were more pronounced in drier climates due to greater crop water stress. Our results are in contrast with the findings of Ogle *et al.* (2012) who observed under NT a yield decline in areas of the United States with higher rainfall whereas a yield increase in the drier regions of the United States. Explanations as to what caused these contradictory results between these two meta-analyses are speculative. The data set used by Ogle *et al.* (2012) was limited to studies conducted in North America; our data set included yield studies from across the world and may have included more extreme climatic conditions. Moreover, our approach to separate the studies into dry and humid climatic environments differs from the approach used by Ogle *et al.* (2012), which was based on minimum and maximum temperature and precipitation, and 'annualized' for the steady-state equation.

As mentioned above, changes in disease pressure may be another cause for a yield decline under NT/RT. Fernandez *et al.* (2009) conducted a review of the impact of tillage systems in the Canadian prairies on cereal diseases caused by *Fusarium* spp. They concluded that the implementation of RT and its concurrent increase in the use of glyphosate were associated with an increase in the occurrence of *Fusarium* spp., even if the rotation included non-cereal crops. Although their review did not include a yield component, *Fusarium* pathogens are an important disease of cereal crops and can lead to severe reductions in yield (Parry *et al.*, 1995). Yield declines under NT/RT compared to CT systems may also be caused by slower plant development in early spring and delayed tasseling because of cooler spring soil temperatures in the NT/RT systems (Halvorson *et al.*, 2006; Iragavarapu & Randall, 1995). It has been suggested that if the spring temperatures are cool, pre-plant tillage operations may be needed to increase yield (Sims *et al.*, 1998). Cooler soil temperatures in NT systems where residues form a soil cover can reduce evaporation losses and thereby increase soil moisture content compared to CT systems (Sims *et al.*, 1998; Alvarez & Steinbach, 2009). If increased disease pressure and a delay in plant development under NT/RT are the main causes of the observed yield decline, it could lead to an increase in available soil N, which in turn, can lead to an increase in N_2O emissions.

Although changes in weed population and pressure have been reported following the adoption of NT/RT (Cirujeda *et al.*, 2011; Sosanoskie *et al.*, 2006), its impact on yield appears to be limited (Mas & Verdu, 2003).

Nitrogen fertilizer placement

Our results support the hypothesis that placement of fertilizer N (>5 cm depth) can be an effective strategy for mitigating N_2O emissions in NT/RT systems. Using a combination of soil measurements and process modeling, Venterea & Stanenas (2008) concluded that deep placement of N fertilizer could be an effective means to reduce N_2O emissions in NT systems. Similarly, Venterea *et al.* (2011) noted that several studies showing greater N_2O emissions in NT compared with CT soils used N fertilizer applied on or close to the surface (e.g., Venterea *et al.*, 2005; Baggs *et al.*, 2003; Ball *et al.*, 1999), whereas several studies showing lower N_2O emissions with NT used subsurface N application (e.g., Venterea *et al.*, 2005; Omonode *et al.*, 2011; Ussiri *et al.*, 2009; Jacinthe & Dick, 1997). This result is not surprising based on observations showing that both nitrification and denitrification potential tend to decrease rapidly with depth in NT soils, whereas microbial activity and concentrations of C substrates that support it, are more vertically uniform in CT soils (Groffman, 1985; Linn & Doran, 1984b; Venterea & Stanenas, 2008). Thus, deep N placement may simply decrease the supply of inorganic N substrates within the most biologically active zone where they can be converted to N_2O via nitrification and/or denitrification. Venterea *et al.* (2005) also hypothesized that higher water content and bulk density (and therefore greater WFPS) that are commonly observed in NT soil could provide more opportunity for reduction of N_2O to N_2 with deeper N placement (Linn & Doran, 1984a). These results imply a recommendation for deep N placement as a means of mitigating N_2O in NT/RT systems. However, one caveat that should be noted is that while injection of N fertilizer in concentrated bands (e.g., using anhydrous ammonia or granular urea) is often used for deep N placement, banding has also been shown to increase N_2O emissions compared to more uniformly applied fertilizer possibly due to NH_3 toxicity effects on nitrifying bacteria (e.g., Venterea *et al.*, 2010; Engel *et al.*, 2010; Fujinuma *et al.*, 2011). Although further studies on this topic are needed, deep placement of other chemical forms such as urea ammonium nitrate (UAN) are recommended for N_2O mitigation. Deep N placement can also help to reduce NH_3 volatilization losses and increase overall crop N use efficiency, and therefore this practice is expected to have multiple benefits (Mengel *et al.*, 1982).

Yield-scaled N_2O emissions

In our meta-analysis, the most profound effect of tillage on yield-scaled N_2O emissions was observed in dry climates (Fig. 1c). Higher yield-scaled N_2O emissions under dry climatic conditions were driven by a highly significant reduction in crop yield but without a concurrent reduction in area-scaled N_2O emissions. From this meta-analysis it can further be concluded that conversion to NT/RT in dry climates leads to an early increase in the yield-scaled N_2O emissions. However, when NT/RT has been practiced for ≥ 10 years, yield-scaled N_2O emissions are reduced significantly compared to CT systems (Fig. 2c).

The yield-scaled approach has been suggested as a more comprehensive index to assess N_2O emissions in agricultural systems (Mosier *et al.*, 2006; Van Groenigen *et al.*, 2010; Grassini & Cassman, 2012). Yield-scaled values reflect N_2O or GHG emissions per unit of product, i.e. ton of grain, rather than N_2O or GHG emissions per areal basis as it is commonly expressed. The justification for using a yield-scaled approach rather than the conventional areal approach is that if a certain tonnage of food is needed to feed the world population, management practices should focus on producing crops with the lowest N_2O emissions per ton. These management practices may lead to higher N_2O emissions per ha, and as the cropping system becomes more optimized, this would lower the yield-scaled emissions. As yield-scaled emissions take into account yield (and indirectly through crop yield the effect of soil type, climatic conditions, and management practices on N use), the yield-scaled approach can be considered a modified form of a Tier 2 approach in assessing N_2O emission from cropping systems. The emission of N_2O is not solely driven by the amount of N-fertilizer applied (Tier 1), but dependent on the overall performance of the cropping system; i.e., N uptake and crop yield related to N fertilizer applied.

By following the yield-scaled approach, deep placement of N fertilizer and long-term NT/RT practices in humid climates led to a significant decline in N_2O emission per ton of grain. This management practice should therefore be recommended.

Overall conclusions

It has been estimated that NT is practiced on 5% of the 1379 Mha of cultivated land globally (Lal *et al.*, 2004). In 2009, approximately 35.5% of US cropland was not tilled (Horowitz *et al.*, 2010). There has been a rapid adoption of the conversion of CT to NT/RT management practices. Our meta-analysis showed no overall change in area-scaled N_2O emissions when land was converted from CT to NT/RT. Likewise climate (dry or humid) had no significant impact on area-scaled N_2O emissions when NT/RT was implemented. Furthermore, we were not able to confirm a significant correlation between soil texture and NT/RT effects on N_2O emissions as reported earlier (Rochette, 2008). We observed, however, that when NT/RT management practices were implemented for ≥ 10 years, N_2O emissions reduced significantly, confirming earlier findings (Six *et al.*, 2004). As NT/RT practices with fertilizer placement at a depth ≥ 5 cm led to large reduction in N_2O emissions, in particular in a humid climate, this management practice should be promoted to reduce N_2O emissions in agriculture.

We found a highly significant reduction in yield for both humid and dry climates, and for both long- and short-term experiments. A particularly strong reduction of 12% in yield was observed for short-term NT/RT practices in dry climates. Since this meta-analysis was limited to studies reporting both yield and N_2O emissions, and also because our results related to yield differs in some respects from other recent analyses, additional investigation in this area is needed.

The reduction in yield due to NT/RT should be a concern, because its increasing acceptance by farmers could have an overall impact on world food production. The yield reduction is likely caused by a number of factors, such as an increase in fungal diseases and changes in biophysical properties of the soil like higher moisture leading to a delay in seeding and germination.

Overall, yield-scaled N_2O emissions did not change following the conversion from CT to NT/RT (Fig. 1c). In dry climates, the lower yield under NT/RT led to a significant increase in yield-scaled N_2O emissions, particularly for short-term NT/RT practices. The increase in yield-scaled N_2O emissions, however, was temporal in nature as a significant reduction in yield-scaled N_2O emissions manifested itself when the NT/RT was implemented for ≥ 10 years.

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