# Stimulation of N$_2$O emission by conservation tillage management in agricultural lands: A meta-analysis

Kun Mei[a,1], Zhenfeng Wang[a,1], Hong Huang[a], Chi Zhang[a], Xu Shang[a], Randy A. Dahlgren[a,b], Minghua Zhang[a,b], Fang Xia[a,*]

[a] *Southern Zhejiang Water Research Institute, Key Laboratory of Watershed Environmental Science and Health of Zhejiang Province, Wenzhou Medical University, Wenzhou 325035, China*
[b] *Department of Land, Air, and Water Resources, University of California, Davis, CA, 95616, United States*

ABSTRACT

Conservation tillage has been widely adopted in agricultural lands worldwide and is considered a potential strategy for climate change mitigation through enhanced carbon sequestration. However, conservation tillage may alter soil N$_2$O emissions, which may diminish the potential climate change mitigation benefits. Based on 212 observations from 40 publications, a meta-analysis was conducted to quantitatively assess the effects of climate regimes, initial soil properties, and type/duration of agricultural practices on soil N$_2$O emission following application of conservation tillage. Overall, conservation tillage significantly increased soil N$_2$O emission by 17.8% compared to conventional tillage. The greatest increase in N$_2$O emission was observed from soils in tropical climates (70.1%) experiencing short-term (29.3%) application of conservation tillage. Soil pH and clay content significantly influenced N$_2$O emission, while overall soil texture and soil organic carbon (SOC) were not effective predictors of soil N$_2$O emission following conservation tillage. According to the categorical meta-analysis, agricultural practices, including water, residue, and rotation managements and crop types, significantly affected soil N$_2$O emission following conservation tillage. Conservation tillage induced N$_2$O emissions were mitigated with rain-fed cropping systems, residue removal, crop rotation and cultivation of beans and some vegetables. Significant categorical variables affecting N$_2$O emission were mainly attributed to soil aeration and substrate availability, which were important factors affecting nitrification and denitrification processes. Overall, the conservation tillage induced N$_2$O emission factor ($EF_{ad}$) increased by 0.40%, suggesting an attenuation of climate change benefits from increased N$_2$O emission. Our meta-analysis provides a scientific basis for assessing the effects of conservation tillage on N$_2$O emissions and provides site-specific information to mitigate N$_2$O emissions associated with conservation tillage practices.

## 1. Introduction

Global warming attributed to the anthropogenic emissions of greenhouse gases (GHG) has increased the global temperature by ~0.89 °C in the 20th century (IPCC, 2013). Approximately 13% of total GHG emissions were contributed from agricultural lands and N$_2$O emission from agriculture accounted for 61% of total anthropogenic N$_2$O emissions (Montzka et al., 2011). The large N$_2$O emissions from agricultural lands are of particular concern given both its high global warming potential (GWP-N$_2$O = 298) relative to CH$_4$ (21) and CO$_2$ (1) and its contribution to stratospheric ozone depletion (Li et al., 2014; Hou et al., 2016).

Conservation tillage, including no-tillage and reduced tillage

management, is increasingly being adopted on agricultural lands worldwide. About 10% of global arable lands, *i.e.* ~125 million hectares, are currently managed using conservation tillage (Friedrich et al., 2012). The adoption of conservation tillage has demonstrated important benefits for soil carbon sequestration in topsoil, soil erosion, soil quality and crop yields (Seta et al., 1993; Baker et al., 2007; Das et al., 2014; Powlson et al., 2014; Pittelkow et al., 2015). However, there is considerable debate concerning the effects of conservation tillage on climate change mitigation due to the highly variable effects of conservation tillage on N$_2$O emissions. Various studies found increase (Lognoul et al., 2017), decrease (Mutegi et al., 2010), and no differences (Guardia et al., 2016) in N$_2$O emissions resulting from adoption of conservation tillage practices. These inconsistent effects may be

associated with the duration of conservation tillage practices with short-term application (< 10 years) reported to stimulate $N_2O$ emission while long-term application (> 10 year) decreases $N_2O$ emission (Six et al., 2010). Additionally, climate regimes and various soil properties are reported to have a strong effect on soil $N_2O$ emission.

Soil $N_2O$ emission primarily results from nitrification and denitrification processes in soil. Under relatively aerobic conditions, $NH_4^+$ is converted to $NO_3^-$ (nitrification) along with $N_2O$ emission by autotrophic nitrifiers, In contrast, under anaerobic conditions, heterotrophic denitrifiers convert $NO_3^-$ to $N_2O$ and $N_2$ (denitrification) (Khalil et al., 2004). Soil aeration status (e.g., $O_2$ availability) is a dominant factor controlling nitrification and denitrification processes and their potential $N_2O$ production. In addition, soil physical and chemical properties, such as soil texture, pH, organic content, clay content, etc., play significant roles in $N_2O$ emission dynamics. For instance, fine-textured soils often have higher $N_2O$ emissions than coarse-textured soils due to slower $O_2$ diffusion rates leading to lower soil $O_2$ concentrations that favor denitrification (Pelster et al., 2012). However, other studies have shown lower $N_2O$ emission from fine-textured soils as low gas diffusivity allowed greater time for more complete reduction of $N_2O$ to $N_2$ (Weitz et al., 2001). Higher microbially-labile organic matter contents also favor enhanced denitrification by providing substrate for heterotrophic denitrifier growth, which leads to more rapid $O_2$ consumption (Hill and Cardaci, 2004). High $N_2O$ emission may also be favored in alkaline soils due to more suitable growth conditions for both nitrifiers and denitrifiers (Bárta et al., 2010; Tierling and Kuhlmann, 2018). Furthermore, agricultural practices, such as N fertilization, crop species, crop rotation and water management may have strong influences on $N_2O$ emission (Kudo et al., 2014; Trost et al., 2016). Numerous studies have investigated the impacts of soil properties and agricultural practices on soil $N_2O$ emissions in conservation tillage systems and found diverse and contradictory results that hinder the overall assessment of conservation tillage impacts on climate change mitigation. Previous meta-analyses have also examined various aspects of $N_2O$ emissions from conservation tillage. Van Kessel et al. (2013) investigated changes in $N_2O$ emission in response to different categorical conservation tillage practices and found strong influences from the duration of conservation practices and climate regimes. Their metaanalysis focused on the magnitude of $N_2O$ emission under contrasting conservation tillage regimes, but did not consider specific soil properties (pH, texture and organic content) and widely-used agricultural practices (rotation, water and residue management). Zhao et al. (2016) analyzed the relationship between specific-conditions and greenhouse gas emissions in no-till farming systems using meta-regression based on a regional database in China, but this analysis was limited in scale.

A detailed assessment of the influence of conservation tillage practices on soil $N_2O$ emission is critical to determine the potential for conservation tillage practices to mitigate climate change. This study aimed to assess the effects of conservation tillage on soil $N_2O$ emission relative to conventional tillage by conducting a meta-analysis of peerreviewed field studies. Specifically, we attempt to address the following questions: i) How do climate regime and experimental duration affect soil $N_2O$ emissions following application of conservation tillage practices? ii) Do initial soil properties affect the response of $N_2O$ emission to conservation tillage practices? and iii) Can agricultural practices mitigate $N_2O$ emission associated with conservation tillage? This comprehensive meta-analysis is significant for developing strategies for the future expansion of conservation tillage and for enhancing agricultural practices to mitigate greenhouse gas emission from agricultural lands.

## 2. Materials and methods

### 2.1. Data collection

A comprehensive literature review was carried out in Web of Science to identify peer-reviewed articles with $N_2O$ emissions

comparisons for conservation tillage with conventional tillage in sideby-side paired field trials. Conservation tillage in this meta-analysis included no-tillage and reduced tillage practices, such as chisel tillage and shallow/lower depth tillage. The keywords 'tillage', 'nitrous oxide', '$N_2O$', and 'greenhouse gas' were used as search terms. Specific criteria considered in selecting paired trials were: i) studies conducted in the field; ii) studies reported cumulative soil $N_2O$ emissions (kg $N_2O$-N $ha^{-1}$) for at least one entire crop season duration for both conservation and conventional tillage treatments; iii) studies reported the mean and number of field replicates; and iv) studies for which N input rate was reported or could be accurately calculated. The data in most studies were reported in tables and extracted directly. For data presented in figures, 'GetData Graph Digitizer' software was used to extract data (Version 2.26: http://www.getdata-graph-digitizer.cm/download). According to the criteria listed above, a total of 212 comparisons from 40 field studies were available for the meta-analysis.

For each study, the cumulative emission of $N_2O$ (kg $N_2O$-N $ha^{-1}$), number of replicates and standard deviations (SD) for both conservation and conventional treatments were extracted directly. Unit conversion was performed as necessary, such as global warming potential (GWP of 298 for $N_2O$) and the $N_2O$ emission was reported as kg $N_2O$ $ha^{-1}$. The SD was computed when only the standard error (SE) was reported:

$$SD = SE \times \sqrt{n}$$

where $n$ is the number of replicates. The SD value was assigned as 20% and 21% for conservation and conventional tillage, respectively, in studies where SD/SE was absent, as these values were the relative averages of the reported SD values for $N_2O$ emission in our dataset (Skinner et al., 2014).

In addition to $N_2O$ emission data, other related information for each study was also included in the dataset: location (longitude and latitude), climate (annual precipitation and temperature), experimental duration, crop species, soil properties (*e.g.*, texture, pH, clay content, SOC), and agricultural practices (crop rotation, residue management, water management and N fertilization rate). For studies not reporting the climate information, we estimated the missing data from Wikipedia in accordance with site locations.

### 2.2. Data analysis

We conducted a random-effects meta-analysis to assess $N_2O$ emission under conservation tillage versus conventional tillage. The natural log of the response ratio ($lnR$) was calculated in each paired trial to compare the effect size of $N_2O$ emission between conservation and conventional tillage.

$$lnR = ln\left(\frac{X_t}{X_c}\right) = ln(X_t) - ln(X_c)$$

where $X_t$ is the mean value of $N_2O$ emission with conservation tillage and $X_c$ is the mean value of $N_2O$ emission in conventional tillage as control.

The variance of $lnR$ (V) for each study was estimated:

$$V = \left(\frac{SD_t^2}{n_t X_t^2}\right) + \left(\frac{SD_c^2}{n_c X_c^2}\right)$$

where $SD_t$ and $SD_c$ are the standard deviations of all comparisons in the conservation and conventional tillage groups; and $n_t$ and $n_c$ are the number of replicates for the treatment and control groups, respectively.

The meta-analysis was conducted using a nonparametric weighting function, and the mean weighted effect size was calculated as:

$$\overline{lnR} = \frac{\sum (lnR_i \times \omega_i)}{\sum \omega_i}$$

where $lnR_i$ was the effect size of $N_2O$ emission in the *i*th comparison,

**Table 1**
Categorical variables, number of observations for NT/RT and CT amendments (n), various levels in each categorical variable (L), between-group heterogeneity (Q_B) in the random-categorical meta-analysis.

| | Variable | n | L1 | L2 | L3 | L4 | L5 | Q_B |
|---|---|---|---|---|---|---|---|---|
| Experimental conditions | Climate Zone | 212 | Warm temperate | Cool temperate | Tropical | | | 26.3* |
| | Duration (year) | 212 | ≤3 | 3-10 | >10 | | | 8.1* |
| Soil properties | pH | 179 | ≤6.5 | 6.5-7.3 | >7.3 | | | 9.8* |
| | SOC (g kg$^{-1}$) | 171 | ≤15 | 15-30 | >30 | | | 3.4 |
| | Soil texture | 164 | Coarse | Medium | Fine | | | 4.4 |
| | Clay content (%) | 91 | ≤20 | >20 | | | | 13.3* |
| Agricultural practice | N application rate (kg ha$^{-1}$) | 212 | ≤150 | 150-250 | ≥250 | | | 13.3* |
| | Crop type | 200 | Wheat | Rice | Maize | Bean | Others | 17.4* |
| | Rotation | 212 | Rotation | No rotation | | | | 5.1* |
| | Residue management | 205 | Residue retained | Residue moved | | | | 20.6* |
| | Water management | 164 | Irrigated | Rain-fed | | | | 9.5* |
| | Tillage management | 212 | Reduced tillage | No-tillage | | | | 0.5 |

Note:
* Represents significance level of 0.05.

and $\omega_i$ was the weight calculated as:

$$\omega = \frac{1}{V}$$

where V is the variance of ln$R$ as stated above.

This meta-analysis was specifically designed to explore the influence of soil properties, climate regimes and agricultural practices on N$_2$O emission in conservation tillage systems. Thus, the variables were separated into different categories consisting of 3 groups that included 12 categorical variables selected to determine the effect size of N$_2$O emission under conservation tillage relative to conventional tillage. Each variable was separated into several levels. For example, according to the climate zone classification of IPCC, climate regimes were divided into warm temperate, cool temperate and tropical (Maillard & Angers, 2014); N application rate was grouped into ≤150, 150–250 and ≥250 kg ha$^{-1}$; and residue management into residue retained or residue moved. Detailed information for different levels in each categorical variable is provided in Table 1. A categorical randomized-effects meta-analysis model was developed to compare the categorical mean effect size and determine any significant differences among categorical groups. Total heterogeneity (Q$_T$) for each variable was partitioned into two parts, within-group heterogeneity (Q$_W$) and between-group heterogeneity (Q$_B$) using chi-square distributions. Correspondingly, conservation tillage has a significant effect when different categories within each variable have a significant Q$_B$.

We calculated overall mean effect size and generated 95% bootstrapped confidence intervals (CIs, 4999 interactions) in METAWIN 2.1 software (Rosenberg et al., 2000). The effect size was considered significant if the 95% CI did not overlap with the zero value. To improve explanatory power, the mean effect size was transformed back to the percentage change of N$_2$O emission for conservation tillage relative to conventional tillage and was computed as $((e^{\overline{\ln R}}-1) \times 100\%)$.

Here we defined an additional N$_2$O emission factor ($EF_{ad}$), which is the conservation tillage-induced change in N$_2$O emission compared to conventional tillage when N fertilizer is applied. The conservation tillage-induced $EF_{ad}$ was calculated as:

$$EF_{ad}(\%) = (X_t - X_c)/N \times 100$$

where $N$ is the N application rate (kg N ha$^{-1}$).

## 3. Results

### 3.1. Effect of conservation tillage versus conventional tillage on soil N$_2$O emissions

The continuous randomized-effects model identified significant relationships between effect sizes of N$_2$O emissions under conservation tillage versus precipitation and N fertilizer application rate (Table 2).

**Table 2**
Relationships between the effect size of soil N$_2$O emission under conservation tillage relative to conventional tillage for climate conditions (precipitation and temperature), soil properties (pH, SOC, TN, clay, bulk density) and N application rate. A continuous random-effects model was used to calculate statistical results, including total heterogeneity among studies (Q$_T$), the heterogeneity explained by regression model (Q$_M$), and residual error heterogeneity (Q$_E$). Significant relationships were identified as $p$ value < 0.05.

| Variable | Q$_T$ | Q$_M$ | Q$_E$ | Slope | $p$ | n |
|---|---|---|---|---|---|---|
| Precipitation | 263.9 | 4.0 | 259.9 | −0.0002 | 0.046* | 212 |
| Temperature | 250.5 | 2.9 | 247.6 | 0.0107 | 0.086 | 212 |
| pH | 257.1 | 0.2 | 256.9 | −0.0136 | 0.663 | 178 |
| SOC | 255.8 | 0.2 | 255.6 | 0.0013 | 0.618 | 170 |
| TN | 196.8 | 2.0 | 194.8 | −0.0315 | 0.158 | 147 |
| Clay | 136.9 | 0.2 | 136.7 | −0.0013 | 0.640 | 90 |
| Bulk Density | 182.3 | 0.7 | 181.6 | −0.2549 | 0.270 | 107 |
| N application rate | 278.5 | 5.5 | 273.0 | 0.0008 | 0.019* | 211 |

Effect size was negatively correlated with precipitation and positively correlated with N application rate. The effect size was not correlated with temperature, soil pH, SOC, TN, clay content or bulk density. The significant correlation with precipitation ($p = 0.046$) and near significant level with temperature ($p = 0.086$) demonstrate the site-specific conditions associated with climate in affecting N$_2$O emission in conservation tillage systems.

Overall, the mean effect size of soil N$_2$O emission for conservation tillage versus conventional tillage was 17.8% (95% CI: 9.6–27.3%). Conservation tillage was mainly divided into two categories, no-tillage and reduced tillage. No-tillage showed a significant increase in soil N$_2$O emission as compared to conventional tillage (average: 19.2%, 95% CI: 9.3–29.8%), while no significant effect was observed in the reduced tillage systems (average: 12.3%, 95% CI: −0.5–31.7%) (Fig. 1a). However, the categorical randomized-effects model showed no significant differences in soil N$_2$O emissions for the two conservation tillage systems compared to conventional tillage ($p = 0.552$). In contrast, the categorical randomized-effects model showed a significant difference between climate regimes ($p < 0.001$, Fig. 1b). Soil N$_2$O emissions were significantly higher in the tropical climate (average: 74.1%, 95% CI: 34.8–119.9%) and warm temperate climate (average: 17.0%, 95% CI: 6.5–29.2%). In contrast, there was no significant difference for soil N$_2$O emissions between conservation tillage and conventional tillage (average: -1.7%, 95% CI: -10.5–8.4%) in the cool temperate climate.

The effect size of conservation tillage on N$_2$O emission was also dependent on the duration of the field trial as indicated by the significant differences among various levels of experimental duration (Fig. 2a). Compared to conventional tillage, the incremental increase in soil N$_2$O emissions from application of conservation tillage generally
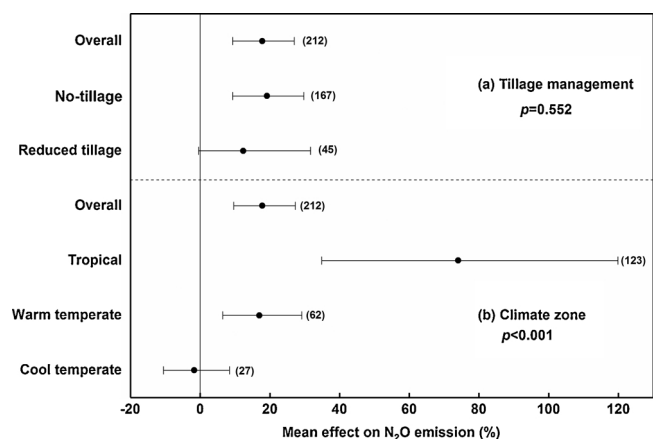
**Fig. 1.** Effect of tillage management (a) and climate regime (b) on soil $N_2O$ emission following application of conservation tillage management (mean ± 95% confidence interval; number of observations in parentheses). A significant effect was observed when there was no overlap with the zero value; significant difference was identified between various levels with a *p* value < 0.05.
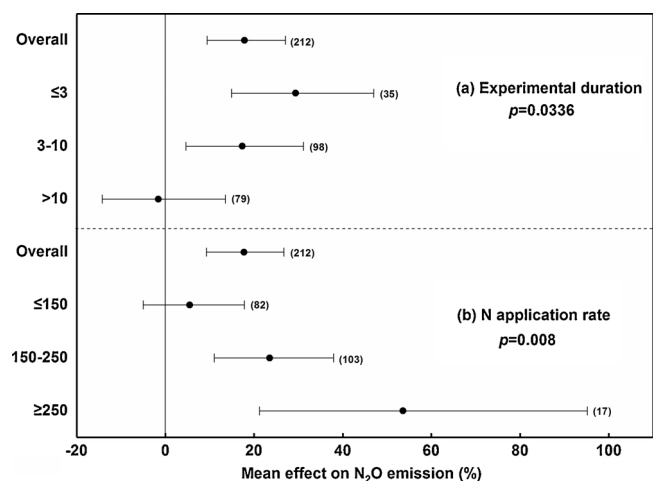


**Fig. 2.** Effect of conservation tillage duration (a) and N application rate effect (b) on soil $N_2O$ emission following application of conservation tillage management (mean ± 95% confidence interval; number of observations in parentheses). A significant effect was observed when there was no overlap with the zero value; significant difference was identified between various levels with a *p* value < 0.05.

decreased with increasing experimental duration. Notably, significantly elevated $N_2O$ emissions were indicated for studies with short (≤3 yrs, average: 29.3%, 95% CI: 14.9–47.0%) and medium term duration (3–10 yrs: average: 17.3%, 95% CI: 4.6–31.1%). There was no significant difference in $N_2O$ emissions for long-term (> 10 yrs) application of conservation tillage (average: 1.6%, 95% CI: -14.3–13.5%). Additionally, the $N_2O$ emission effect size showed a significant increase with increasing N application rates (*p* = 0.008, Fig. 2b). While no significant change in soil $N_2O$ emission was observed at application rates ≤150 kg ha$^{-1}$ (average: 5.5%, 95% CI: -5.0–17.8%), significant increases were identified for N application rates of 150–250 (average: 23.5%, 95% CI: 11.0–37.9%) and ≥250 kg ha$^{-1}$ (average: 53.6%, 95% CI: 21.22–95.15%).

Soil properties played an important role in soil $N_2O$ emissions (Fig. 3). Though non-significant (*p* = 0.337), there were some apparent characteristic trends in the mean effect size within SOC categories. In general, the average stimulation of conservation tillage-induced soil $N_2O$ emission increased with increasing SOC (Fig. 3a). On average, conservation tillage significantly increased soil $N_2O$ emissions by 12.0% (95% CI: 1.3–24.5%) in the SOC range of 15-30 g kg$^{-1}$ and by 22.0%
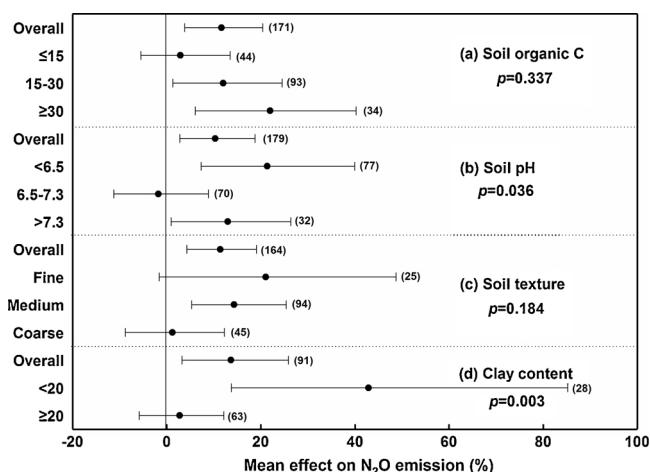


**Fig. 3.** Effect of soil organic C (a), pH (b) and texture (c) on soil $N_2O$ emission following application of conservation tillage management (mean ± 95% confidence interval; number of observations in parentheses). A significant effect was observed when there was no overlap with the zero value; significant difference was identified between various levels with a *p* value < 0.05.

(95% CI: 6.1–40.3%) when SOC exceeded 30 g kg$^{-1}$. Soil pH significantly affected soil $N_2O$ emissions after adoption of conservation tillage compared to conventional tillage (*p* = 0.036, Fig. 3b). Conservation tillage significantly increased soil $N_2O$ emissions by an average of 21.3% (95% CI: 7.3–39.9%) in acidic soils and 13.0% (95% CI: 0.9–26.4 %) in alkaline soils. However, there was no significant change in soil $N_2O$ emissions at neutral soil pH levels (average: -1.8%, 95% CI: -11.3–8.8%). Soil texture significantly affected soil $N_2O$ emissions for conservation tillage versus conventional tillage in medium-textured soils (average: 14.3%, 95% CI: 5.3–25.4%), but not in fine-textured (average: 21.1%, 95% CI: -1.6–48.7%) or coarse-textured (average: 1.23%, 95% CI: -8.76-12.22%) soils (Fig. 3c). Clay content showed a significant effect on soil $N_2O$ emissions (*p* = 0.003, Fig. 3d) at clay contents < 20% resulting in a 42.9% stimulation in soil $N_2O$ emissions (95% CI: 13.7–85.2%), while no effect was evident when clay content exceeded 20% (average: 2.7%, 95% CI: -7.0–13.5%).

Agricultural practices within conservation tillage systems further altered soil $N_2O$ emissions (Fig. 4). There was a significant but highly variable response of $N_2O$ emissions between different water management practices (*p* = 0.003, Fig. 4a). Soil $N_2O$ emissions under rain-fed
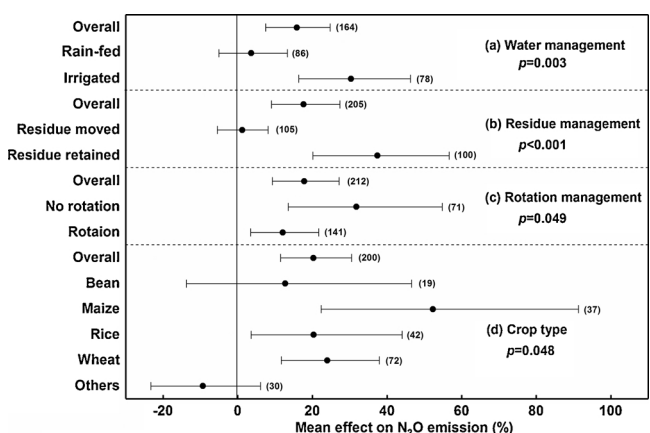


**Fig. 4.** Effect of water management (a), residue management (b), rotation management (c) and crop type (d) on soil $N_2O$ emission following application of conservation tillage management (mean ± 95% confidence interval; number of observations in parentheses). A significant effect was observed when there was no overlap with the zero value; significant difference was identified between various levels with a *p* value < 0.05.

systems were enhanced by 3.6% (95% CI: -5.1–13.3%) by conservation tillage relative to conventional tillage and by 30.4% (95% CI: 16.3–46.3%) under irrigation water management. Similarly, residue management significantly affected soil $N_2O$ emissions in conservation tillage ($p < 0.001$, Fig. 4b). Conservation tillage induced soil $N_2O$ emission increased by 31.8% (95% CI: 13.5–54.8%) for non-rotation systems compared to a 12.1% (95% CI: 3.5–21.7%) increase for crop rotation systems (Fig. 4c). Conservation tillage induced soil $N_2O$ emission varied significantly among various cropping systems when compared to conventional tillage ($p = 0.048$, Fig. 4d). Three of five investigated crop species were identified to promote soil $N_2O$ emissions in conservation versus conventional tillage systems. The highest stimulation of $N_2O$ emission was associated with maize (average: 52.3%, 95% CI: 22.3–91.1%), followed by wheat (average: 20.4%, 95% CI: 11.7–37.9%) and rice (average: 20.3%, 95% CI: 3.6–44.1%). In contrast, no significant differences were recorded for beans and other cropping system (*e.g.*, vegetables).

### 3.2. Additional soil $N_2O$ emission factors

Overall, the average conservation tillage-induced $N_2O$ emission factors ($EF_{ad}$) (additional $N_2O$ contributed by conservation tillage relative to conventional tillage as control) was 0.40% (Fig. 5). There was no significant difference in $EF_{ad}$ between no-tillage (1.32%) and reduced tillage (0.23%) systems ($p = 0.400$, Fig. 5a). The conservation tillage-induced $EF_{ad}$ showed significant differences among climate zones with average $EF_{ad}$ in tropical climates (1.54%) being significantly higher than in warm (0.15%) and cool temperate (0.08%) climates. No significant differences were observed as a function of soil texture (medium = 0.24%, fine = 0.18%, coarse = 0.06%) or for rotation (0.34%) versus no rotation (0.23%) management. Retention of crop residues was associated with higher $EF_{ad}$ (0.51%) than residue removal (0.11%). Additionally, the $EF_{ad}$ following application of conservation tillage showed a higher $EF_{ad}$ in irrigated (0.55%) versus rain-fed (0.18%) agricultural systems. Regardless of conservation tillage category, the $EF_{ad}$ showed a significant negative correlation with duration of the applied conservation practice when residue was moved (Fig. 6a),
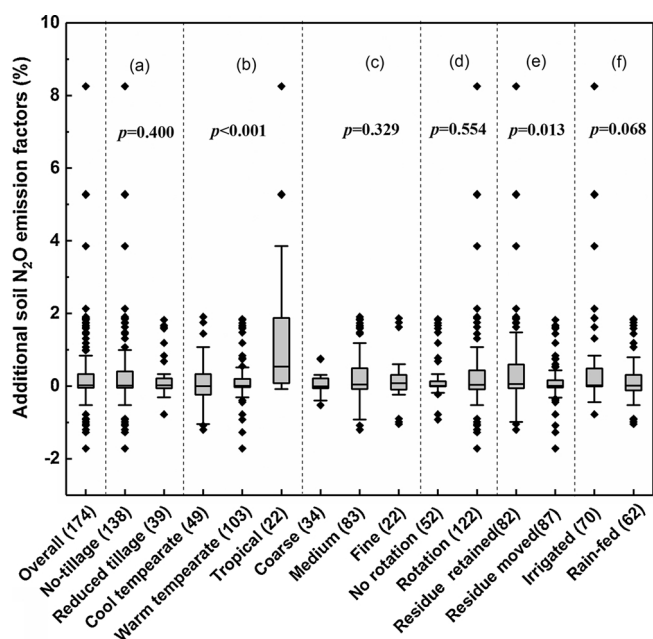
which indicates a diminishing influence of conservation tillage on soil $N_2O$ emission with increasing time. The decreased $N_2O$ emissions with duration of conservation tillage was more pronounced for reduced tillage systems than for no-tillage systems, which was consistent with the $EF_{ad}$ value. According to the relationship, the effect of no-tillage and reduced tillage practices on enhancing the $EF_{ad}$ would dissipate after 7 and 17 years, respectively. The regulating influence of soil property was enhanced when residue was retained, especially with respect to soil texture (Fig. 6b). A strong positive correlation was observed between $EF_{ad}$ and silt content in no-tillage systems ($n = 26$, $R^2 = 0.156$, $p = 0.046$). According to the identified relationships among these variables, at silt contents greater than 22.3%, no-tillage systems would have a positive $EF_{ad}$ compared to conventional tillage and vice versa. A positive correlation was also detected between $EF_{ad}$ and soil clay content in reduced tillage systems. When soil clay content reached 15.8%, reduced tillage management resulted in a positive $EF_{ad}$ relative to conventional tillage and vice versa.

## 4. Discussion

Conservation tillage is promoted as an effective method for carbon sequestration and thus a possible mitigation strategy for climate change (Lal, 2004). However, considerable controversy exists concerning how conservation tillage affects soil $N_2O$ emissions, which may offset potential carbon-related climate change mitigation benefits (Antle and Ogle, 2012). $N_2O$ emissions are primarily controlled by the microbiological processes of nitrification and denitrification. Whereas the heterotrophic denitrification process occurs under anaerobic conditions, nitrification is an aerobic process (Stevens et al., 1997). Therefore, the integrated effects of soil physical, chemical and biological factors, such as soil aeration, pH, temperature, moisture, texture and substrate availability, function together to affect soil $N_2O$ emission dynamics. Furthermore, agricultural practices, such as irrigation, fertilization and cropping systems, play important direct/indirect roles in soil $N_2O$ emissions. Given the wide range of integrative factors affecting $N_2O$ emissions, a comprehensive meta-analysis can provide a powerful approach for gaining important insights into the importance of specific factors regulating $N_2O$ emission across a wide range of spatial and temporal scales.

### 4.1. Effects of conservation tillage on soil $N_2O$ emission

Overall, the implementation of conservation tillage significantly affected soil $N_2O$ emission in this meta-analysis (Fig. 2); however, non-significant differences were observed for different conservation tillage practices. These results are consistent with an analysis by Van Kessel et al. (2013). Meta-regression results indicated some detailed information concerning differences in no-tillage versus reduced tillage practices on soil $N_2O$ emission. At the initiation of conservation tillage, soil compaction can moderate soil aeration and stimulate $N_2O$ emission through denitrification. However, substrate limitation (due to the removal of residue) suppressed this initial stimulation leading to decreased $N_2O$ emission over time (Rochette et al., 2008). With retention of residues, sufficient substrate (especially labile organic C forms) is available to support the $N_2O$-producing heterotrophic microbial community. With sufficient substrate availability, soil aeration becomes a dominant factor regulating $N_2O$ emission in conservation tillage systems. As shown in Fig. 6b, $N_2O$ emission rate was regulated by the interactions of conservation tillage and soil texture. $N_2O$ emission in both conservation tillage practices displayed a significant positive correlation in the fine particle size classes (silt and clay), which was consistent with the higher $N_2O$ emissions in fine-textured soils observed by Choudhary et al. (2002). Conservation tillage may improve bulk density and water holding capacity, especially in the fine-textured soils which are prone to generate anaerobic microsite hotspots for $N_2O$ production in otherwise aerobic soils (Bouwman et al., 2002; Rochette,

**Fig. 5.** Boxplots of additional soil $N_2O$ emission factors ($EF_{ad}$, %) for conservation tillage application for different categories of conservation tillage (a), climate regime (b), soil texture (c), rotation management (d), residue management (e), and water management (f). Significant differences were recorded at $p < 0.05$.
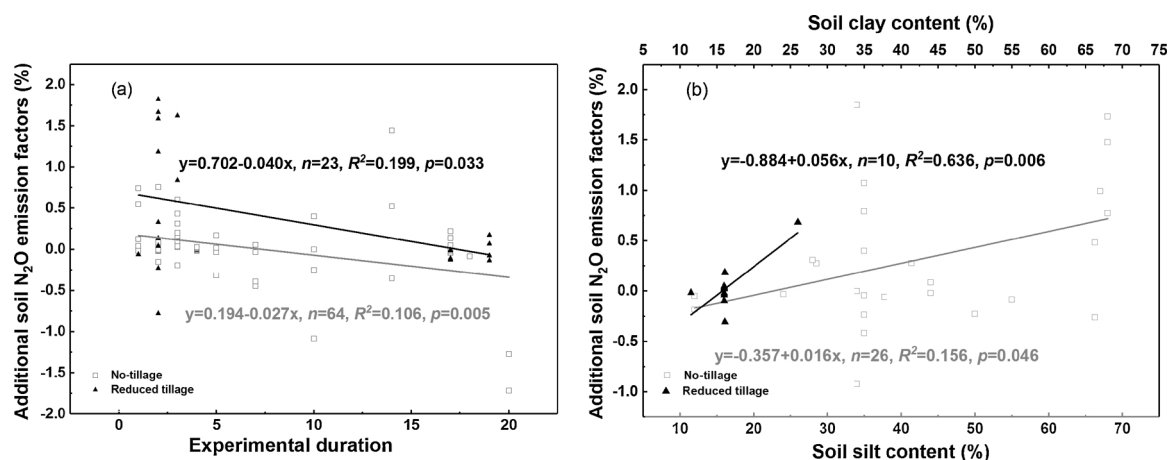
**Fig. 6.** Relationship between $EF_{ad}$ and experimental duration (a, residue moved), soil prosperities (b, residue retained) under different conservation tillage categories compared to conventional tillage. A significant relationship was identified for $p < 0.05$.

2008).

### 4.2. Climate and duration effect on $N_2O$ emission

Significant differences were recorded in conservation tillage induced soil $N_2O$ emissions among climate regimes. Temperature and precipitation are the primary factors regulating $N_2O$ emission across climate regimes. A significant negative correlation was recorded between effect size and precipitation (Table 2), consistent with the findings of Van Kessel et al. (2013) who reported a larger mean effect size in dry climates than humid climates upon implementation of reduced tillage. Increasing amounts of precipitation lead to higher soil moisture and lower soil oxygen concentrations, which strongly regulate nitrification and denitrification dynamics. Higher water-fill pore space (WFPS) was observed in no-tillage systems compared to conventional tillage during the dry season, but no difference was observed during the normal wet portion of the year (Venterea et al., 2006). WFPS differences were more pronounced between tillage practices under lower precipitation scenarios, which resulted from increased denitrification-induced $N_2O$ emission in conservation tillage relative to conventional tillage. In addition, the $N_2O$ emission effect size showed a weak positive correlation ($p = 0.086$) with temperature (Table 2), which was further supported by the higher increase of $N_2O$ emissions in tropical and warm temperate climate regimes (Fig. 1b). These findings are similar to those found by Zhao et al. (2016). Nitrification is favored at optimal soil temperature and moisture conditions of 25–40 °C and WFPS of 30–70%, respectively. Within the optimal conditions, nitrifier activities are enhanced with increasing soil temperature leading to the potential for increased soil $N_2O$ emissions (Hu et al., 2013). However, contradictory results have shown higher $N_2O$ emissions from soils in conventional tillage versus no-tillage with increasing temperature (Tu and Li, 2017).

Conservation tillage-induced $N_2O$ emissions were affected by experimental duration. Short- to medium-term implementation of conservation tillage significantly increased soil $N_2O$ emission, especially in the first 3 years following the initiation of conservation tillage. However, a negative mean effect size was measured for studies with long-term experimental duration ($> 10$ years). Similar changes in $N_2O$ emissions with duration of conservation tillage were reported by Six et al. (2010), with an increase of $N_2O$ emissions in the first 10 years and a decrease thereafter. These changes associated with duration of conservation tillage may be attributed to attainment of new steady-state soil conditions, such as soil structure, compaction, WFPS and aeration, which are not optimal for soil microbes to produce $N_2O$ by denitrification and/or nitrification processes.

### 4.3. Effects of initial soil properties on $N_2O$ emission

Soil $N_2O$ emissions are strongly correlated with soil denitrification-nitrification processes that are driven by soil microbes, which in turn are largely affected by several soil properties. SOC and generalized soil texture had no significant differences on $N_2O$ emissions following implementation of conservation tillage. A trend of increasing $N_2O$ emission with increasing SOC content was reported by Li et al. (2005). High SOC provides more substrate for heterotrophic denitrifiers, which should favor enhanced denitrification and $N_2O$ emissions (Russenes et al., 2016). Soil texture strongly affects soil aeration and thus is often implicated as an important factor regulating $N_2O$ emissions. As nitrification is considered to be the dominant process generating $N_2O$ in generally well aerated, coarse-textured soils (Zhou et al., 2013), application of conservation tillage in these soils may result in soil compaction and poor aeration, suppressing nitrification and its associated $N_2O$ emissions. In contrast, denitrification is often the primary $N_2O$-generating process in fine-textured soils due to a generally higher prevalence of anoxic microsites (Gu et al., 2013). Therefore, application of conservation tillage to fine-textured soils may result in the development of additional anaerobic conditions through compaction and greater water retention owing to the higher micropore content of compacted soils, which favor the development of additional anaerobic microsites for denitrification.

Soil pH and clay content were identified to significantly affect the $N_2O$ emission effect size from the implementation of conservation tillage. Our analysis indicated a significant increase of $N_2O$ emissions in acidic and alkaline soils but not in neutral soils. Greater $N_2O$ emissions in acidic soils have been previously reported (Samad et al., 2016; Liu et al., 2010). In acidic soils, stepwise denitrification was purported to be suppressed by an attenuation of reductase ($N_2OR$) activities that hinder $N_2O$ conversion to $N_2$, resulting in the accumulation of $N_2O$ in acidic soils (Liu et al., 2014). In contrast, nitrifiers generally perform better in neutral to slightly alkaline soils (Sánchez-García et al., 2014), which may contribute to increased $N_2O$ emissions in alkaline soils. The effect of clay content on $N_2O$ emission in our analysis contradicts the expectations of increasing $N_2O$ emission with increasing clay content (Chen et al., 2013). The significant increase of $N_2O$ emission in soils with low clay content was mostly associated with medium-textured soils, which was consistent with the results of our soil texture evaluation. However, the sample size for low clay content soils was small, which could bias the results. More comparisons are necessary for a rigorous exploration of the effect of clay content on soil $N_2O$ emission in conservation tillage systems.
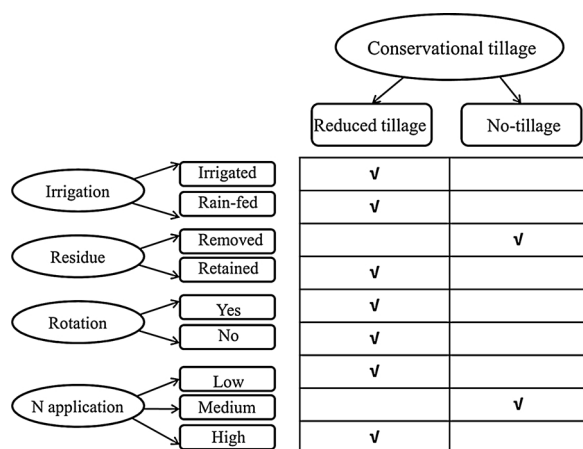
**Fig. 7.** Conservation tillage criteria for mitigation of additional soil $N_2O$ emission. N application rate classified as Table 1.

### 4.4. Effect of agricultural practices on $N_2O$ emission

As expected, increasing N application rates led to increased $N_2O$ emissions (Fig. 2b, $p < 0.05$). Similar results were reported from short-term trials evaluating the influence of N application on $N_2O$ emissions in Mediterranean soils (Plaza-Bonilla et al., 2014). Enhanced inorganic N from fertilization would be expected to intensify nitrification-denitrification processes resulting in increased $N_2O$ production. A linear response of $N_2O$ emission to N application rate was identified when the N fertilizer rate was less or equal to that required to achieve maximum crop yield, while an exponential increase in $N_2O$ emission was observed in soils with higher N inputs (Halvorson et al., 2008; Van Groenigen et al., 2010).

Contrasting water management practices showed a significant influence on soil $N_2O$ emission in conservation tillage systems (Fig. 4a). Irrigation significantly increased soil $N_2O$ emissions, consistent with the findings of Cayuela et al. (2016). The drying and wetting cycles created by irrigation provide an ideal environment for coupled nitrification-denitrification. Nitrate production during the dry period is available for denitrification when irrigation increases the WFPS leading to potential anaerobic conditions (Shi et al., 2013).

A significant difference was found between residue retained and residue removed treatments following implementation of conservation tillage, consistent with the report by Baggs et al. (2003). Retention of residues provides substrate for microbial growth through mineralization, which should increase denitrifier and nitrifier abundance depending on oxygen content (Burger and Jackson, 2003). Inorganic N released from residue by mineralization would further stimulate the $N_2O$ production processes. Finally, consumption of soil $O_2$ from enhanced organic matter decomposition may contribute to a greater prevalence of anaerobic conditions that favor denitrification (Chen et al., 2013).

Our analysis indicated that crop rotation reduced $N_2O$ emission from conservation tillage as compared to non-rotation systems. Previously, no significant effect of crop rotation on $N_2O$ emission was found by Omonode et al. (2011). As our analysis indicated a relatively weak significance level ($p = 0.049$) for crop rotation effects on soil $N_2O$ emission dynamics, further investigations are warranted to better understand the complex interactions between crop rotation and $N_2O$ emission.

Our meta-analysis showed a crop-specific effect on conservation tillage induced $N_2O$ emissions (Fig. 4d). The higher $N_2O$ emissions from maize, wheat and rice may be related to the higher N fertilizer application rates for these crops as compared to the lower and insignificant effects from beans and other crop types (mainly vegetables) that generally receive lower N fertilization rates. The relatively small increase of $N_2O$ emissions determined in rice paddies following conservation tillage was similar to that reported by Zhang et al. (2015) and is possibly due to the dominance of anaerobic conditions that favor complete denitrification (conversion of $N_2O$ to $N_2$) and thus a lower yield of $N_2O$ relative to $N_2$.

## 5. Implications and conclusions

This meta-analysis, which assessed conservation tillage induced $N_2O$ emissions, was based only on field trial results in order to provide conclusions deemed relevant to real-world field conditions. Conservation tillage practices have been reported to reduce $CO_2$ emissions by ~21% (Abdalla et al., 2016). However, application of conservation tillage significantly increased soil $N_2O$ emission by ~17.8% compared to conventional tillage in our analysis, which offsets the potential climate change mitigation benefits associated with soil carbon sequestration. To provide guidance for minimizing the negative effects from $N_2O$ emission, we synthesized the results from our $EF_{ad}$ analysis to a criterion-based guide for minimizing the impacts of specific agricultural practices in reduced tillage and no-tillage systems on $N_2O$ emissions (Fig. 7). Overall, reduced tillage (versus no-tillage) produced more favorable results and was advantageous regardless of rotation or water management practices. Only in the case of residue removal and medium application rates for N fertilizer did no-tillage result in less enhancement of $N_2O$ emission compared to reduced tillage.

In summary, adoption of conservation tillage increased soil $N_2O$ emission, especially for the no-tillage practice. IPCC estimated a 1.00% $N_2O$ emission factor by fertilizer and an additional 0.40% emission of $N_2O$ was determined from this meta-analysis. Enhanced conservation tillage induced $N_2O$ emission was more prominent in tropical and warm temperate climates. The enhanced $N_2O$ emissions diminished with increasing duration of conservation tillage, particularly after 10 years of application. Conservation tillage induced $N_2O$ emissions were strongly affected by several initial soil properties (*e.g.*, pH and clay content) and agricultural practices (*e.g.*, water, residue and rotation management, and crop type). Based on this analysis, criteria to minimize $N_2O$ emission were developed for reduced tillage and no-tillage systems. These criteria can assist agricultural land managers in minimizing the conservation tillage offsets of climate change mitigation due to enhanced $N_2O$ emission.

## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.still.2018.05.006.

## References

Abdalla, K., Chivenge, P., Ciais, P., Chaplot, V., 2016. No-tillage lessens soil $CO_2$ emissions the most under arid and sandy soil conditions: results from a meta-analysis. Biogeosciences 13, 3619–3633.

Antle, J.M., Ogle, S.M., 2012. Influence of soil C, $N_2O$ and fuel use on GHG mitigation with no-till adoption. Clim. Change 111, 609–625.

Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H., Cadisch, G., 2003. Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage. Plant Soil 254, 361–370.

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration - what do we really know. Agr. Ecosyst. Environ. 118, 1–5.

Bárta, J., Melichová, T., Vaněk, D., Picek, T., Šantrůčková, H., 2010. Effect of pH and dissolved organic matter on the abundance of nirK and nirS denitrifiers in spruce forest soil. Biogeochemistry 101, 123–132.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H., 2002. Emissions of $N_2O$ and NO from fertilized fields: summary of available measurement data. Glob. Biogeochem. Cy.

16, 1–6.

Burger, M., Jackson, L.E., 2003. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. Soil Biol. Biochem. 35, 29–36.

Cayuela, M.L., Aguilera, E., Sanz-Cobena, A., Adams, D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L., Alfaro, M.A., Pappa, V.A., 2016. Direct nitrous oxide emissions in Mediterranean climate cropping systems: emission factors based on a meta-analysis of available measurement data. Agr. Ecosyst. Environ. 238, 25–35.

Chen, H., Li, X., Hu, F., Shi, W., 2013. Soil nitrous oxide emissions following crop residue addition: a meta-analysis. Glob. Change Biol. 19, 2956–2964.

Choudhary, M.A., Akramkhanov, A., Saggar, S., 2002. Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. Agr. Ecosyst. Environ. 93, 33–43.

Das, A., Ghosh, P.K., Lal, R., Saha, R., Ngachan, S., 2014. Soil quality effect of conservation practices in maize-rapeseed cropping system in eastern Himalaya. Land Degrad. Dev. 28, 1862–1874.

Friedrich, T., Derpsch, R., Kassam, A.H., 2012. Overview of the global spread of conservation agriculture. Field Actions Sci. Rep. 6, 1–7.

Gu, J., Nicoullaud, B., Rochette, P., Grossel, A., Hénault, C., Cellier, P., Richard, G., 2013. A regional experiment suggests that soil texture is a major control of $N_2O$ emissions from tile-drained winter wheat fields during the fertilization period. Soil Biol. Biochem. 60, 134–141.

Guardia, G., Tellez-Rio, A., García-Marco, S., Martin-Lammerding, D., Tenorio, J.L., Ibáñez, M.Á., Vallejo, A., 2016. Effect of tillage and crop (cereal versus legume) on greenhouse gas emissions and global warming potential in a non-irrigated Mediterranean field. Agr. Ecosyst. Environ. 221, 187–197.

Halvorson, A.D., Del Grosso, S.J., Reule, C.A., 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. J. Environ. Qual. 37, 1337–1344.

Hill, A.R., Cardaci, M., 2004. Denitrification and organic carbon availability in riparian wetland soils and subsurface sediments. Soil Sci. Soc. Am. J. 68, 320–325.

Hou, H., Chen, H., Cai, H., Yang, F., Li, D., Wang, F., 2016. $CO_2$ and $N_2O$ emissions from Lou soils of greenhouse tomato fields under aerated irrigation. Atmos. Environ. 132, 69–76.

Hu, Z., Zhou, Y., Cui, H., Chen, S., Xiao, Q., Liu, Y., 2013. Effects of diurnal warming on soil $N_2O$ emission in soybean field. Environ. Sci. 34, 2961–2967.

IPCC, 2013. Intergovernmental panel on climate change). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Khalil, K., Mary, B., Renault, P., 2004. Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by $O_2$ concentration. Soil. Biol. Biochem. 36, 687–699.

Kudo, Y., Noborio, K., Shimoozono, N., Kurihara, R., 2014. The effective water management practice for mitigating greenhouse gas emissions and maintaining rice yield in central Japan. Agr. Ecosyst. Environ. 186, 77–85.

Lal, R., 2004. Carbon emission from farm operations. Environ. Int. 30, 981–990.

Li, C., Frolking, S., Butterbach-Bahl, K., 2005. Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. Clim. Change 72, 321–338.

Li, L., Xu, J., Hu, J., Han, J., 2014. Reducing nitrous oxide emissions to mitigate climate change and protect the ozone layer. Environ. Sci. Technol. 48, 5290–5297.

Liu, B., Frostegard, A., Bakken, L.R., 2014. Impaired reduction of $N_2O$ to $N_2$ in acid soils is due to a posttranscriptional interference with the expression of nosZ. Mbio 5, 1–10.

Liu, B., Mørkved, P.T., Frostegård, Å., Bakken, L.R., 2010. Denitrification gene pools, transcription and kinetics of NO, $N_2O$ and $N_2$ production as affected by soil pH. Fems Microbiol. Ecol. 72, 407–417.

Lognoul, M., Theodorakopoulos, N., Hiel, M.P., Regaert, D., Broux, F., Heinesch, B., Bodson, B., Vandenbol, M., Aubinet, M., 2017. Impact of tillage on greenhouse gas emissions by an agricultural crop and dynamics of $N_2O$ fluxes: insights from automated closed chamber measurements. Soil Till. Res. 167, 80–89.

Maillard, É., Angers, D.A., 2014. Animal manure application and soil organic carbon stocks: a meta-analysis. Glob. Change Biol. 20, 666–679.

Montzka, S.A., Dlugokencky, E.J., Butler, J.H., 2011. Non-$CO_2$ greenhouse gases and climate change. Nature 476, 43–50.

Mutegi, J.K., Munkholm, L.J., Petersen, B.M., Hansen, E.M., Petersen, S.O., 2010. Nitrous oxide emissions and controls as influenced by tillage and crop residue management strategy. Soil Biol. Biochem. 42, 1701–1711.

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 Sci. Soc. Am. J. 75, 152–163.

Pelster, D.E., Chantigny, M.H., Rochette, P., Angers, D.A., Rieux, C., Vanasse, A., 2012. Nitrous oxide emissions respond differently to mineral and organic nitrogen sources in contrasting soil types. J. Environ. Qual. 41, 427–435.

Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., Van Groenigen, K.J., Lee, J., Van Gestel, N., Six, J., Venterea, R.T., Van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. Field Crops Res. 183, 156–168.

Plaza-Bonilla, D., Álvaro-Fuentes, J., Arrúe, J.L., Cantero-Martínez, C., 2014. Tillage and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed Mediterranean area. Agr. Ecosyst. Environ. 189, 43–52.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change 4, 678–683.

Rochette, P., 2008. No-till only increases $N_2O$ emissions in poorly-aerated soils. Soil Till. Res. 101, 97–100.

Rochette, P., Angers, D.A., Chantigny, M.H., Bertrand, N., 2008. Nitrous oxide emissions respond differently to no-till in a loam and a heavy clay soil. Soil Sci. Soc. Am. J. 72, 1363–1369.

Rosenberg, M.S., Adams, D.C., Gurevitch, J., 2000. MetaWin: Statistical Software for Meta Analysis. Version 2.1. Sinauer Associates, Sunderland, Massachusetts.

Russenes, A.L., Korsaeth, A., Bakken, L.R., Dörsch, P., 2016. Spatial variation in soil pH controls off-season $N_2O$ emission in an agricultural soil. Soil Biol. Biochem. 99, 36–46.

Samad, M.S., Bakken, L.R., Nadeem, S., Clough, T.J., de Klein, C.A.M., Richards, K.G., Lanigan, G.J., Morales, S.E., 2016. High-resolution denitrification kinetics in pasture soils link $N_2O$ emissions to pH, and denitrification to C mineralization. Plos One 11, e151713.

Sánchez-García, M., Roig, A., Sanchez-Monedero, M.A., Cayuela, M.L., 2014. Biochar increases soil N2O emissions produced by nitrification-mediated pathways. Front. Environ. Sci. 2 1–10.

Seta, A.K., Blevins, R.L., Frye, W.W., Barfield, B.J., 1993. Reducing soil erosion and agricultural chemical losses with conservation tillage. J. Environ. Qual. 22, 661–665.

Shi, Y., Wu, W., Meng, F., Zhang, Z., Zheng, L., Wang, D., 2013. Integrated management practices significantly affect $N_2O$ emissions and wheat–maize production at field scale in the North China Plain. Nutr. Cycl. Agroecosys. 95, 203–218.

Six, J., Ogle, S.M., Jay Breidt, F., Conant, R.T., Mosier, A.R., Paustian, K., 2010. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Glob. Change Biol. 10, 155–160.

Skinner, C., Gattinger, A., Muller, A., Stolze, M., Ruser, R., Niggli, U., 2014. Greenhouse gas fluxes from agricultural soils under organic and non-organic management - a global meta-analysis. Sci. Total Environ. 468–469, 553–563.

Stevens, R.J., Laughlin, R.J., Burns, L.C., Arah, J.R.M., Hood, R.C., 1997. Measuring the contributions of nitrification and denitrification to the flux of nitrous oxide from soil. Soil Biol. Biochem. 29, 139–151.

Tierling, J., Kuhlmann, H., 2018. Emissions of nitrous oxide ($N_2O$) affected by pH-related nitrite accumulation during nitrification of N fertilizers. Geoderma 310, 12–21.

Trost, B., Prochnow, A., Meyer-Aurich, A., Drastig, K., Baumecker, M., Ellmer, F., 2016. Effects of irrigation and nitrogen fertilization on the greenhouse gas emissions of a cropping system on a sandy soil in northeast Germany. Eur. J. Agron. 81, 117–128.

Tu, C., Li, F., 2017. Responses of greenhouse gas fluxes to experimental warming in wheat season under conventional tillage and no-tillage fields. J. Environ. Sci. 54, 314–327.

Van Groenigen, J.W., Velthof, G.L., Oenema, O., Van Groenigen, K.J., Van Kessel, C., 2010. Towards an agronomic assessment of $N_2O$ emissions: a case study for arable crops. Eur. J. Soil Sci. 61, 903–913.

Van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., Van Groenigen, K.J., 2013. Climate, duration, and N placement determine $N_2O$ emissions in reduced tillage systems: a meta-analysis. Glob. Chang Biol. 19, 33–44.

Venterea, R.T., Baker, J.M., Dolan, M.S., Spokas, K.A., 2006. Carbon and nitrogen storage are greater under biennial tillage in a Minnesota corn-soybean rotation. Soil Sci. Soc. Am. J. 70, 1752–1762.

Weitz, A.M., Linder, E., Frolking, S., Crill, P.M., Keller, M., 2001. $N_2O$ emissions from humid tropical agricultural soils: effects of soil moisture, texture and nitrogen availability. Soil Biol. Biochem. 33, 1077–1093.

Zhang, L., Zheng, J., Chen, L., Shen, M., Zhang, X., Zhang, M., Bian, X., Zhang, J., Zhang, W., 2015. Integrative effects of soil tillage and straw management on crop yields and greenhouse gas emissions in a rice–wheat cropping system. Eur. J. Agron. 63, 47–54.

Zhao, X., Liu, S., Pu, C., Zhang, X., Xue, J., Zhang, R., Wang, Y., Lal, R., Zhang, H., Chen, F., 2016. Methane and nitrous oxide emissions under no-till farming in China: a meta-analysis. Glob. Change Biol. 22, 1372–1384.

Zhou, M., Zhu, B., Butterbach-Bahl, K., Zheng, X., Wang, T., Wang, Y., 2013. Nitrous oxide emissions and nitrate leaching from a rain-fed wheat-maize rotation in the Sichuan Basin, China. Plant Soil 362, 149–159.