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The Responses of Soil N_2O Emissions to Residue Returning Systems: A Meta-Analysis

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Received: 19 December 2018; Accepted: 26 January 2019; Published: 31 January 2019



Abstract: Background: Much attention has been focused on the influences of residue returning on N_2O emissions. However, comprehensive quantification of the effect size on N_2O emission following crop residue returning in subtropical, tropical and warm temperate conditions remains untested. Methods: To identify site-specific factors that influence N_2O emission (kg N_2O-N ha^{-1}) in residue returning systems, we performed a meta-analysis involving 260 comparisons from 72 studies. Results: The data indicated that significant promoting effects were observed under residue returning by rotary tillage, no-tillage and mulch, whereas N_2O release was significantly inhibited by 8% under residue returning by plough. For other contributors, the stimulatory and significant effects occurred in upland fields, under short- and medium-term residue returning durations, acidic/neutral soils, medium organic C and clay content. Nitrogen fertilizer application significantly stimulated N_2O emission, even though application rate at 100–150 kg N ha^{-1} was inhibitory. Although a negative correlation between residue C/N ratio and N_2O emission has been shown, residue returning could not reduce N_2O emission with a higher C/N ratio and amount. Conclusions: Some options, such as converting residue returning methods, decreasing N fertilizer application rate, and regulating soil C/N ratio could be adopted to mitigate soil N_2O emission following residue returning.

Keywords: residue returning; N_2O emission; land use; soil properties; N fertilizer application; meta-analysis

1. Introduction

Anthropogenic greenhouse gas emission (e.g., CO_2, CH_4, and N_2O) is a major contributor to global warming [1], and agricultural activities account for 10–12% of total anthropogenic greenhouse gas emission [2]. Agriculture was responsible for more than 61% of N_2O emissions, resulting from agricultural inputs and direct soil-derived N_2O [3,4]. There are continuous concerns regarding N_2O emission due to its contribution to both global warming and ozone layer depletion [5]. In fact, N_2O has been identified as the most significant anthropogenic ozone-depleting compound [6]. In a time horizon of 100 years, it has been shown to have 265 and 28 times greater global warming potential than CO_2 and CH_4, respectively [1].

Soil N_2O is naturally produced through the processes of microbial nitrification and/or denitrification [7]. Under aerobic soil conditions, N_2O is mainly derived from nitrification process, in which autotrophic nitrifiers convert NH_4^+ to NO_3^-. However, under anaerobic soil conditions, denitrification is the main pathway for N_2O production. During this process, heterotrophic denitrifiers transform NO_3^- to N_2O and N_2 [8]. Generally, denitrification is believed to be the main source of N_2O production in soils, as N_2O yield potential of denitrification is much higher (1–100%) than nitrification

(0.1–1%) [9,10]). The ratio between the gaseous products of denitrification depends on NO_3^- availability, oxygen (O_2) availability in the soil and/or microsites, amount of easily decomposable C as an energy source, soil pH, and microbial community structure [11,12]. Chen et al. [13] have reported that nitrification and denitrification dominate soil N_2O production when soil water-filled pore spaces were at 30–60% and 50–90%, respectively. Furthermore, N_2O emission dynamics are controlled by other factors, including soil temperature and agricultural management practices [14–16]. For example, a positive correlation between N_2O fluxes and soil temperatures was found, and no tillage can improve soil structure and lower its temperature, which in turn could reduce N_2O emission [17–19].

Crop residue returning, as an important management practice, is widely popular due to its benefits of increasing soil fertility and grain yields [20–22]. Meanwhile, this process also brings soil N_2O emission via regulating soil C and N availability and microbial activities, etc. [23–25]. Mosier et al. [26] calculated that crop residue could produce 0.4 million metric tons of N_2O-N $year^{-1}$ globally. However, contradictory views exist in the literature regarding the influence of residue returning on N_2O production and release. Several studies have reported that residue returning stimulates N_2O emission [27–29], while others have reported inhibitory effects [30,31]. These results indicate that crop residues may play multiple roles, such as an organic N fertilizer, organic C substrate, and energy provider in regulating soil N_2O production and emission [13]. Crop residue could further modify soil aeration by improving soil aggregation and microbial O_2 demand, a major factor mediating soil nitrification and denitrification processes for N_2O production. In addition, the effects of residue application on soil N_2O emission depend on soil properties [4,32,33]. For example, soil pH can affect the decomposition rate of crop residues, as well as C and N sources for microbial denitrification [34]; soil texture could impact soil permeability and water condition, and thus residue decomposition rate and N transformation process [35]. Hence, taking soil properties into consideration is necessary when estimating N_2O emission associated with crop residues.

Meta-analysis is a systematic process applied to research data from a variety of experiments to analyze and summarize the estimated quantitative average effects [36]. In recent years, this method has been used to assess the effects of agricultural management practice's driving factors on N_2O emissions. For example, Liu et al. [37] conducted a meta-analysis to assess the impacts of fertilizer application on soil N_2O emissions. Shan and Yan [38] applied a meta-analysis and found that crop residue application methods could affect N_2O release, but the effect sizes were treated as unknown due to limited datasets. Therefore, more information is required regarding the effect size of residue returning attributers (e.g., climate condition, soil initial organic C content, residue returning methods and amount) on N_2O emissions. The objective of this study was to conduct a meta-analysis to comprehensively quantify the effect size of crop residue returning on N_2O emission, varying soil conditions, and residue returning attributes based on field experiments.

2. Materials and Methods

2.1. Data Collection

A detailed evaluation was performed of peer-reviewed journal articles from the Web of Science (1900–2017). "Straw", "residue", "tillage", "N_2O", "nitrous oxide", and "greenhouse gas" were selected as search keywords. Data were collected from 72 publications, which included both no-residue returning (controls) and residue returning treatments. Only field scale studies were selected for this meta-analysis (Figure 1). Specific residue returning methods chosen for comparative analysis included residue returning with conventional tillage/plowing/plough/20 cm depth/25 cm depth (PT), rotary tillage/shallow-rotary tillage/10 cm depth/12 cm depth/15 cm depth (RT), no-tillage/reduced tillage/zero tillage (NT), and mulch (MC). No-residue returning condition was set as the control. When collecting the paired experiments, we considered the following criteria: (1) Field scale studies on N_2O emission were performed using the closed chamber-gas chromatography method

in agroecosystem; (2) tillage and residue returning were clearly stated; (3) cumulative N_2O emission could be obtained from each study.

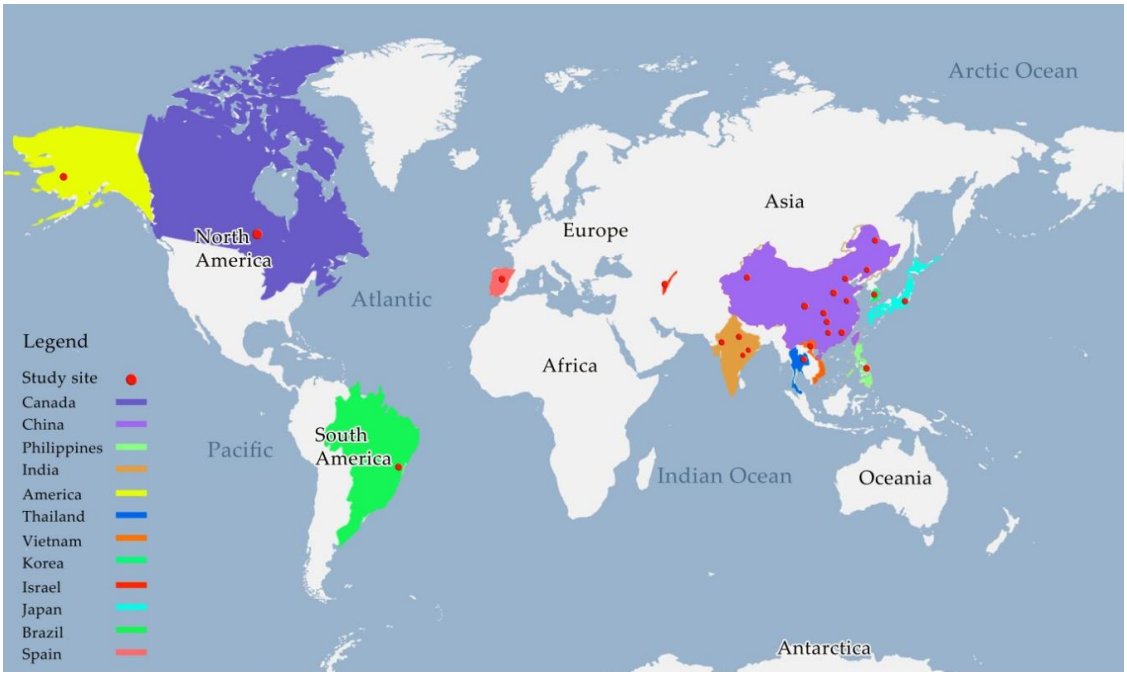


Figure 1. Location of experimental sites included in our meta-analysis.

From the 72 studies, data listed in tables were obtained directly, whereas, data presented in. figures were extracted using the "Getdata Graph Digitizer, Version 2.26" software (Version 2.26: Getdata Graph Digitizer, Fedorov S, Krasnoyarsk, Russia). A total of 260 observations from 72 field studies were collected for this meta-analysis. Other related information including the location (longitude and latitude), mean annual precipitation, annual mean temperature, climate regimes, pH, cropping systems, crop species, soil types, N fertilizer application, and residue returning duration were obtained from the selected studies. More detailed information regarding these published papers is represented in Supplementary Table S1.

For all studies, the cumulative N_2O emission, replications, and standard deviation (SD) of both no-residue and residue returning treatments were obtained directly. If N_2O emission was shown as the value of global warming potential, the unit was converted. SD was estimated through the value of standard errors (SE) using Equation (1):

$$SD = SE \times \sqrt{n}, \quad (1)$$

where n is replications. The average SD value was estimated as 23% and 36% for controls and residue returning treatments, respectively. For absent SD and SE, values were the relative mean values of SD for N_2O emissions in the dataset [39].

2.2. Data Analysis

A random-effects meta-analysis was carried out to explore the impact of experimental conditions, initial soil properties, and agricultural management practices on N_2O emissions (kg N_2O-N ha^{-1}) associated with crop residues. The natural logarithm of response ratio (ln*R*) was adopted as the effect size of the comparing soil N_2O emissions between controls and residue returning treatments [40].

$$\ln R = \ln \frac{X_t}{X_c} = \ln(X_t) - \ln(X_c), \quad (2)$$

where X_c and X_t represented the average value of N_2O emission in controls and residue returning treatments, respectively.

For each study, the variance (υ) of ln$R$ was estimated as follows:

$$\upsilon = \frac{SD_t^2}{n_t X_t^2} + \frac{SD_c^2}{n_c X_c^2}, \quad (3)$$

where SD_c and SD_t represented the standard deviations of all comparisons in controls and residue returning treatments, respectively; and n_t and n_c present repetition numbers for residue returning treatments and the controls, respectively. The weight effect sizes were calculated using Equation (4):

$$\ln R = \frac{\sum(ln\ R_i \times \omega_i)}{\sum \omega_i}, \quad (4)$$

where lnR_i was the effect size, and ω_i was the weight of corresponding comparisons. ω_i was computed as follows:

$$\omega = \frac{1}{\upsilon}, \quad (5)$$

where υ was the variance of ln$R$ as stated above.

The aim of this meta-analysis was to explore how soil and residue returning attributes drive soil N_2O emissions. Therefore, to determine significant differences in effect size under residue and no-residue returning treatments, the attributes were classified into three different groups (experimental conditions, soil initial properties, and agricultural management practices), which included 11 categorical variables (climate zone, land use, residue returning duration, pH, soil organic C content, soil texture, clay content, N fertilizer input, crop residue C/N ratio, residue returning amount and methods). Every categorical variable was then divided into several levels. The detailed classification is shown in Table 1. For each attribute, total heterogeneity (Q_t) was divided into within-group (Q_w) and between-group (Q_b) variations. The significance of Q_b represents mean effect sizes that are significantly different between various levels of the categorical group [41]. The Q statistic obeyed a chi-square distribution with k−1 degrees of freedom, where k was the number of paired observations for a categorical variable between residue returning treatments.

In order to determine mean effect size, METAWIN 2.1 software was performed and 95% bootstrapped confidence intervals (CIs) were generated [41]. Relative to control, the treatments were considered significantly positive or negative if the 95% CIs for cumulative seasonal N_2O emission changes did not overlap with zero [42]. p values for differences between categories of studies were calculated in METAWIN 2.1 software. For simplicity, ln$R$ analysis results were back-transformed and reported as percentage change under residue returning relative to the controls, and the calculation equation was $((e^{\ln R} - 1) \times 100\%)$ [4].

Table 1. Categorical variables, numbers of studies and paired observations for crop residue returning relative to no-residue returning treatments, levels (L) of each variable, between-group heterogeneity (Q_b), and significant p values in the meta-analysis.

Groups	Variable	Studies	Observations	L1	L2	L3	L4	L5	L6	L7	*Qb*	*P*
Experimental conditions	Climate zone	72	260	Subtropical	Tropical	Warm temperate					16.12	0.002
	Land use	72	260	Upland	Paddy-upland	Paddy					19.45	0.001
	Residue returning duration (year)	72	260	≦2	2–5	>5					3.60	0.213
Soil initial properties	pH	65	216	≦6.5	6.5–7.3	>7.3					1.76	0.492
	Soil organic C content (g kg^{-1})	64	207	≦10	10–18	>18					88.37	0.049
	Soil texture	50	144	Clay	Clay loam	Loam	Sandy clay	Sandy clay loam	Sandy loam	Silt loam	34.59	0.001
	Clay content (%)	37	96	≦15	15–25	>25					4.05	0.202
	N fertilizer input (kg N ha^{-1})	66	231	≦100	100–150	150–250	>250				100.07	0.058
Agricultural management practices	Crop residue C: N	39	96	≦45	45–100	>100					20.01	0.001
	Residue returning amount (kg DM ha^{-1})	58	199	≦4000	4000–6000	>6000					29.97	0.39
	Residue returning method	72	260	PT	RT	MC	NT				126.8	0.016

Note: PT means residue returning with conventional tillage/plowing/plough/20 cm depth/25 cm depth; RT means residue returning with rotary tillage/shallow-rotary tillage/10 cm depth/12 cm depth; NT means residue returning with no-tillage/reduced tillage/zero tillage; MC means residue mulch on the fields.

3. Results

3.1. Residue Returning Methods, Amounts, and C/N Ratio

Overall, residue returning had significant, positive effects on soil N_2O emission compared to no-residue returning, with an increase by 8% (Figure 2a). RT, MC, and NT significantly increased N_2O emission by 11%, 16%, and 35%, respectively, compared to the controls (Figure 2a), while PT resulted in a significant decrease by 8%. There were also significant differences in N_2O emissions between different residue returning methods. Soil N_2O emissions were significantly higher in NT than MC and RT, which were also significantly higher than PT treatments, while no significant effects were founded between RT and MC (Figure 2a).

The effect size of residue returning on N_2O release was dependent on the amount of residue returning, but no tendency with amount of residue application was observed (Figure 2b). N_2O emissions significantly increased for studies with higher (>6000 kg DM ha^{-1}; mean: 16%) and lower (≦4000 kg DM ha^{-1}; mean: 15%) amounts of residue returning. In addition, no significant effect was found for studies with intermediate (4000–6000 kg DM ha^{-1}; mean: −2%) amounts of residue returning (Figure 2b).

The effect size of residue returning on soil N_2O emission was strongly dependent on the residue C/N ratio, and the effect size generally decreased following residue C/N ratio increase (Figure 2c). Significantly elevated N_2O emission were noted at residue C/N ratios at ≦45 (mean: 50%) and 45–100 (mean: 21%), whereas, no significant effect was observed when the residue C/N ratio exceeded 100 (mean: −31%; Figure 2c).

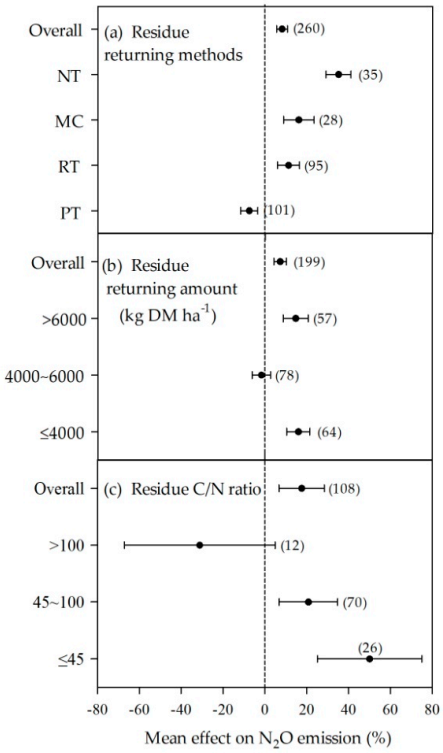


Figure 2. Effects of residue returning methods. (**a**) residue returning amount; (**b**) and residue C/N ratio; (**c**) on N_2O emission following residue application (mean ± 95% CIs). The number of observations was shown in parentheses. The effect was considered significant if the 95% CIs of the mean effect did not overlap with zero. Note: PT represents residue returning with conventional tillage/plowing/plough/20 cm depth/25 cm depth; RT represents residue returning with rotary tillage/shallow-rotary tillage/10 cm depth/12 cm depth; NT represents residue returning with no-tillage/reduced tillage/zero tillage; MC represents residue mulch on the fields.

3.2. Climate Zone, Land Use, and Residue Returning Duration

Regarding climate zone, residue returning significantly increased soil N_2O emissions relative to no-residue returning in both warm temperate (mean: 31%) and tropical (mean: 54%) climate zones (Figure 3a). In contrast, the observed inhibitory effect was not significant in the subtropical (mean: −3%) climate zone (Figure 3a).

The effect size of residue returning on N_2O emission varied with land use types (Figure 3b). Soil N_2O release increased significantly in upland fields (mean: 24%), decreased significantly on paddy fields (mean: −19%), and no effect was observed on upland-paddy fields (mean: −2%; Figure 3b). Meanwhile, there was a significant difference of N_2O release between upland and paddy fields.

The effect of residue returning on N_2O release relied on the residue returning duration (Figure 3c). Mean effect size from short studies (2 year) was significantly enhanced by 15% relative to no-residue returning. However, there were no significant effects on N_2O emissions for medium term (2–5 year) and long term (>5 year) duration studies following residue application (Figure 3c). In addition, a negative correlation was found between N_2O emission and residue returning duration.

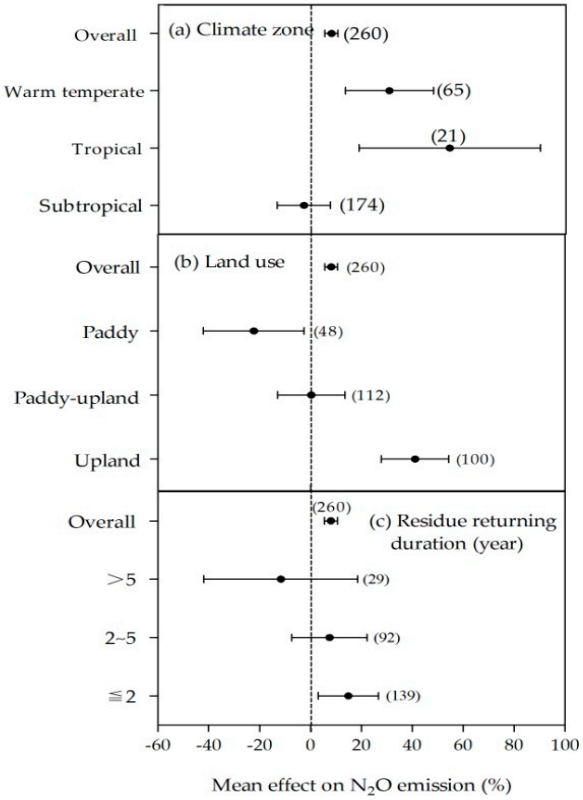


Figure 3. Effects of climate zone (**a**), land use; (**b**) and residue returning duration; (**c**) on N_2O emission following residue returning (mean ± 95% CIs). The number of observations is shown in parentheses. The effect was considered significant if the 95% CIs of the mean effect did not overlap with zero.

3.3. Soil pH, Soil Organic C Content, Soil Texture, and Clay Content

Soil pH significantly affected soil N_2O release after adopting residue returning compared to controls, and stimulatory effects were observed for acidic soils (pH ≦ 6.5) and neutral soils (6.5–7.3) (Figure 4a). However, in alkaline soils (>7.3), there were no significant changes in soil N_2O release. On average, different values of soil organic C resulted in varying effects of residue returning, where N_2O emission were significantly enhanced by 21% at a 10–18 g kg^{-1} range, significantly reduced by 11% at values exceeding 18 g kg^{-1} (Figure 4b), and no significant effect was observed below 10 g kg^{-1} (Figure 4b).

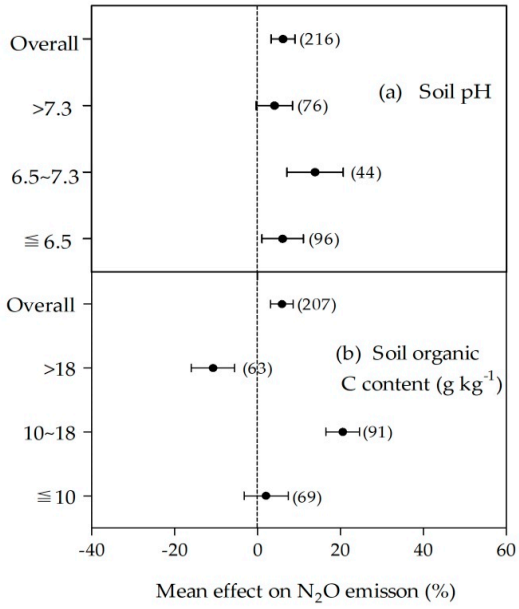


Figure 4. Effects of soil pH (**a**) and soil organic C content; (**b**) on N_2O emission following residue returning (mean ± 95% CIs). The number of observations is shown in parentheses. The effect was considered significant if the 95% CI of the mean effect did not overlap with zero.

According to the United State Department of Agriculture (USDA) soil texture triangle, in this study we segregated soils into seven different textural classes. As shown in Figure 5a, the effects of residue returning on soil N_2O release were discrepant depending on soil types. In the soils of clay loam and sandy clay loam, residue returning significantly stimulated soil N_2O emissions. While in other soils types—except silt loam soils—residue returning significantly suppressed N_2O release. A significant negative effect on soil N_2O emissions was shown at clay content ≦15% (mean: −27%), whereas, N_2O emission was significantly stimulated by 22% at 15–25% clay content (Figure 5b). No significant effect was observed when clay content was over 25% (Figure 5b).

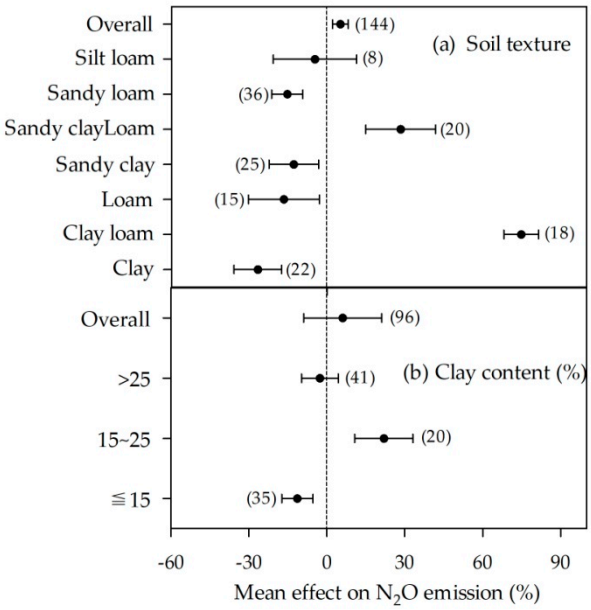


Figure 5. Effects of soil texture (**a**) and soil clay content; (**b**) on N_2O emission following residue returning (mean ± 95% CIs). The number of observations is shown in parentheses. The effect was considered significant if the 95% CIs of the mean effect did not overlap with zero.

3.4. Nitrogen Fertilizer Application

On average, relative to the controls, N fertilizer application significantly increased soil N_2O emissions following residue returning. First, soil N_2O emission decreased significantly, and then increased significantly with an increasing N input following residue returning (Figure 6). Significant stimulatory effects were observed at N input rates of ≦100 (mean: 36%), 150–250 (mean: 14%), and >250 kg N ha^{-1} (mean: 22%), whereas an N fertilizer application rate of 100–150 kg N ha^{-1} (mean: −12%) resulted in a significant decrease following residue returning (Figure 6).

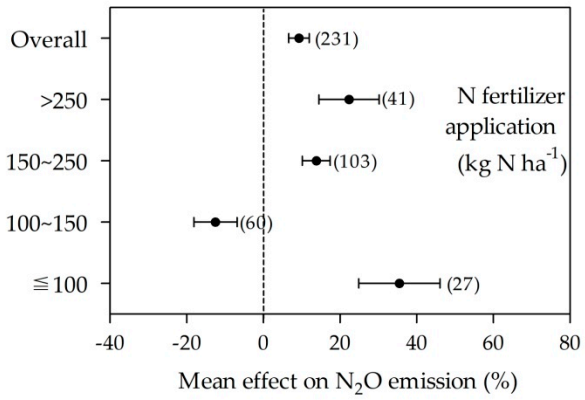


Figure 6. Effects of N fertilizer input (kg N ha^{-1}) on N_2O emission following residue returning (mean ± 95% CIs). The number of observations is shown in parentheses. The effect was considered significant if the 95% CIs of the mean effect did not overlap with zero.

4. Discussion

4.1. Effects of Residue Returning Methods on N_2O Emission

Our meta-analysis showed that residue returning significantly increased soil N_2O emissions, relative to no-residue returning, which indicating that changes in quantity and quality of soil C and N substrate and environmental conditions from residue application may favor N_2O production and emission because N_2O emissions are moderated by multiple factors such as soil inorganic N and organic C availability, soil O_2 condition, soil temperature and soil moisture [10]. Residue returning methods are considered major influencers of soil N_2O emissions, due to their effects on soil microbial activities and ventilation [30,43]. Our meta-analysis showed that RT and NT both significantly stimulated N_2O release compared to the controls. Soil compaction in RT and NT can moderate soil aeration condition and promote N_2O production through denitrification [44]. On the other hand, RT and NT can provide organic C as the energy source for heterotrophic microbial communities [45], which leading to more rapid O_2 consumption and increasing the anaerobic environment, thus stimulating the denitrification process [46,47]. These results were consistent with the analysis by Mei et al. [48] and Zhao et al. [49]. However, Shan and Yan [38] reported that although residue returning enhanced N_2O release, no significant difference was found between residue returning and controls. This could be related to the different comparison numbers (only 68 comparisons were collected in the previously published paper [38]). MC significantly increased soil N_2O emissions compared to the controls. Residue mulch on the surface of soils is generally found in upland areas, and MC possibly results in favorable soil moisture conditions, high soil temperatures, and excess N availability for microbial activities, thus promoting N_2O production [50–52]. Additionally, higher O_2 demands following residue application promote microbial denitrification for N_2O emission [53].

In this study, PT significantly inhibited N_2O release compared to controls, which might be attributed to a more effective reduction of N_2O to N_2 during denitrification. Although residue-derived soil dissolved C was available in PT compared to no-residue returning [54], PT created more pores and improved soil aeration condition, which promoting the conversion of labile organic matter to CO_2,

consequently, leading to a lower rates of denitrification [55]. In addition, our results show that N_2O emission in PT was significantly lower than that in RT and NT. On one hand, PT may decrease bulk density and increase gas-diffusion capacity, leading to a decrease in surface-water-retention capability. As a result, the soil anaerobic condition and topsoil denitrification potential decreased [56]. On the other hand, PT had lower bacterial biomass [57] and CO_2 emission than RT and NT [58]. Chen et al. [13] also found a positive correlation between soil N_2O and CO_2 emissions following residue returning.

4.2. Effects of Residue Returning Amount, and Residue C/N Ratio on N_2O Emission

Residue returning could considerably alter soil availability of NH_4^+ and NO_3^-, the major factors controlling nitrification and denitrification processes, respectively. N_2O emission significantly increased when residue returning amounts were at high and low levels, while no significant effects were observed at medium levels. The reason was mainly related to soil C/N ratio. With increasing residue application amounts, the C/N ratio increased, leading to net N immobilization and reducing N_2O production [59]. This result was identified by the correction between N_2O emission and residue C/N ratio (Figure 7). Higher quantities of residue returning resulted in elevated inputs of C and N into soils. This promoted the soil's heterotrophic microbial respiration, activities, and accelerated soil oxygen consumption to build an anaerobic environment that promotes denitrification [60], thus stimulating soil N_2O production. Previous studies [61,62] have also reported similar increase in N_2O emissions with increasing residue amounts.

The negative correlation between residue C/N ratio and soil N_2O emission has been previously reported [38,63]. In our meta-analysis, the effect size generally decreased with increasing crop residue C/N ratio (Figure 7), and these values were significant at ratios below 100. With low residue C/N ratio, crop residue returning could supply enough N to meet crop growth, and improve soil microbial communities, further promoting N_2O production and emission [64]. In contrast, crop residue with high C/N ratio increased N consumption and caused more N immobilization during residue degradation, thus, leading to lower N_2O yields. In addition, other characters of crop residue, including lignin, polyphenol, and dissolved C may also play important roles in soil N_2O production and emission [65]. However, relevant studies are lacking, and more are needed regarding the effects of returning residue characters on N_2O emissions.

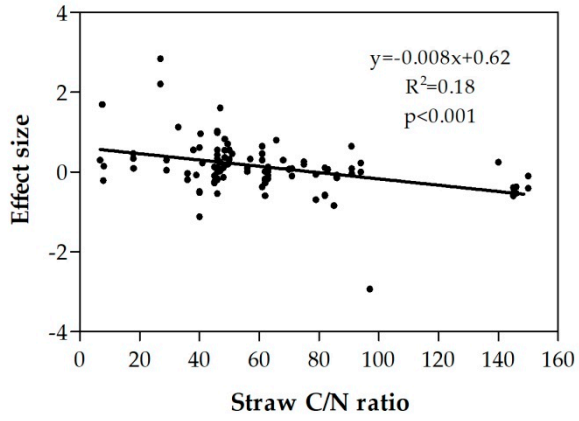


Figure 7. Linear relationship between residue C/N ratio and mean effect size of N_2O emission.

4.3. Effects of Climate Zone, Land Use, and Residue Returning Duration on N_2O Emission

Previous studies have identified that climate regimes can be considered as an impact factor of soil microbial nitrification/ denitrification processes, and N_2O emissions through regulating soil moisture and temperature [66]. Our study indicated that relative to no-residue returning, residue returning significantly increased N_2O emission by an average of 54% and 31% in warm temperate and tropical climate zones, respectively. In general, nitrification is favored at optimal soil temperature of

25–40 °C [17]. Tropical climate with high temperatures may enhance nitrification activities, thus leading to N_2O production increase [67]. In warm temperate, coefficients of N turnover rate and microbial decomposition of residues were faster, which can promote heterotrophic microbial growth and increase soil respiration, thus resulting in an anoxic condition [68]. Subtropical zones with frequent droughts in the dry season and extreme rainfall events in the wet season [69] can affect soil N transformations by disturbing soil moisture, temperature, microbial activities, etc. [70]. Our meta-analysis showed a negative effect on N_2O emission in subtropical zones associated with residue returning but with no significant difference. The possible explanation might be that precipitation reduction in dry season could decrease net nitrification and N mineralization rates, while wet season with large precipitation events causes substantial NO_3- losses via leaching [71], thus leading to small changes in average N_2O emission.

In this study, soil N_2O emission was closely related to land use types, where upland significantly increased but paddy fields significantly decreased N_2O emissions. Previous studies reported similar results [37,72]. In upland fields, residue returning created higher soil temperatures and water content, which enhanced microbial activities of nitrifier and denitrifier. This resulted in a more anaerobic environment, promoting denitrification and stimulating N_2O production [73]. In paddy fields, N_2O release derived from both nitrification and denitrification processes, which mainly occurs during the stage of alternate wetting and drying [74].

Residue returning significantly enhanced N_2O release in short- and medium-term, especially in the 2–5 year interval relative to controls. Microbial denitrification is believed to be a primary source of N_2O [75], and C availability is one of the most important factors controlling denitrification rates [76]. Hence, residues with higher decomposition rates in short-term periods can provide C and N sources for denitrifiers [25,44] to stimulate microbial activities and N_2O emissions. With the increasing of residue returning duration, more organic matter content input could improve soil structure and aeration conditions due to increased faunal and microbial activity, and thus reduce the favorable tendency for N_2O formation [44,77].

4.4. Effects of Initial Properties on N_2O Emission

Soil pH has been identified as a key regulator for N_2O production [10]. Our meta-analysis indicated that acidic soils (pH $\leq$ 6.5) and neutral soils (pH: 6.5–7.3) both had stimulatory effects on N_2O production. In acidic soils, stepwise denitrification processes might be inhibited by a reduction of reductase (N_2OR) activities, which could prevent N_2O conversion to N_2, leading to an increase in N_2O yield [78]. In contrast, autotrophic nitrifiers generally prefer neutral soils [79], and heterotrophic denitrifiers also function better at neutral than acidic soils [80], hence, the meta-analysis indicated that significant effect of neutral soil were the greatest at neutral conditions. Similar results were reported by Chen et al. [13]. Soil organic C had positive effects on N_2O production when the content was 10–18 g kg^{-1}, but with the content >18 g kg^{-1}, an inhibitory effect was observed. Soil organic C could be a sufficient C source for heterotrophic denitrifiers, thus improving soil microbial activities [81], but active microorganisms will absorb native soil N into their biomass, leading to net N immobilization with higher soil organic C [82]. Notably, this N consumption will weaken nitrification and/or denitrification processes, and thus decrease soil N_2O production.

Soil texture and clay content are often implicated in regulating N_2O emission due to their impact on soil aeration and organic matter decomposition rates [83]. In our study, soil N_2O emission significantly increased in clay loam and sandy clay loam soils. Generally, N_2O formation and release were mainly attributed to the nitrification process in well-aerated and coarse-textured soils [84], whereas, denitrification is the primary process in fine-textured soils [59]. The clay loam and sandy clay loam soils belong to medium-textured soils, which could result in N_2O production from both nitrification and denitrification processes, thus leading to a higher N_2O emission. In other soil types, N_2O release was significantly inhibited, and a finding that was inconsistent with other research [13]. A possible explanation was related to different residue returning methods, which could alter soil

aeration and water holding capacity [85]. Additionally, our study showed that significant increase in soil N_2O emission with medium clay content was consistent with results of soil texture estimation. However, a significant and negative effect was observed when clay content was ≦15%. These changes may be attributed to the associative influences of clay content on anaerobic microorganisms and soil denitrification process [86].

4.5. Effects of N Fertilizer Application Rate on N_2O Emission

It is generally accepted that N_2O emission is significantly enhanced with the increase of N fertilizer application rate [87]. Furthermore, our study shows that N fertilizer application significantly affects N_2O production. Similar results have been reported with synthetic N fertilizer application, which improves nitrification and denitrification processes, leading to increased N_2O production [88]. However, significant negative effects and lower N_2O release were observed at the N application rate of 100–150 kg ha^{-1} regarding of residue returning. These data demonstrated that this N application level was the optimal application rate to achieve the crop yield demand level [89], and the finding has been reported by other researchers [90,91]. Kim et al. [92] proposed a conceptual model of the relationship between N_2O emission and N fertilizer application rate. They found that before crop growth demand, a linear increase exists between N_2O emissions and N application levels, then an exponential increase beyond N levels demanded by crops and soil microbes, finally a steady state due to soil organic C limits. Therefore, it is possible that reducing N fertilizer application rate to adjust crop growth will mitigate N_2O emissions [93].

Although these results provide clear information on N_2O emissions following residue application, there are still some shortcomings in our meta-analysis. Firstly, the collected experimental sites are mainly from Asia, especially China, other areas, such as Russia, Northern Europe, Africa, Australia, and New Zealand are not involved. Secondly, as widely known that soil temperatures and moisture levels have great effects on N_2O production and emission, however, our meta-analysis did not analyze this effect sizes due to the variability and absence of detailed information. Therefore, further studies will be helpful for understanding the effect of residue returning on N_2O emission from a global perspective regarding soil temperature and water-filled pore space.

5. Conclusions

In this meta-analysis, we found that residue returning increased N_2O emissions, and the effects were positively related to residue amount and N input, but negatively associated with residue C/N ratio. In warm temperate and tropical climate zones, residue returning treatments have significant stimulatory effects on N_2O emissions. For land use types, soil N_2O release significantly increased in upland fields, but significantly decreased in paddy fields following residue returning. The effects of crop residue returning on N_2O emissions relied on the soil's initial properties, especially soil organic C content and texture. Significant stimulatory effects occurred when pH < 7.3, in soils with 15–25% clay content, or in soils with an organic C range of 10–18 g kg^{-1}. The effect of residue returning on soil N_2O emissions can be regulated by N fertilizer application rates due to crop yield demands, and negative effects were indicated at N fertilizer application rates at 100–150 kg N ha^{-1} associated with crop residue returning. Therefore, appropriate strategies, such as converting residue returning methods, regulating soil C/N ratio and soil aeration conditions, and reducing N fertilizer application rate can be adopted to mitigate N_2O emission associated with crop residues.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/3/748/s1, Table S1: Detailed information.

Author Contributions: Methodology, H.N. and Z.L.; software, H.N.; validation, H.N. and C.Q.; formal analysis, H.N. and C.Q.; resources, H.N. and C.Q.; data curation, H.N.; writing—original draft preparation, H.N.; writing—review and editing, H.N.; visualization, H.N.; supervision, Z.L.; project administration, Z.L.; funding acquisition, Z.L.

Funding: This research was funded by the Key Projects in the National Science & Technology Pillar Program (Grant number: 2012BAD14B12), and the Jiangsu Agriculture Science and Technology Innovation Fund (Grant number: CX(18)3074).

Acknowledgments: We would like to thank Chunhui Liu from Nanjing Agricultural University and Yu Jiang from University of Exeter for their kindly help on data analysis of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. IPCC. Summary for policymakers. In *Climate Change: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, A.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK, 2013; pp. 5–14.
2. Smith, P.; Martino, D.; Cai, Z.; Gwary, D.; Janzen, H.; Kumar, P.; McCarl, B.; Ggle, S.; O'Mara, F.; Rice, C. Greenhouse gas mitigation in agriculture. *Philos. Trans. R. Soc. B* **2008**, *363*, 789–813. [CrossRef] [PubMed]
3. Montzka, S.A.; Dlugokencky, E.J.; Butler, J.H. Non-CO_2 greenhouse gases and climate change. *Nature* **2011**, *476*, 43–50. [CrossRef]
4. Van Kessel, C.; Venterea, R.; Six, J.; Adviento-Borbe, M.A.; Linquist, B.; Van Groenigen, K.J. Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: A meta-analysis. *Glob. Chang. Biol.* **2013**, *19*, 33–44. [CrossRef] [PubMed]
5. Wuebbles, D.J. Nitrous oxide: No laughing matter. *Science* **2009**, *326*, 56–57. [CrossRef] [PubMed]
6. Ravishankara, A.R.; Daniel, J.S.; Portmann, R.W. Nitrous oxide (N_2O): The dominant ozone-depleting substance emitted in the 21st century. *Science* **2009**, *326*, 123–125. [CrossRef]
7. Bremner, J.M. Sources of nitrous oxide in soils. *Nutr. Cycl. Agroecosyst.* **1997**, *49*, 7–16. [CrossRef]
8. Khalil, K.; Mary, B.; Renault, P. Nitrous oxide production by nitrification and denitrification in soil aggregates as affected by O_2 concentration. *Soil. Biol. Biochem.* **2004**, *36*, 687–699. [CrossRef]
9. Anderson, I.C.; Poth, M.; Homstead, J.; Burdige, D. A comparison of NO and N_2O production by the autotrophic nitrifier Nitrosomonas europaea and the heterotrophic nitrifier Alcaligenes faecalis. *Appl. Environ. Microbiol.* **1993**, *59*, 3525–3533.
10. Butterbach-Bahl, K.; Baggs, E.M.; Dannenmann, M.; Kiese, R.; Zechmeister-Boltenstern, S. Nitrous oxide emissions from soils: How well do we understand the processes and their controls? *Philos. Trans. R. Soc. B* **2013**, *368*, 20130122. [CrossRef]
11. Bakken, L.R.; Bergaust, L.; Liu, B.; Frostegard, A. Regulation of denitrification at the cellular level: A clue to the understanding of N_2O emissions from soils. *Philos. Trans. R. Soc. B* **2012**, *367*, 1226–1234. [CrossRef]
12. Schaufler, G.; Kitzler, B.; Schindlbacher, A.; Skiba, U.; Sutton, M.A.; Zechmeister-Boltenstern, S. Greenhouse gas emissions from European soils under different land use: Effects of soil moisture and temperature. *Eur. J. Soil Sci.* **2010**, *61*, 683–696. [CrossRef]
13. Chen, H.H.; Li, X.C.; Hu, F.; Shi, W. Soil nitrous oxide emissions following crop residue addition: A meta-analysis. *Glob. Chang. Biol.* **2013**, *19*, 2956–2964. [CrossRef] [PubMed]
14. Aulakh, M.S.; Doran, J.W.; Mosier, A.R. Soil denitrification-significance, measurement, and effects of management. *Adv. Soil Sci.* **1992**, *18*, 1–57.
15. Han, Z.; Todd, W.M.; Drinkwater, L.E. N_2O emissions from grain cropping systems: A meta-analysis of the impacts of fertilizer-based and ecologically-based nutrient management strategies. *Nutr. Cycl. Agroecosyst.* **2017**, *107*, 335–355. [CrossRef]
16. Decock, C. Mitigating nitrous oxide emissions from corn cropping systems in the midwestern US: Potential and data gaps. *Environ. Sci. Technol.* **2014**, *48*, 4247–4256. [CrossRef] [PubMed]
17. Agehara, S.; Warncke, D.D. Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. *Soil Sci. Soc. Am. J.* **2005**, *69*, 1844–1855. [CrossRef]
18. Wang, X.J.; Yang, X.R.; Zhang, Z.J.; Ye, X.; Kao, C.M.; Chen, S.H. Long-term effect of temperature on N_2O emission from the denitrifying activated sludge. *J. Biosci. Bioeng.* **2014**, *117*, 298–304. [CrossRef]
19. Venterea, R.T.; Maharjan, B.; Dolan, M.S. Fertilizer source and tillage effects on yield-scaled nitrous oxide emissions in a corn cropping system. *J. Environ. Qual.* **2011**, *40*, 1521–1531. [CrossRef]

20. Memon, M.S.; Guo, J.; Tagar, A.A.; Perveen, N.; Ji, C.Y.; Memon, S.A.; Memon, N. The effects of tillage and straw incorporation on soil organic carbon status, rice crop productivity, and sustainability in the rice-wheat cropping system of eastern China. *Sustainability* **2018**, *10*, 961. [CrossRef]
21. Turmel, M.S.; Speratti, A.; Baudron, F.; Verhulst, N.; Govaerts, B. Crop residue management and soil health: A systems analysis. *Agric. Syst.* **2014**, *134*, 6–16. [CrossRef]
22. Huang, S.; Zeng, Y.J.; Wu, J.F.; Shi, Q.H.; Pan, X.H. Effect of crop residue retention on rice yield in China: A meta-analysis. *Field Crops Res.* **2013**, *154*, 188–194. [CrossRef]
23. Gregorutti, V.C.; Caviglia, O.P. Nitrous oxide emission after the addition of organic residues on soil surface. *Agric. Ecosyst. Environ.* **2017**, *246*, 234–242. [CrossRef]
24. Henderson, S.L.; Dandie, C.E.; Patten, C.L.; Zebarth, B.J.; Burton, D.L.; Trevors, J.T.; Goyer, C. Changes in denitrifier abundance, denitrification gene mRNA levels, nitrous oxide emissions, and denitrification in anoxic soil microcosms amended with glucose and plant residues. *Appl. Environ. Microbiol.* **2010**, *76*, 2155–2164. [CrossRef]
25. Miller, M.N.; Zebarth, B.J.; Dandie, C.E.; Burton, D.L.; Goyer, C.; Trevors, J.T. Crop residue influence on denitrification, N_2O emissions and denitrifier community abundance in soil. *Soil Biol. Biochem.* **2008**, *40*, 2553–2562. [CrossRef]
26. Mosier, A.; Kroeze, C.; Nevison, C.; Oenema, O.; Seitzinger, S.; Van Cleemput, O. Closing the global N_2O budget: Nitrous oxide emissions through the agricultural nitrogen cycle. *Nutr. Cycl. Agroecosyst.* **1998**, *52*, 225–248. [CrossRef]
27. Shang, Q.Y.; Yang, X.X.; Gao, C.M.; Wu, P.P.; Liu, J.J.; Xu, Y.C.; Shen, Q.R.; Zou, J.W.; Guo, S.W. Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: A 3-year field measurement in long-term fertilizer experiments. *Glob. Chang. Biol.* **2011**, *17*, 2196–2210. [CrossRef]
28. Xia, L.L.; Wang, S.W.; Yan, X.Y. Effects of long-term straw incorporation on the net global warming potential and the net economic benefit in a rice–wheat cropping system in China. *Agric. Ecosyst. Environ.* **2014**, *197*, 118–127. [CrossRef]
29. Mutegi, J.K.; Munkholm, L.J.; Petersen, B.M.; Hansen, E.M.; Petersen, S.O. Nitrous oxide emissions and controls as influenced by tillage and crop residue management strategy. *Soil Biol. Biochem.* **2010**, *42*, 1701–1711. [CrossRef]
30. Ma, E.D.; Zhang, G.B.; Ma, J.; Xu, H.; Cai, Z.C.; Yagi, K. Effects of rice straw returning methods on N_2O emission during wheat-growing season. *Nutr. Cycl. Agroecosyst.* **2010**, *88*, 463–469. [CrossRef]
31. Sander, B.O.; Samson, M.; Buresh, R.J. Methane and nitrous oxide emissions from flooded rice fields as affected by water and straw management between rice crops. *Geoderma* **201**, *235–236*, 355–362. [CrossRef]
32. Kudo, Y.; Noborio, K.; Shimoozono, N.; Kurihara, R. The effective water management practice for mitigating greenhouse gas emissions and maintaining rice yield in central Japan. *Agric. Ecosyst. Environ.* **2014**, *186*, 77–85. [CrossRef]
33. Tierling, J.; Kuhlmann, H. Emissions of nitrous oxide (N_2O) affected by pH-related nitrite accumulation during nitrification of N fertilizers. *Geoderma* **2018**, *310*, 12–21. [CrossRef]
34. Shaaban, M.; Wu, Y.; Peng, Q.; Wu, L.; van Zwoeten, L.; Khalid, M.S.; Younas, A.; Lin, S.; Zhao, J.; Bashir, S.; et al. The interactive effects of dolomite application and residue incorporation on soil N_2O emissions. *Eur. J. Soil Sci.* **2018**, *69*, 502–511. [CrossRef]
35. Weitz, A.M.; Linder, E.; Frolking, S.; Crill, P.M.; Keller, M. N_2O emissions from humid tropical agricultural soils: Effects of soil moisture, texture and nitrogen availability. *Soil Biol. Biochem.* **2001**, *33*, 1077–1093. [CrossRef]
36. Mann, C. Meta-analysis in the breech. *Science* **1990**, *249*, 476–480. [CrossRef] [PubMed]
37. Liu, S.W.; Lin, F.; Wu, S.; Ji, C.; Sun, Y.; Jin, Y.G.; Li, S.Q.; Li, Z.F.; Zou, J.W. A meta-analysis of fertilizer-induced soil NO and combined NO+N_2O emissions. *Glob. Chang. Biol.* **2017**, *23*, 2520–2532. [CrossRef] [PubMed]
38. Shan, J.; Yan, X.Y. Effects of crop residue returning on nitrous oxide emissions in agricultural soils. *Atmos. Environ.* **2013**, *71*, 170–175. [CrossRef]
39. Skinner, C.; Gattinger, A.; Muller, A.; Mader, P.; Flieβbach, A.; Stolze, M.; Ruser, R.; Niggli, U. Greenhouse gas fluxes from agricultural soils under organic and non-organic management–a global meta-analysis. *Sci. Total Environ.* **2014**, *468–469*, 553–563. [CrossRef]
40. Hedges, L.V.; Olkin, I. *Statistical Methods for Meta-Analysis*; Academic Press: New York, NY, USA, 1985.

41. Rosenberg, M.S.; Adams, D.C.; Gurevitch, J. *METAWIN, Statistical Software for Meta-Analysis*, version 2; Sinauer: Sunderland, MA, USA, 2000.
42. Chen, D.G.; Peace, K.E. *Applied Meta-Analysis with R*; CRC Press: Boca Raton, FL, USA, 2013.
43. Flechard, C.R.; Ambus, P.; Skiba, U.; Rees, R.M.; Hensen, A.; van Amstel, A.; van den Pol-van Dasselaar, A.; Soussana, J.F.; Jones, M.; Clifton-Brown, J.; et al. Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe. *Agric. Ecosyst. Environ.* **2007**, *121*, 135–152. [CrossRef]
44. Six, J.; Ogle, S.M.; Breidt, F.J.; Conant, R.T.; Mosiers, A.R.; Paustian, K. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. *Glob. Chang. Biol.* **2004**, *10*, 155–160. [CrossRef]
45. Rochette, P. No-till only increases N_2O emissions in poorly-aerated soils. *Soil Tillage Res.* **2008**, *101*, 97–100. [CrossRef]
46. Senbayram, M.; Chen, R.; Budai, A.; Bakken, L.; Dittert, K. N_2O emission and the $N_2O/(N_2O+N_2)$ product ratio of denitrification as controlled by available carbon substrates and nitrate concentrations. *Agric. Ecosyst. Environ.* **2012**, *147*, 4–12. [CrossRef]
47. Van Zwieten, L.; Kimber, S.W.L.; Morris, S.G.; Singh, B.P.; Grace, P.R.; Scheer, C.; Rust, J.; Downie, A.E.; Cowie, A.L. Pyrolysing poultry litter reduces N_2O and CO_2 fluxes. *Sci. Total Environ.* **2013**, *465*, 279–287. [CrossRef] [PubMed]
48. Mei, K.; Wang, Z.F.; Huang, H.; Zhang, C.; Shang, X.; Dahlgren, R.A.; Zhang, M.H.; Xia, F. Stimulation of N_2O emission by conservation tillage management in agricultural lands: A meta-analysis. *Soil Tillage Res.* **2018**, *182*, 86–93. [CrossRef]
49. Zhao, X.; Liu, S.L.; Pu, C.; Zhang, X.Q.; Xue, J.F.; Zhang, R.Z.; Wang, Y.Q.; Lal, R.; Zhang, H.L.; Chen, F. Methane and nitrous oxide emissions under no-till farming in China: A meta-analysis. *Glob. Chang. Biol.* **2016**, *22*, 1372–1384. [CrossRef] [PubMed]
50. Dobbie, K.E.; Smith, K.A. Nitrous oxide emission factors for agricultural soils in Great Britain: The impact of soil water-filled pore space and other controlling variables. *Glob. Chang. Biol.* **2003**, *9*, 204–218. [CrossRef]
51. Horváth, L.; Grosz, B.; Machon, A.; Tuba, Z.; Nagy, Z.; Czóbel, S.Z.; Balogh, J.; Péli, E.; Fóti, S.Z.; Weidinger, T.; et al. Estimation of nitrous oxide emission from Hungarian semi-arid sandy and loess grasslands; effect of soil parameters, grazing, irrigation and use of fertilizer. *Agric. Ecosyst. Environ.* **2010**, *139*, 255–263. [CrossRef]
52. Hu, X.K.; Su, F.; Ju, X.T.; Gao, B.; Oenema, O.; Chrstie, P.; Huang, B.X.; Jiang, R.F.; Zhang, F.S. Greenhouse gas emissions from a wheat-maize double cropping system with different nitrogen fertilization regimes. *Environ. Pollut.* **2013**, *176*, 198–207. [CrossRef] [PubMed]
53. Zhang, Y.Y.; Liu, J.F.; Mu, Y.J.; Xu, Z.; Pei, S.W.; Lun, X.X.; Zhang, Y. Nitrous oxide emissions from a maize field during two consecutive growing seasons in the North China Plain. *J. Environ. Sci.* **2012**, *24*, 160–168. [CrossRef]
54. Millar, N.; Baggs, E.M. Relationships between N_2O emissions and water-soluble C and N contents of agroforestry residues after their addition to soil. *Soil Biol. Biochem.* **2005**, *37*, 605–608. [CrossRef]
55. Elmi, A.A.; Madramootoo, C.; Hamel, C.; Liu, A. Denitrification and nitrous oxide to nitrous oxide plus dinitrogen ratios in the soil profile under three tillage systems. *Bio. Fertil. Soils* **2003**, *38*, 340–348. [CrossRef]
56. Zhang, Z.S.; Guo, L.J.; Liu, T.Q.; Li, C.F.; Cao, C.G. Effects of tillage practices and straw returning methods on greenhouse gas emissions and net ecosystem economic budget in rice-wheat cropping systems in central China. *Atmos. Environ.* **2015**, *122*, 636–644. [CrossRef]
57. Lognoul., M.; Theodorakopoulos, N.; Hiel, M.-P.; Regaert, D.; Broux, F.; Heinesch, B.; Bodson, B.; Vandenbol, M.; Aubinet, M. Impact of tillage on greenhouse gas emissions by an agricultural crop and dynamics of N_2O fluxes: Insights from automated closed chamber measurements. *Soil Tillage Res.* **2017**, *167*, 80–89. [CrossRef]
58. Kainiemi, V.; Arvidsson, J.; Kätterer, T. Effects of autumn tillage and residue management on soil respiration in a long-term field experiment in Sweden. *J. Plant Nutr. Soil Sci.* **2015**, *178*, 189–198. [CrossRef]
59. Jiang, J.Y.; Huang, Y.; Zong, L.G. Influence of water controlling and straw application on CH_4 and N_2O emissions from rice field. *China Environ. Sci.* **2003**, *23*, 552–556. (In Chinese)
60. Cannavo, P.; Richaume, A.; Lafolie, F. Fate of nitrogen and carbon in the vadose zone: In situ and laboratory measurements of seasonal variations in aerobic respiratory and denitrifying activities. *Soil Biol. Biochem.* **2004**, *36*, 463–478. [CrossRef]

61. Gan, Y.T.; Campbell, C.A.; Jansen, H.H.; Lemke, R.; Liu, L.P.; Basnyat, P.; McDonald, C.L. Carbon input to soil by oilseed and pulse crops in semiarid environment. *Agric. Ecosyst. Environ.* **2009**, *132*, 290–297. [CrossRef]
62. Goglio, P.; Grant, B.B.; Smith, W.N.; Desjardins, R.L.; Worth, D.E.; Zentner, R.; Malhi, S.S. Impact of management strategies on the global warming potential at the cropping system level. *Sci. Total Environ.* **2014**, *490*, 921–933. [CrossRef]
63. Huang, Y.; Zou, J.W.; Zheng, X.H.; Wang, Y.S.; Xu, X.K. Nitrous oxide emissions as influenced by amendment of plant residues with different C:N ratios. *Soil Biol. Biochem.* **2004**, *36*, 973–981. [CrossRef]
64. Vigil, M.F.; Kissel, D.E. Equations for estimating the amount of nitrogen mineralized from crop residues. *Soil Sci. Soc. Am. J.* **1991**, *55*, 757–761. [CrossRef]
65. Barnard, R.; Leadley, P.W.; Hungate, B.A. Global change, nitrification, and denitrification: A review. *Glob. Biogeochem. Cycl.* **2005**, *19*, 13. [CrossRef]
66. Xu, R.; Prentice, I.C.; Spahni, R.; Niu, H.S. Modelling terrestrial nitrous oxide emissions and implications for climate feedback. *New Phytol.* **2012**, *196*, 472–488.
67. Feng, J.; Chen, C.; Zhang, Y.; Song, Z.; Deng, A.; Zheng, C.; Zhang, W. Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: A meta-analysis. *Agric. Ecosyst. Environ.* **2013**, *164*, 220–228. [CrossRef]
68. Zhou, G.Y.; Wei, X.H.; Wu, Y.P.; Liu, S.G.; Huang, Y.H.; Yan, J.H.; Zhang, D.Q.; Zhang, Q.M.; Liu, J.X.; Meng, Z.; et al. Quantifying the hydrological responses to climate change in an intact forested small watershed in Southern China. *Glob. Chang. Biol.* **2011**, *17*, 3736–3746. [CrossRef]
69. Zhou, M.H.; Zhu, B.; Wang, S.J.; Zhu, X.Y.; Vereecken, H.; Bruggemann, N. Stimulation of N_2O emission by manure application to agricultural soils may largely offset carbon benefits: A global meta-analysis. *Soil Tillage Res.* **2017**, *182*, 86–93.
70. Reichmann, L.G.; Sala, O.E.; Peters, D.P.C. Water controls on nitrogen transformations and stocks in an arid ecosystem. *Ecosphere* **2013**, *4*, 1–17. [CrossRef]
71. Chen, J.; Xiao, G.L.; Kuzyakov, Y.; Jenerette, G.D.; Ma, Y.; Liu, W.; Wang, Z.F.; Shen, W.J. Soil nitrogen transformation responses to seasonal precipitation changes are regulated by changes in functional microbial abundance in a subtropical forest. *Biogeosciences* **2017**, *14*, 2513–2525. [CrossRef]
72. Liu, C.Y.; Wang, K.; Meng, S.X.; Zheng, X.H.; Zhou, Z.X.; Han, S.H.; Chen, D.L.; Yang, Z.P. Effects of irrigation, fertilization and crop straw management on nitrous oxide and nitric oxide emissions from a wheat-maize rotation field in northern China. *Agric. Ecosyst. Environ.* **2011**, *140*, 226–233. [CrossRef]
73. Cai, Z.C.; Xing, G.X.; Yan, X.Y.; Xu, H.; Tsuruta, H.; Yagi, K.; Minami, K. Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. *Plant Soil.* **1997**, *196*, 7–14. [CrossRef]
74. Wrage, N.; Lauf, J.; Prado, A.D.; Pinto, M.; Pietrzak, S.; Yamulki, S.; Oenema, O.; Gebauer, G. Distinguishing sources of N_2O in European grasslands by stable isotope analysis. *Rapid Commun. Mass Spectrom.* **2004**, *18*, 1201–1207. [CrossRef]
75. Beauchamp, E.G.; Trevors, J.T.; Paul, J.W. Carbon sources for bacterial denitrification. *Adv. Soil Sci.* **1989**, *10*, 113–142.
76. Malhi, S.S.; Lemke, R.; Wang, Z.H.; Chhabra, B.S. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. *Soil Tillage Res.* **2006**, *90*, 171–183. [CrossRef]
77. Ussiri, D.A.N.; Lal, R.; Jarecki, K. Nitrous oxide and methane emissions from long term tillage under a continuous corn cropping system in Ohio. *Soil Tillage Res.* **2009**, *104*, 247–255. [CrossRef]
78. Liu, B.; Frostegard, A.; Bakken, L.R. Impaired reduction of N_2O to N_2 in acid soils is due to a posttranscriptional interference with the expression of nosZ. *mBio* **2014**, *5*, 1–10. [CrossRef] [PubMed]
79. Sánchez-García, M.; Roig, A.; Sanchez-Monedero, M.A.; Cayuela, M.L. Biochar increases soil N_2O emissions produced by nitrification-mediated pathways. *Front. Environ. Sci.* **2014**, *2*, 25.
80. Simek, M.; Cooper, J.E. The influence of soil pH on denitrification: Progress towards the understanding of this interaction over the last 50 years. *Eur. J. Soil Sci.* **2002**, *53*, 345–354. [CrossRef]
81. Russenes, A.L.; Korsaeth, A.; Bakken, L.R.; Dörsch, P. Spatial variation in soil pH controls off-season N_2O emission in an agricultural soil. *Soil Biol. Biochem.* **2016**, *99*, 36–46. [CrossRef]

82. De Figueiredo, C.C.; de Oliveira, A.D.; dos Santos, I.L.; Ferreira, E.A.B.; Malaquias, J.; de Sá, M.A.C.; de Carvalho, A.M.; dos Santos, J.D.D.G., Jr. Relationships between soil organic matter pools and nitrous oxide emissions of agroecosystems in the Brazilian Cerrado. *Sci. Total Environ.* **2018**, *618*, 1572–1582. [CrossRef]
83. Skiba, U.; Ball, B. The effect of soil texture and soil drainage on emissions of nitric oxide and nitrous oxide. *Soil Use Manag.* **2002**, *18*, 56–60. [CrossRef]
84. Zhou, M.; Zhu, B.; Butterbach-Bahl, K.; Zheng, X.; Wang, T.; Wang, Y. Nitrous oxide emissions and nitrate leaching from a rain-fed wheat-maize rotation in the Sichuan Basin, China. *Plant Soil.* **2013**, *362*, 149–159. [CrossRef]
85. Gu, J.; Nicoullaud, B.; Rochette, P.; Grossel, A.; Hénault, C.; Cellier, P.; Richard, G. 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.* **2013**, *60*, 134–141. [CrossRef]
86. Rochette, P.; Angers, D.A.; Chantigny, M.H.; Bertrand, N. Nitrous oxide emissions respond differently to no-till in a loam and a heavy clay soil. *Soil Sci. Soc. Am. J.* **2008**, *72*, 1363–1369. [CrossRef]
87. Huang, T.; Yang, H.; Huang, C.C.; Ju, X.T. Effect of fertilizer N rates and straw management on yield-scaled nitrous oxide emissions in a maize-wheat double cropping system. *Field Crops Res.* **2017**, *204*, 1–11. [CrossRef]
88. Plaza-Bonilla, D.; Álvaro-Fuentes, J.; Arrúe, J.L.; Cantero-Martínez, C. Tillage and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed Mediterranean area. *Agric. Ecosyst. Environ.* **2014**, *189*, 43–52. [CrossRef]
89. Bouwman, A.F.; Boumans, L.J.M.; Batjes, N.H. Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. *Glob. Biogeochem. Cycl.* **2002**, *16*, 6–13. [CrossRef]
90. Ju, X.T.; Xing, G.X.; Chen, X.P.; Zhang, S.L.; Zhang, L.J.; Liu, X.J.; Cui, Z.L.; Yin, B.; Christie, P.; Zhu, Z.L.; et al. Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 3041–3046. [CrossRef] [PubMed]
91. Qin, S.P.; Wang, Y.Y.; Hu, C.S.; Oenema, O.; Li, X.X.; Zhang, Y.M.; Dong, W.X. Yield-scaled N_2O emissions in a winter wheat summer corn double-cropping system. *Atmos. Environ.* **2012**, *55*, 240–244. [CrossRef]
92. Kim, D.G.; Hernandez-Ramirez, G.; Giltrap, D. Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input. A meta-analysis. *Agric. Ecosyst. Environ.* **2013**, *168*, 53–65. [CrossRef]
93. Van Groenigen, J.W.; Velthof, G.L.; Oenema, O.; Van Groenigen, K.J.; Van Kessel, C. Towards an agronomic assessment of N_2O emissions: A case study for arable crops. *Eur. J. Soil Sci.* **2010**, *61*, 903–913. [CrossRef]



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