The Responses of Soil N$_2$O Emissions to Residue Returning Systems: A Meta-Analysis

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Abstract: Background: Much attention has been focused on the influences of residue returning on N$_2$O emissions. However, comprehensive quantification of the effect size on N$_2$O emission following crop residue returning in subtropical, tropical and warm temperate conditions remains untested.

Methods: To identify site-specific factors that influence N$_2$O emission (kg N$_2$O-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$_2$O 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$_2$O 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$_2$O emission has been shown, residue returning could not reduce N$_2$O 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$_2$O emission following residue returning.

Keywords: residue returning; N$_2$O emission; land use; soil properties; N fertilizer application; meta-analysis

1. Introduction

Anthropogenic greenhouse gas emission (e.g., CO$_2$, CH$_4$, and N$_2$O) 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$_2$O emissions, resulting from agricultural inputs and direct soil-derived N$_2$O [3,4]. There are continuous concerns regarding N$_2$O emission due to its contribution to both global warming and ozone layer depletion [5]. In fact, N$_2$O 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$_2$O is naturally produced through the processes of microbial nitrification and/or denitrification [7]. Under aerobic soil conditions, N$_2$O 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$_2$O production. During this process, heterotrophic denitrifiers transform NO$_3^-$ to N$_2$O and N$_2$ [8]. Generally, denitrification is believed to be the main source of N$_2$O production in soils, as N$_2$O yield potential of denitrification is much higher (1–100%) than nitrification.
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$_2$O production when soil water-filled pore spaces were at 30–60% and 50–90%, respectively. Furthermore, N$_2$O emission dynamics are controlled by other factors, including soil temperature and agricultural management practices [14–16]. For example, a positive correlation between N$_2$O fluxes and soil temperatures was found, and no tillage can improve soil structure and lower its temperature, which in turn could reduce N$_2$O 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$_2$O 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$_2$O-N year$^{-1}$ globally. However, contradictory views exist in the literature regarding the influence of residue returning on N$_2$O production and release. Several studies have reported that residue returning stimulates N$_2$O 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$_2$O 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$_2$O production. In addition, the effects of residue application on soil N$_2$O 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$_2$O 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$_2$O emissions. For example, Liu et al. [37] conducted a meta-analysis to assess the impacts of fertilizer application on soil N$_2$O emissions. Shan and Yan [38] applied a meta-analysis and found that crop residue application methods could affect N$_2$O 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$_2$O emissions. The objective of this study was to conduct a meta-analysis to comprehensively quantify the effect size of crop residue returning on N$_2$O 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$_2$O”, “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$_2$O emission were performed using the closed chamber-gas chromatography method
in agroecosystem; (2) tillage and residue returning were clearly stated; (3) cumulative N\textsubscript{2}O emission could be obtained from each study.

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\textsubscript{2}O emission, replications, and standard deviation (SD) of both no-residue and residue returning treatments were obtained directly. If N\textsubscript{2}O 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):

\[
SD = SE \times \sqrt{n},
\]

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\textsubscript{2}O 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\textsubscript{2}O emissions (kg N\textsubscript{2}O-N ha\textsuperscript{-1}) associated with crop residues. The natural logarithm of response ratio (ln\(R\)) was adopted as the effect size of the comparing soil N\textsubscript{2}O emissions between controls and residue returning treatments [40].

\[
\ln R = \ln \frac{X_i}{X_c} = \ln(X_i) - \ln(X_c),
\]
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 ($\nu$) of $\ln R$ was estimated as follows:

$$\nu = \frac{SD_c^2}{n_tC^2} + \frac{SD_t^2}{n_tX_t^2},$$

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):

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

where $\ln R_i$ was the effect size, and $\omega_i$ was the weight of corresponding comparisons. $\omega_i$ was computed as follows:

$$\omega = \frac{1}{\nu},$$

where $\nu$ 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             | Q_b       | 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          |                |               |           |          |
| Soil initial properties | Residue returning duration (year)| 72      | 260          | ≤2             | 2–5           | >5             | 3.60          | 0.213          |                |               |           |          |
|                         | 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           | 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        | 20.01         | 0.001          |                |               |           |          |
| Agricultural management practices | Crop residue C: N | 39      | 96           | ≤45            | 45–100        | >100           | 29.97         | 0.39           |                |               |           |          |
|                         | Residue returning amount (kg DM ha⁻¹) | 58      | 199          | ≤4000         | 4000–6000     | >6000          | 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$_2$O emission compared to no-residue returning, with an increase by 8% (Figure 2a). RT, MC, and NT significantly increased N$_2$O 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$_2$O emissions between different residue returning methods. Soil N$_2$O 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$_2$O release was dependent on the amount of residue returning, but no tendency with amount of residue application was observed (Figure 2b). N$_2$O 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$_2$O 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$_2$O 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$_2$O 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.](image)

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).
N₂O 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 N₂O 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 N₂O release were discrepant depending on soil types. In the soils of clay loam and sandy clay loam, residue returning significantly stimulated soil N₂O emissions. While in other soils types—except silt loam soils—residue returning significantly suppressed N₂O release. A significant negative effect on soil N₂O emissions was shown at clay content ≤15% (mean: −27%), whereas, N₂O 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 N₂O 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 N₂O emissions following residue returning. First, soil N₂O 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 N₂O 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 N₂O Emission

Our meta-analysis showed that residue returning significantly increased soil N₂O 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 N₂O production and...
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![Figure 6](image_url)  
Figure 6. Effects of N fertilizer input (kg N ha$^{-1}$) on N$_2$O 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.

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Our meta-analysis showed that residue returning significantly increased soil N$_2$O 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$_2$O production and emission because N$_2$O 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$_2$O 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$_2$O release compared to the controls. Soil compaction in RT and NT can moderate soil aeration condition and promote N$_2$O 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$_2$O 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$_2$O 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$_2$O production [50–52]. Additionally, higher O$_2$ demands following residue application promote microbial denitrification for N$_2$O emission [53].

In this study, PT significantly inhibited N$_2$O release compared to controls, which might be attributed to a more effective reduction of N$_2$O 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 N₂O 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 CO₂ emission than RT and NT [58]. Chen et al. [13] also found a positive correlation between soil N₂O and CO₂ emissions following residue returning.

4.2. Effects of Residue Returning Amount, and Residue C/N Ratio on N₂O Emission

Residue returning could considerably alter soil availability of NH₄⁺ and NO₃⁻, the major factors controlling nitrification and denitrification processes, respectively. N₂O 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 N₂O production [59]. This result was identified by the correction between N₂O 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 N₂O production. Previous studies [61,62] have also reported similar increase in N₂O emissions with increasing residue amounts.

The negative correlation between residue C/N ratio and soil N₂O 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 N₂O 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 N₂O yields. In addition, other characters of crop residue, including lignin, polyphenol, and dissolved C may also play important roles in soil N₂O production and emission [65]. However, relevant studies are lacking, and more are needed regarding the effects of returning residue characters on N₂O emissions.

![Figure 7. Linear relationship between residue C/N ratio and mean effect size of N₂O emission.](image)

4.3. Effects of Climate Zone, Land Use, and Residue Returning Duration on N₂O Emission

Previous studies have identified that climate regimes can be considered as an impact factor of soil microbial nitrification/denitrification processes, and N₂O emissions through regulating soil moisture and temperature [66]. Our study indicated that relative to no-residue returning, residue returning significantly increased N₂O 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
Tropical climate with high temperatures may enhance nitrification activities, thus leading to \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) 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 \( \text{NO}_3^- \) losses via leaching \[71\], thus leading to small changes in average \( \text{N}_2\text{O} \) emission.

In this study, soil \( \text{N}_2\text{O} \) emission was closely related to land use types, where upland significantly increased but paddy fields significantly decreased \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) production \[73\]. In paddy fields, \( \text{N}_2\text{O} \) release derived from both nitrification and denitrification processes, which mainly occurs during the stage of alternate wetting and drying \[74\].

Residue returning significantly enhanced \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) \[75\], 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 \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) formation \[44,77\].

### 4.4. Effects of Initial Properties on \( \text{N}_2\text{O} \) Emission

Soil pH has been identified as a key regulator for \( \text{N}_2\text{O} \) production \[10\]. Our meta-analysis indicated that acidic soils (pH ≤ 6.5) and neutral soils (pH: 6.5–7.3) both had stimulatory effects on \( \text{N}_2\text{O} \) production. In acidic soils, stepwise denitrification processes might be inhibited by a reduction of reductase (\( \text{N}_2\text{OR} \)) activities, which could prevent \( \text{N}_2\text{O} \) conversion to \( \text{N}_2 \), leading to an increase in \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) production.

Soil texture and clay content are often implicated in regulating \( \text{N}_2\text{O} \) emission due to their impact on soil aeration and organic matter decomposition rates \[83\]. In our study, soil \( \text{N}_2\text{O} \) emission significantly increased in clay loam and sandy clay loam soils. Generally, \( \text{N}_2\text{O} \) 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 \[39\]. The clay loam and sandy clay loam soils belong to medium-textured soils, which could result in \( \text{N}_2\text{O} \) production from both nitrification and denitrification processes, thus leading to a higher \( \text{N}_2\text{O} \) emission. In other soil types, \( \text{N}_2\text{O} \) 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 N₂O 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 N₂O Emission

It is generally accepted that N₂O emission is significantly enhanced with the increase of N fertilizer application rate [87]. Furthermore, our study shows that N fertilizer application significantly affects N₂O production. Similar results have been reported with synthetic N fertilizer application, which improves nitrification and denitrification processes, leading to increased N₂O production [88]. However, significant negative effects and lower N₂O 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 N₂O emission and N fertilizer application rate. They found that before crop growth demand, a linear increase exists between N₂O 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 N₂O emissions [93].

Although these results provide clear information on N₂O 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 N₂O 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 N₂O 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 N₂O 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 N₂O emissions. For land use types, soil N₂O release significantly increased in upland fields, but significantly decreased in paddy fields following residue returning. The effects of crop residue returning on N₂O 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 N₂O 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 N₂O 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.

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