Return of crop residues to arable land stimulates N₂O emission but mitigates NO₃[−] leaching: a meta-analysis

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Accepted: 5 July 2021 / Published online: 4 October 2021
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Abstract

Incorporation of crop residues into the soil has been widely recommended as an effective method to sustain soil fertility and improve soil carbon sequestration in arable lands. However, it may lead to an increase in the emission of nitrous oxide (N₂O) and leaching of nitrate (NO₃[−]) to groundwater due to higher nitrogen (N) availability after crop residue incorporation. Here, we conducted a meta-analysis based on 345 observations from 90 peer-reviewed studies to evaluate the effects of crop residue return on soil N₂O emissions and NO₃[−] leaching for different locations, climatic and soil conditions, and agricultural management strategies. On average, crop residue incorporation significantly stimulated N₂O emissions by 29.7%, but decreased NO₃[−] leaching by 14.4%. The increase in N₂O emissions was negatively and significantly correlated with mean annual temperature and mean annual precipitation, and with the most significant changes occurring in the temperate climate zone. Crop residues stimulated N₂O emission mainly in soils with pH ranging between 5.5 and 6.5, or above 7.5 in soils with low clay content. In addition, crop residue application decreased NO₃[−] leaching significantly in soils with sandy loam, silty clay loam, and silt loam textures. Our analysis reveals that an appropriate crop residue management adapted to the site-specific soil and environmental conditions is critical for increasing soil organic carbon stocks and decreasing nitrogen losses. The most important novel finding is that residue return, despite stimulation of N₂O emissions, is particularly effective in reducing NO₃[−] leaching in soils with loamy texture, which are generally among the most productive arable soils.

Keywords Nitrous oxide · Nitrate leaching · Soil texture · Tillage · Straw · Fertilizer

1 Introduction

Nitrous oxide (N₂O) emission and nitrate (NO₃[−]) leaching from intensively managed cropland cause significant threats to adjacent environmental compartments (Bodirsky et al. 2012; Yang et al. 2018). N₂O has a 298 times greater global warming potential (GWP) than carbon dioxide (CO₂) and accelerates ozone depletion (Ravishankara et al. 2009). Intensively managed agricultural soils emit approx. 3.5 Mt N₂O-N year^{−1} (Pachauri et al. 2014), globally contributing

almost 60% to the anthropogenic N₂O and 21% to the overall N₂O emission (IPCC 2013). Nitrate leaching is another critical N loss pathway that leads to surface water eutrophication as well as groundwater pollution (Di and Cameron 2002). Therefore, finding strategies for improving nitrogen (N) retention in soil is highly relevant for making intensive agricultural production more sustainable (Fig. 1).

Return of crop residues with high carbon (C) content has great potential to improve N retention in soils (Yang et al. 2015). The annual production of crop residues reached nearly 4 billion metric tons at the beginning of the twenty-first century (Lal 2005). This indicates that appropriate utilization of crop residues with high N retention capacity could maintain soil fertility and reduce N losses effectively (Liu et al. 2014; Powlson et al. 2008). The C:N ratio of plant tissue is an important indicator of residue quality and decomposability, which is closely related to the immobilization of N, mainly by stimulating N retention in microbial biomass and increasing N sorption by the humus fraction (Chen et al. 2013). Crop residues with a low C:N ratio (<25), such as legume residues,

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Fig. 1 Example of crop residue management after harvest, which affects soil nitrogen retention (N_2O emission and NO_3^- leaching). Left: crop residue incorporation; right: crop residue removal. Photographs: Zhijie Li.

can be easily decomposed by the soil microbial community in a short time period, resulting in the release of available N, which can further undergo soil nitrification and denitrification (Reichel et al. 2018). The release of available N from crop residues can be beneficial for increasing crop yield in the next growing season, but only if it is not lost from the soil beforehand (Mooshammer et al. 2014; Whitmore and Groot 1997). However, residue decomposition can create anaerobic hotspots in the soil, which may stimulate denitrification, hence partially thwarting the benefit of soil C sequestration (Zhou et al. 2017a, b). Crop residues with C:N ratio greater than 25 are usually more recalcitrant and force microorganisms to take up N from soil to meet their N need; i.e., the decomposition of crop residues with high C:N ratio causes subsequent microbial N immobilization. As a consequence, the temporary shortage of soil N might restrict nitrification and denitrification, with beneficial effects on NO_3^- and N_2O losses (Aulakh et al. 2001; Cleveland and Liptzin 2007).

Cropland management strategies can affect the impact of residue return on soil N retention (Xia et al. 2014). For example, the application rate and composition of synthetic fertilizers affect soil nutrient availability, and different plowing methods can strongly affect the soil aggregate structure (Van Kessel et al. 2013; Xia et al. 2018). The effect of crop residue return on soil N retention is also influenced by soil properties. For instance, soil pH regulates the decomposition rate of crop residues providing N to nitrifiers and denitrifiers (Chen et al. 2013). Soil pH values of 7 or higher are favorable for denitrification (Wijler and Delwiche 1954), and the influence of crop residue return on the reduction of soil N_2O emissions was found to be most significant at pH 7.1–7.8 (Chen et al. 2013). Soil physical properties like pore size distribution, bulk density (BD), and water holding capacity content are key variables that control crop residue degradation and N transformation in soil (Chen et al. 2013). Climatic conditions, such as

mean annual temperature (MAT) and precipitation (MAP), can also affect N_2O emissions and NO_3^- leaching in combination with crop residue application (Butterbach-Bahl et al. 2013; Liu et al. 2017).

Even though several meta-analyses evaluating the responses of N losses to residue return have been published, to our knowledge a comprehensive assessment accompanied by cropland management strategies on soil N retention, N_2O emission, and NO_3^- leaching is lacking so far. Therefore, we conducted a global meta-analysis including 345 observations from 90 studies to systematically evaluate the overall effect of crop residue return on soil N retention and N losses (N_2O emission and NO_3^- leaching) (Fig. S1). We hypothesize that (1) residue return will stimulate N_2O emission, but mitigate NO_3^- leaching; and (2) the effectiveness of residue return on N losses will be governed by soil type, crop residue characteristics, climatic conditions, and cropland management.

2 Materials and methods

2.1 Data sources

To find the relevant literature for our meta-analysis, we used Web of Science, Google Scholar, and China National Knowledge to search for publications focusing on the comprehensive analysis of residue return and its effect on soil N losses, published before 11 January 2020. The search terms were “(residue OR straw OR organic amendment)” AND “(N_2O emission OR NO_3^- leaching).” In addition, we limited our selection to those publications of experimental studies that fulfilled the following criteria: (a) the study was based on practice-relevant field, mesocosm, and lysimeter experiments, excluding lab experiments; (b) N losses (N_2O emission or NO_3^- leaching) in the experiment were measured for at least

one growing season (observations made over several growing seasons were averaged); (c) experimental and control plots had been established in the same ecosystem and included at least one comparison of N losses; (d) statistical information such as mean values of N₂O emission and NO₃⁻ leaching, standard deviation (SD), and samples size in the experiment were directly extractable from the tables of the published articles, or were extracted from the graphs with the GetData Graph Digitizer software (version 2.26: <http://getdata-graph-digitizer.com/download.php>).

The selected studies provided information on (i) geographic coordinates (latitude and longitude), (ii) climatic zones ((sub)tropical, and temperate), (iii) land use type (paddy soil and upland soil), (iv) MAT and MAP; (v) soil texture, soil organic carbon (SOC), total nitrogen (TN), extractable P (EP), C:N ratio, pH, and BD; (vi) fertilizer composition (single N fertilizer or NPK compound fertilizer), N fertilizer types (urea, NH₄NO₃, (NH₄)₂SO₄, or NH₄HCO₃), and application times (number of fertilizer applications per growing season), and (vii) residue type, tillage method, and experimental duration. Crop residues were divided into low C:N residues with C:N < 25, and high C:N residues with C:N ≥ 25.

As some studies did not include the information on climate or soil properties, we obtained the missing data from the World Climate Database (<https://www.worldclim.org>) and the Harmonized World Soil Database v1.2 ((FAO) 2012) according to the geographic locations. The resolution of the data was 30 s for the World Climate Database and 5 min for the Harmonized World Soil Database. If the geographic locations were given in the unit of decimal degrees (DD), we converted them to degrees/minutes/seconds (DMS) with a DMS-DD converter (<https://www.fcc.gov/media/radio/dms-decimal>). Based on these selection criteria, we identified 345 observations from 90 peer-reviewed articles on a global scale. Specifically, the number of observations for N₂O emission was 255 (Table S2), and 90 for NO₃⁻ leaching (Table S3).

2.2 Data analysis

The effect size, evaluating the responses of N₂O emission and NO₃⁻ leaching to crop residue return, is defined as the natural logarithm of the response ratio (lnRR) (Hedges et al. 1999).

$$\ln RR = \ln \left(\frac{X_t}{X_c} \right) \quad (1)$$

where X_t and X_c are the mean value of the variable with (treatment) or without (control) crop residue return, respectively.

The variance (v) of each study was estimated as follows:

$$v = \frac{S_t^2}{n_t X_t^2} + \frac{S_c^2}{n_c X_c^2} \quad (2)$$

where n_t and n_c are the sample sizes of each variable in treatment and control groups, while S_t and S_c are the SD for the treatment and control groups, respectively. If only the standard error (SE) was given, the corresponding SD was recalculated.

This meta-analysis was performed using a nonparametric weighting function, and the weighting factor (W_{ij}), weighted response $\ln RR_{++}$, and standard error $S(\ln RR_{++})$ were calculated as follows:

$$W_{ij} = \frac{1}{v} \quad (3)$$

$$\ln RR_{++} = \frac{\sum_{i=1}^m \sum_{j=1}^k W_{ij} \ln RR_{ij}}{\sum_{i=1}^m \sum_{j=1}^k W_{ij}} \quad (4)$$

$$S(\ln RR_{++}) = \sqrt{\frac{1}{\sum_{i=1}^m \sum_{j=1}^k W_{ij}}} \quad (5)$$

where m is the number of groups and k is the number of comparisons.

The 95% bootstrap confidence interval (CI) of $\ln RR_{++}$ was calculated according to Curtis and Wang (1998) by bootstrapping 4999 iterations (Rosenberg et al. 1997):

$$95\% \text{CI} = \ln RR_{++} \pm S(\ln RR_{++}) \quad (6)$$

If the 95% CI of $\ln RR_{++}$ for a given variable overlapped with zero, the response to crop residue return was considered not significantly different between treatment and control.

The frequency distribution of $\ln RR$, reflecting the variability of crop residue effects among individual studies, was calculated with the following Gaussian function:

$$y = \alpha \exp \left[-\frac{(x - \mu)^2}{2\sigma^2} \right] \quad (7)$$

where y is the frequency of $\ln RR$ values within an interval, x is the mean value of $\ln RR$ for that interval, μ and σ^2 are the mean and variance across all $\ln RR$ values, respectively, and α is a coefficient indicating the expected number of $\ln RR$ at $x = \mu$.

The statistical tests were considered significant at the $p < 0.05$ level. All of the meta-analysis procedures were conducted using MetaWin 2.1 software (Sinauer Associates, Inc., Sunderland, MA, USA), and statistical analyses were performed using SPSS 21.0 (IBM Deutschland GmbH, Ehningen, Germany) for Windows.

2.3 Sensitivity analysis and publication bias

We conducted a sensitivity analysis to estimate the effects of crop residue return on N₂O emissions and NO₃⁻ leaching. First, a mixed model was established to calculate $\ln RR_{++}$ and reduce the disturbance of extreme variables simultaneously.

Then, we excluded $\ln RR$ randomly and decreased the $\ln RR$ numbers included in $\ln RR_{++}$ from 100 to 60%. Once the $\ln RR_{++}$ presented a significant difference between each other, it passes the sensitivity analysis unsuccessfully. Potential publication bias was analyzed with funnel plot analysis and Egger's indicator test (Egger et al. 1997) with the Stata Statistical Software (version 16, 2019, StataCorp LLC, College Station, TX, USA), using a 95% confidence interval.

3 Results

Our sensitivity analysis showed that the results of the meta-analysis did not change significantly after stepwise reduction of the number of observations, demonstrating the reliability of our analysis (Fig. S2). In addition, no publication bias was found when our data were analyzed with the funnel plot and Egger's test (Fig. S3).

The individual $\ln RR$ values of soil N_2O emissions or NO_3^- leaching were all normally distributed, but varied greatly among the observations (Fig. 2a, b). The $\ln RR$ of N_2O emission exhibited a great variability among the different studies, with a range from -2.26 to 3.06 (Fig. 2a), while the mean value of $\ln RR$ across all the 90 pairs of NO_3^- leaching was -0.12 (range from -2.85 to 1.39) (Fig. 2b). A higher N_2O emission but lower NO_3^- leaching was observed from cropland soil amended with crop residues compared to the non-amended control, but the differences were not significant (Fig. 2c, d).

The $\ln RR_{++}$ of soil N_2O emission and NO_3^- leaching to crop residue application differed between climate zones (Fig. 3; Table S1). Overall, crop residue application significantly stimulated N_2O emission by 29.7%, with a significantly higher increase of 35.7% in the temperate zone (Fig. 3a; Table S2). In contrast, no significant effect of crop residue application on N_2O emission was observed for tropical zones (Fig. 3a; Table S2). The mean value of $\ln RR_{++}$ across all responses of NO_3^- leaching to crop residue application was -0.14 (Fig. 3b; Table S3). The response of N_2O emission and NO_3^- leaching to residue application was affected by land use type. Upland soil amended with crop residues showed a significant increase of N_2O emission, which was 46% higher than control (Fig. 3a; Table S2). Conversely, it decreased the N_2O emission by 18% in paddy soil (Fig. 3a; Table S2). In contrast, crop residue application mitigated NO_3^- leaching in upland and paddy soil simultaneously (Fig. 3b; Table S3). The $\ln RR$ of N_2O emission was significantly and positively correlated with latitude, but not with longitude, MAT, and MAP (Table 1). In contrast, the $\ln RR$ of NO_3^- leaching had a significant and positive relationship with longitude, but no significant relationship with latitude, MAT, and MAP (Table 1).

Soil properties had a significant effect on the $\ln RR_{++}$ of N_2O emission and NO_3^- leaching (Table 1). Compared with

the control, crop residue application significantly increased N_2O emission by 54.0% when soil pH 5.5–6.5, and by 28.9% for soil pH > 7.5 (Fig. 4a; Table S2). The $\ln RR_{++}$ of N_2O emission showed negative linear correlations with pH, SOC, TN, EP, and BD, whereas the opposite was true for the correlation with C:N (Table 1). Generally, crop residue application mitigated soil NO_3^- leaching, and the decrease was significant for soil pH 6.5–7.5 (Fig. 4b). Moreover, the $\ln RR$ of NO_3^- leaching to crop residue application was significantly correlated with SOC, TN, EP, and BD (Table 1). Crop residue return caused a particularly strong and significant increase in soil N_2O emissions except for soil with clay texture, indicating that clay content is an important determinant of the soil N_2O emission response to crop residue application (Fig. 4a). Compared with the control, NO_3^- leaching from sandy loam, silty clay loam, and silt loam showed a significant negative response to crop residue application, with a decrease of 32.4%, 32.0%, and 39.5%, respectively (Fig. 4b, Table S3).

The $\ln RR_{++}$ of N_2O emission and NO_3^- leaching across all the studies varied with the fertilizer components, N fertilizer types, and fertilizer application times (Table S1). In comparison with the control, the overall effect of synthetic fertilizer application on N_2O emissions in combination with residue application was not significant, and the response of N_2O emissions to NPK compound fertilizer and single N fertilizers was statistically similar (Fig. 5a). In addition, the different N forms had no significant effect on N_2O emissions when applied with crop residues (Fig. 5a). Fertilizer application frequencies higher than four times per growing season could mitigate N_2O emission by 31.9% incorporated with crop residue application (Fig. 5a; Table S2). Nitrogen fertilizer composition significantly controlled the effect size of crop residue application on NO_3^- leaching. Application of NPK fertilizer increased the $\ln RR_{++}$ of NO_3^- leaching by 19.8%, whereas it was significantly decreased by 21.9% with application of single N fertilizer (Fig. 5a; Table S3). Among the different forms of synthetic N fertilizers, NH_4NO_3 significantly decreased NO_3^- leaching by 23.2% (Fig. 5a; Table S3). In contrast, the effect of urea did not significantly change the effect of crop residue application on NO_3^- leaching. The analysis also revealed that when the fertilizer was applied only once during the growing season, NO_3^- leaching was significantly reduced by 58.1% (Fig. 5b; Table S3).

The effect of crop residue application on soil N_2O emissions varied across residue types (Table 1). Application of low C:N residues (C:N<25) but also of the high C:N residues maize straw or wheat straw significantly stimulated N_2O emission by 163.4%, 34.9%, and 19.4%, respectively (Fig. 6a; Table S2). In contrast, N_2O emission decreased by 17.1%, 52.3%, and 74.5% with rice straw, sawdust, or sugarcane straw application, respectively (Fig. 6a; Table S2). Crop residue application generally decreased NO_3^- leaching, e.g., by 19.1% with wheat straw application (Fig. 6b; Table S3).

Fig. 2 Frequency distributions of response ratios (lnRR) of N_2O emission (a) and NO_3^- leaching (b) to crop residue application. The curves were fitted with a Gaussian function, and the mean value, coefficient of

determination (R^2) and significance level (p), and sample size (n) are shown. Linear regression between N_2O emission (c) and NO_3^- leaching (d) from control and treatment.

Tillage was also found to bias the effect of crop residue application on N_2O emissions. A significant increase in N_2O emissions occurred when no tillage or reduced tillage was performed on the top 10 cm layer (Fig. 6a). In addition, short experimental duration (<1 year) was associated with a significant increase in N_2O emissions by 117.8% (Fig. 6a; Table S2). In contrast to N_2O emission, tillage and duration of crop residue application had on average no significant effect on soil NO_3^- leaching relative to the control (Fig. 6b).

4 Discussion

4.1 Climatic conditions

Our analysis revealed that crop residue application significantly stimulated N_2O emission on average by 29.7% (Table S2).

Relative to the control, crop residue application caused an insignificant increase of N_2O emission in the tropical zone (Fig. 3), and the effect size of N_2O emission to crop residue return was characterized by a significantly negative linear relationship with MAT and MAP at the large scale (Table 1). This might be explained primarily by MAT and MAP being a function of climate and geographical location, which affect microbial nitrification and denitrification processes and subsequently N_2O emission and NO_3^- leaching (Barnard et al. 2006; Xu et al. 2012). The high temperatures in the tropical and subtropical zone might stimulate organic matter (OM) decomposition if there is enough precipitation, thereby improving N availability for nitrifiers and denitrifiers. However, the C released from crop residues might offset the N availability by stimulating soil microbial N immobilization (Sun et al. 2018). Second, labile C input could stimulate soil respiration and oxygen (O_2) depletion, which can cause O_2

Table 1 Linear or logarithmic regression analysis between the $\ln RR$ of N_2O emission and NO_3^- leaching to residue application as a function of latitude; longitude; MAT: mean annual temperature; MAP: mean annual precipitation; pH; SOC: soil organic carbon; TN: total nitrogen; C:N; EP: extractable phosphorus; BD: bulk density. n , number of observations included in the correlation analysis; R , Pearson's correlation coefficient; p , p value of correlation analysis and the values in bold indicate statistical significance at $p < 0.05$ probability level. $\ln RR$: natural logarithm of the response ratio. Logarithmic regression analysis was chosen when the result of linear regression analysis was insignificant. An asterisk (*) indicates a logarithmic regression relationship between variables and $\ln RR$ of N_2O emission and NO_3^- leaching.

Variables	N_2O emission $\ln RR$			NO_3^- leaching $\ln RR$		
	n	R	p	n	R	p
Latitude	245	0.142	<0.01	77	-0.191	>0.05
Longitude	245	-0.194	<0.05	77	0.248	<0.05
MAT	245	-0.244	<0.001	77	0.088	>0.05
MAP	245	-0.296	<0.001	77	0.057	>0.05
pH	255	-0.047	>0.05	82	-0.023	>0.05
SOC	241	-0.041	>0.05	76	-0.156	<0.05*
TN	209	-0.132	>0.05	45	-0.347	<0.05
C:N	209	0.135	<0.01*	44	-0.270	>0.05
EP	76	-0.368	<0.001	22	-0.461	<0.05
BD	218	-0.076	>0.05	43	0.331	<0.05

limitation in soil and thereby decrease the denitrification-related $N_2O:N_2$ molar ratio by stimulation of complete reduction of N_2O to N_2 (Paul and Beauchamp 1989; Vinten et al. 1998). For instance, greater N_2O emission was observed for sites with lower MAT, potentially caused by a stronger limitation of N_2O reduction by low temperature than N_2O production (Avalakki et al. 1995; Keeney et al. 1979). Third, moisture regulates soil O_2 diffusion. Soil in tropical and subtropical zones with high precipitation has a higher tendency towards

anoxic conditions, which foster complete denitrification with reduction of N_2O to N_2 (Davidson and Swank 1986).

This study further revealed that crop residue application decreased soil NO_3^- leaching by 14.4% relative to the control (Table S3), indicating that residue application improved soil water and fertilizer-N retention capacity in accordance with Blanco-Canqui et al. (2007). Possible reasons could be on the one hand a decrease in leachate percolation (Xia et al. 2018), which leads to an increase in NO_3^- retention, and on the other hand an increase in cation exchange capacity (CEC) (Xia et al. 2018), which reduces the availability of free NH_4^+ in the soil solution for nitrification by deprotonated carboxyl groups and thereby leads to a decrease in nitrification rate (Blanco-Canqui and Lal 2009). A third reason might also be temporary N absorption in soil pores or N adsorption on the surface of undecomposed residues (Yang et al. 2018). Compared with the control, no significant decrease in NO_3^- leaching after crop residue return was observed for the temperate zone. This is perhaps due to the fact that temperate soils with comparably lower MAP have a higher nitrification activity, thereby promoting the accumulation of NO_3^- . In addition, compared with the tropical and subtropical zone, the annually more evenly distributed precipitation in the temperate zone might attenuate the effect of crop residue return on NO_3^- leaching.

4.2 Land use type

Land use type, coupled with the availability of O_2 , soil C, and N substrates, controls soil N_2O emission significantly (Butterbach-Bahl et al. 2013; Davidson et al. 2000). Our statistical results showed an opposite effect of residue return on N_2O emission between upland and paddy soil (Fig. 3; Table S2). The 18% decrease in N_2O emissions from paddy soil could be explained by increasing microbial N

Fig. 3 Weighted response ratios ($\ln RR_{++}$) of soil N_2O emission (a) and NO_3^- leaching (b) to crop residue application in different climate zones and land use types. Mean effect and 95% confidence intervals (CI) are

shown. When the CI does not overlap with zero, the response is considered as significant. Numbers in parentheses indicate the number of observations.

Fig. 4 Weighted response ratios ($\ln RR_{++}$) of soil N_2O emission (a) and NO_3^- leaching (b) to crop residue application in dependence on soil pH and soil texture. The mean effect and 95% CIs are shown. When the

confidence intervals (CI) does not overlap with zero, the response is considered as significant. Numbers in parentheses indicate the number of observations.

immobilization and complete denitrification (Aulakh et al. 2001). Compared with the control, organic amendment degradation accelerates the O_2 consumption in rhizosphere and bulk soil. Hence, it creates an anaerobic condition, which—together higher DOC availability—favored denitrification and a complete reduction of N_2O to N_2 (Firestone and Davidson 1989). Yet, residue return increased N_2O emission by 46% in upland soil, which is similar to the findings of Xia et al. (2018)

and Liu et al. (2014). Compared with paddy soil, the upland ecosystem has a lower moisture content, usually coupled with higher O_2 availability in soil aggregates (Xia et al. 2018). Moreover, available N from residue decomposition favors autotrophic nitrification and heterotrophic denitrification, thereby increasing N_2O rather than N_2 emission, in upland soil (Chen et al. 2013; Davidson et al. 2000).

Fig. 5 Weighted response ratios ($\ln RR_{++}$) of soil N_2O emission (a) and NO_3^- leaching (b) to crop residue application in dependence on the composition of basic fertilizer, N fertilizer type, and the application

time. The mean effect and 95% CIs are shown. If the confidence intervals (CI) does not overlap with zero, the response is considered as significant. Numbers in parentheses indicate the number of observations.

Fig. 6 Weighted response ratios ($\ln RR_{++}$) of soil N₂O emission (a) and NO₃⁻ leaching (b) to crop residue application in dependence on residue type, tillage depth, and duration. The mean effect and 95% confidence

intervals (CI) are shown. If the CI does not overlap with zero, the response is considered as significant. Numbers in parentheses indicate the number of observations.

The responses of NO₃⁻ leaching to residue return were similar in upland or paddy soil (Fig. 3b). Residue return decreased NO₃⁻ leaching by reducing leachate percolation by 14% and 13% in upland and paddy soil, respectively. In upland soil, especially after residue application, soil microorganisms are forced to mine available N to keep the narrow C:N typically found for microbial biomass (Reichel et al. 2018). Moreover, higher SOC content after residue return can increase the cation exchange capacity, which prevents NH₄⁺ loss and reduces its availability for the conversion to NO₃⁻ (Blanco-Canqui and Lal 2009).

4.3 Soil pH

Soil pH is an important factor regulating soil N₂O emission (Butterbach-Bahl et al. 2013). In our meta-analysis, crop residue return remarkably stimulated soil N₂O emission. The increase in N₂O emission was particularly pronounced in soils with pH 5.5–6.5 or >7.5 (Fig. 4a). One potential reason could be the pH sensitivity of the enzyme N₂O reductase (Bakken et al. 2012), i.e., its intolerance to low and high pH, which leads to an inhibition of the reduction of N₂O to N₂ during denitrification at low and high pH, and hence to an increase in the mole fraction of N₂O:N₂ (Koskinen and Keeney 1982; Liu et al. 2010).

Compared with pH-neutral soil, higher N₂O emission in moderately acidic soils could be attributed to faster lignin and cellulose degradation, which stimulates the development of nitrifier and denitrifier communities, especially in N-rich soil (Pometto and Crawford 1986). In contrast, alkaline soil

was shown to have higher N₂O production potential due to the specific stimulation of ammonia-oxidizing bacteria (AOB), associated with a high ammonium oxidation rate (Law et al. 2011). Furthermore, the tendency towards higher N₂O emissions at lower and higher pH could also be due to the fact that the two steps of autotrophic nitrification, i.e., the oxidation of NH₄⁺ to NO₂⁻ by ammonia-oxidizing bacteria (AOB) and archaea (AOA), and of NO₂⁻ to NO₃⁻ by nitrite-oxidizing bacteria (NOB), have differently wide optimum pH ranges, with the optimum pH range of NOB (7.9 ± 0.4) being more narrow than that of AOB (8.2 ± 0.3) and AOA (7 ± 1) (Park et al. 2007; Gubry-Rangin et al. 2011). Any deviation from the optimum pH range of NOB to higher or lower values would favor the first step of nitrification, i.e., the oxidation of NH₄⁺ to nitrite (NO₂⁻), leading to temporary NO₂⁻ accumulation, which in turn can lead to substantial N₂O emission (Venterea 2007).

Soil pH is a critical factor for soil NO₃⁻ leaching (Cevallos et al. 2015). Our analysis indicated that crop residue application significantly decreased NO₃⁻ leaching in neutral soil in contrast to soil with pH > 7.5 (Fig. 4b). It is known that soil pH affects microbial nutrient immobilization and enzyme activity (Cao et al. 2016), but also the physicochemical properties of soil C-additives are crucial for the mitigation of NO₃⁻ leaching. For instance, lime and wood ash increased soil pH and NO₃⁻ leaching (Chinkuyu and Kanwar 1999; Gómez-Rey et al. 2012), while biochar was found to mitigate NO₃⁻ leaching despite an increase of soil pH (Knowles et al. 2011). Compared with fungi, bacteria have a comparably narrow optimum pH of 6.5–7.5, which implies a higher bacterial

activity and biomass in neutral soil than in acid or alkaline soil. Cellulase released by specific microorganisms stimulates the decomposition of crop residues, and the input of larger amounts of labile C enhances in turn microbial N immobilization.

4.4 Soil texture

Soil texture is an important factor shaping the size and distribution of soil pores and, hence, affecting soil aeration and O₂ availability, which are critical for decomposition of crop residues as well as the subsequent soil N transformation and loss pathways (Chen et al. 2013; Skiba and Ball 2002; Xia et al. 2018). Soils with coarse texture and high gas permeability rapidly stimulate crop residue decomposition and microbial respiration (Chen et al. 2013). However, as a consequence of stimulated O₂ consumption after residue incorporation, anoxic microsites might develop in the soil, which favor denitrification and N₂O emission at moderately low redox potential between 200 and 400 mV (Flessa and Beese 1995; Yu and Patrick 2003). In contrast, crop residue return significantly decreased N₂O emission from clay soil (clay content > 55%) (Fig. 4a). This might be due to the generally lower gas diffusivity in clayey soils, which decreases the decomposition rate of degradable organic residues and hence N mineralization, and which promotes even lower redox potentials than in sandy soils, i.e., low enough for N₂O reduction (Jarecki et al. 2008; Weitz et al. 2001). Furthermore, the clayey soils usually also have a higher CEC, which enhances the adsorption of NH₄⁺ by soil clay particles, which in turn can decrease NO₂⁻ production by AOB and NO₂⁻-related N₂O emissions (Venterea et al. 2015).

Soil NO₃⁻ leaching is regulated by the soil hydrologic regime. In this meta-analysis, crop residue application decreased NO₃⁻ leaching by 14.4% (Table S3). Residue application to soil stimulates microbial N retention, which leads to a decrease in NO₃⁻ leaching. Moreover, the straw return can also decrease NO₃⁻ leaching through decreased leachate percolation by increased water holding capacity of the soil (Gu et al. 2013). However, we found that the effect of residue application on NO₃⁻ leaching in sandy soil was not significant (Fig. 4b), which might mainly be attributed to the large pore size and poor water retention capacity of sandy soil (Gaines and Gaines 1994). In addition, the better air permeability of sandy soil is conducive to rapid decomposition of OM and subsequent nitrification of the ammonium released, and together with the inhibition of anaerobic denitrification, NO₃⁻ accumulation and finally NO₃⁻ will be promoted (Gaines and Gaines 1994).

4.5 Synthetic fertilizer application

Our results showed that there was no significant effect of the different components of synthetic fertilizer applied on N₂O emission. Zhou et al. (2017a, b) reported that globally the

application of manure was associated with higher N₂O emissions than synthetic fertilizer, which is mainly due to the larger input of easily available C with manure, stimulating N₂O emission from denitrification. Compared with NH₄⁺ or urea, higher N₂O emission was observed for residue return combined with NO₃⁻ as fertilizer (Fig. 5a). Nitrate fertilizer can serve directly as substrate for denitrification, causing higher N₂O emission together with the easily available C released during crop residue decomposition (Senbayram et al. 2012; Xia et al. 2020).

Excessive or ill-timed application of N fertilizer can lead to an over-supply of N in the soil that cannot be compensated by microbial immobilization anymore, resulting in an enhanced risk of N₂O emission (Hatfield and Cambardella 2001). The present analysis indicated that, compared with other methods, the application frequency of N fertilizer more than four times per growing season could decrease N₂O emission in combination with crop residue return (Fig. 5a). As well-timed, adequate fertilization is beneficial to the direct, demand-driven use of N by plants, excessive N losses can be avoided by this means.

In contrast to N₂O, there was a significant difference between the fertilizer components regarding NO₃⁻ leaching, when jointly applied with crop residues. Compared with single N application, crop residue return combined with NPK fertilizer application increased NO₃⁻ leaching significantly (Fig. 5b). There are two possible explanations. First, NH₄⁺ adsorbed to the soil matrix might be substituted by K⁺ and released to the soil solution, and subsequently converted to NO₃⁻ by nitrification. Second, the concomitant application of P might alleviate or terminate a potential P limitation of nitrifiers, thereby favoring the transformation of NH₄⁺ to NO₃⁻ (Cleveland et al. 2002; Purchase 1974).

Residue return decreased NO₃⁻ leaching after application of urea, albeit non-significantly (Fig. 5b). Urea is quickly hydrolyzed to NH₄⁺, which then can be either adsorbed to the soil matrix or be quickly immobilized by soil microbial biomass, especially after residue application (Jarecki et al. 2008). In contrast, we found that NO₃⁻ leaching was significantly decreased when with NH₄NO₃ application. One reason could be that the NO₃⁻ of NH₄NO₃ can directly serve as substrate for denitrification, which would reduce the NO₃⁻ load of the soil by converting it at least partially to gaseous N forms (N₂O, N₂). However, there are two additional potential explanations: on the one hand, the increase in CEC caused by residue application reduces the availability of free NH₄⁺, thereby limiting nitrification (Blanco-Canqui and Lal 2009; Kim et al. 2012; Qian and Cai 2007); on the other hand, straw enhanced microbial N immobilization due to its high C:N ratio, and by this decreased the substrate availability for nitrification and denitrification (Wang et al. 2014a, b).

4.6 Crop residue type

Previous research showed that easily available C released by residue degradation stimulates soil microbial N transformation from inorganic to organic form (Chen et al. 2013; Ma et al. 2009; Shan and Yan 2013). It is considered an efficient method to maintain soil fertility globally, though the efficiency could depend on residue type. Therefore, the potential risk of environmental pollution has to be evaluated for each crop residue type separately. It was shown previously that soil amended with crop residues with high C:N ratio stimulated microbial N immobilization, in contrast to N-rich crop residues (Baggs et al. 2000; Millar and Baggs 2005). The increase in soil C substrate availability due to incorporation of crop residues with a high content of easily available C, such as wheat straw, in combination with high soil mineral N content can stimulate N_2O emission substantially (Yue et al. 2017). In contrast, N released through the quick decomposition of low C:N residues (C:N < 25), e.g., alfalfa and soybean, provided N in excess of the plant and microbial N demand (Shan and Yan 2013).

Easily available C stimulates microbial growth and activity in particular, provided that the N supply is sufficient, but labile C also serves as electron donor for the reduction steps of denitrification from NO_3^- to N_2 and supplies essential energy for heterotrophic microbial activity (Firestone and Davidson 1989). Therefore, input of labile C to soil can have, as already discussed in the previous sections, basically two effects on N_2O , i.e., a reduction in N_2O emission due to microbial N immobilization, or an increase in N_2O emission due to stimulation of denitrification at intermediate redox potential. Based on our results, the effect size of crop residue return to soil on N_2O emission was significantly and negatively correlated with sawdust, sugarcane straw, or rice straw application (Fig. 6a). In contrast, wheat or maize straw stimulated N_2O emission in our analysis (Fig. 6b), which was also reported by Shan and Yan (2013). Large amounts of high C:N residues with low content of soluble, easily available C, like sawdust, sugarcane, or rice straw, will force heterotrophic microorganisms to mine available N (Cleveland and Liptzin 2007), thereby decreasing the N resource for nitrification and denitrification and subsequent N_2O emission (Baggs et al. 2000). Crop residues with a higher content of soluble, easily available C, like wheat or maize straw, will not only stimulate the growth of heterotrophic soil microorganisms but also stimulate denitrification due to high O_2 consumption, and hence N_2O emission (Reichel et al. 2018).

Our results also showed that wheat straw application inhibited soil NO_3^- leaching significantly, while the effect of return of other residues with different C:N ratios on NO_3^- leaching was not significant (Fig. 6b). This finding suggests that the C:N ratio is not the main factor affecting NO_3^- leaching, but possibly the fraction of easily

available C that stimulates microbial N immobilization (see above), or perhaps either physical characteristics of crop residues that control soil NO_3^- leaching, such as increased water retention, or that particularly wheat straw stimulates denitrification due to the high amount of easily available C, thereby converting most of the NO_3^- to gaseous N forms (N_2O , N_2). Another possible explanation is that wheat straw can reduce NO_3^- and NO_2^- concentrations in the surface soil and percolating water by increasing crop N uptake, thereby decreasing NO_3^- leaching (Yang et al. 2018).

4.7 Tillage

Several tillage methods in combination with crop residue return were used in the studies we analyzed. Our results showed that surface application of crop residues and shallow tillage (0–10 cm) stimulated N_2O emission significantly (Fig. 6a). This is possibly due to increased denitrification activity stimulated by the anoxic conditions caused by the rapid decomposition of incorporated crop residues, associated with high O_2 consumption and fostered by high temperatures in the first 10 cm of the soil (Kandeler et al. 1999; Ma et al. 2009). In contrast, residue return with deep tillage (>10 cm) caused no statistically significant difference in N_2O emission compared to the control (Fig. 6a). Deep tillage reduces the BD of the soil, thereby improving soil O_2 availability and inhibiting denitrification (Khurshid et al. 2006).

In terms of NO_3^- leaching, we did not find a significant influence of the tillage method used for crop residue return (Fig. 6b). This might be due to the fact that soils with different textures react very differently to tillage regarding stimulation or inhibition of mineralization, nitrification, and denitrification. For instance, no significant effect of tillage on NO_3^- leaching was found for a coarse sandy soil, whereas a significant effect was observed for sandy loam soil (Hansen and Djurhuus 1997).

4.8 Duration of the experiments

The duration of arable land management is a critical factor affecting the effect size of crop residue return on soil N retention. Our analyses revealed a significant difference in N_2O emission between soils with and without crop residue return, when the duration of the experiment was less than 1 year (Fig. 6a). A reason could be that the majority of C and N will be released from the residues in the first weeks and/or months, and afterwards the effect will be gradually reduced (Chen et al. 2013). Fast and substantial nutrient release from decomposing crop residues was found to stimulate nitrification and denitrification, favoring O_2 depletion and the formation of partial anoxic conditions, which stimulate N_2O emission rapidly

(Xia et al. 2018). However, no significant difference in N_2O emission between soils with and without crop residue incorporation was observed when the duration of the experiment was longer than 1 year, suggesting a potential adaptation effect of the soil and its microbial community to the treatment.

Our analysis also showed that short-term crop residue return can reduce NO_3^- leaching by more than 10%, in contrast to long-term (> 3 years) crop residue return (Fig. 6b). In the short term, the growing microbial biomass acts as a sink for inorganic soil N, stimulated by the increased input of labile C, thereby reducing the risk of NO_3^- leaching (Zechmeister-Boltenstern et al. 2002). On the contrary, long-term crop residue return might lead to saturation of the SOC pool with subsequent adaptation of the microbial community to this new equilibrium, thereby on the one hand increasing its resistance against disturbance or environmental change, but on the other hand also decreasing its N buffering capacity (Griffiths and Philippot 2013).

4.9 Overall effects of residue return on N losses

So far, some mitigation effects of crop residue return on N runoff were reported (Blanco-Canqui et al. 2006; Xia et al. 2018). The phenomenon could be attributed to the change of soil structure, which leads to an increase in water infiltration rate and a decrease in surface runoff, and thereby to a decreased risk of soil erosion (Lindstrom 1986). Recently, some new perspectives were also presented that crop residue return can increase NH_3 emission by stimulating ammonium-related soil N transformations. For example, Xia et al. (2018) found that crop residue return significantly increased the gross N mineralization rate by 82.4% and dissimilatory NO_3^- reduction to NH_4^+ (DNRA) by 155%. The stimulation of these specific N transformation processes leads to an increase in soil NH_4^+ content, which in turn serves as substrate for NH_3 emission.

4.10 Potential publication bias

We collected data with wide geographic coverage to achieve high robustness of this meta-analysis. The results of funnel plot analysis and Egger's indicator test showed that there was no systematic publication bias in our database. In parallel, we checked the geographic coordinates of the outliers in the funnel plot and found that they were not located in the southern hemisphere (Fig. S3). Therefore, we conclude that the inclusion of data from poorly studied areas of the world did not result in publication bias. Nevertheless, we acknowledge that the lack of data in some areas of the world warrants more intensive study, particularly in the southern hemisphere.

5 Conclusion

Overall, this meta-analysis provides valuable insights into the effect of crop residue return on soil N_2O emission and NO_3^- leaching and their dependence on climate zone, soil properties, and arable land management. We present two major perspectives: First, crop residue application increases soil N_2O emission by stimulating microbial nitrification and denitrification. Second, soil NO_3^- leaching is mitigated by crop residue amendment. Our results reveal some opposing trends when compared with previous studies and provide new guidance for future research. Crop residues need to be applied depending on soil fertility and climatic conditions. For instance, amendment of nutrient-poor soil with low C:N residues is recommended, thereby decreasing the application of synthetic fertilizer, accelerating the recovery of soil fertility, and supplying nutrients for the next growing season, especially in areas with low crop yield. Besides, crop residue return combined with deep tillage should be generally applied based on site-specific soil conditions because N_2O emission and N losses through leaching, runoff, or ammonia (NH_3) volatilization, which pose a risk of soil nutrient loss without safeguarding procedures, are thereby minimized. However, due to differences in soil structure and microbial activity between different soils and sites, the determination of the optimal tillage frequency requires further study. Overall, the focus should be on harnessing the positive effects of crop residue return for maintaining and improving soil fertility and for sustaining or even increasing crop productivity. Ultimately, this will help to balance sustainable farming, economic benefit, and protection of the environment in the future.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13593-021-00715-x>.

Code availability Not applicable.

Authors' contributions NB and RR gave suggestions for this meta-analysis. ZL performed the data collection and analysis, and wrote the paper. NB and RR revised the paper. ZX supported the data analysis process.

Funding Open Access funding enabled and organized by Projekt DEAL. This study was conducted in the INPLAMINT project of the BonaRes initiative, funded by the German Federal Ministry of Education and Research (BMBF, FKZ 031B0508A), and supported by the Chinese Scholarship Council (scholarship no. 201706910069).

Data availability The data of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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