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Is Crop Residue Removal to Reduce N_2O Emissions Driven by Quality or Quantity? A Field Study and Meta-Analysis

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Abstract: In order to quantify the reduction potential for nitrous oxide (N_2O) release from arable soils through the removal of crop residues, we conducted an experiment after sugar beet (*Beta vulgaris* L.) harvest with three treatments: (i) ploughing of the crop residues (+CR:D), (ii) returning residues after ploughing on the surface (+CR:S), and (iii) removal of the residues and ploughing (−CR). N_2O fluxes were measured over 120 days in south Germany. High positive correlations between N_2O fluxes and the CO_2 fluxes and soil nitrate contents suggested denitrification as the main N_2O source. N_2O emissions in +CR:D was higher than in +CR:S (2.39 versus 0.93 kg N_2O−N ha^{-1} 120 d^{-1} in +CR:D and +CR:S). Residue removal in −CR reduced the N_2O emission compared to +CR:D by 95% and to +CR:S by 87%. We further conducted a meta-analysis on the effect of crop residue removal on N_2O emissions, where we included 176 datasets from arable soils with mainly rain fed crops. The overall effect of residue removal showed a N_2O reduction of 11%. The highest N_2O reduction of 76% was calculated for the removal subgroup with C/N-ratio < 25. Neither the remaining C/N-ratio subgroups nor the grouping variables “tillage” or “residue quantity” differed within their subgroup.

Keywords: crop residues; N_2O emissions; C/N ratio; crop removal; sugar beet residues; meta-analysis

1. Introduction

Nitrous oxide (N_2O) is one of the climate relevant trace gases, it accounts for 7.4% of the anthropogenically derived greenhouse effect [1]. It has a long atmospheric lifetime of more than 100 years, and a 296-fold higher global warming potential compared to the same mass of carbon dioxide (CO_2) [2]. Furthermore, N_2O is involved in stratospheric ozone depletion [3,4].

More than 60% of the anthropogenic N_2O is released from the agricultural field [5] with biological denitrification and nitrification as the main sources for N_2O production in soils [6,7] where the contribution of other processes—e.g., nitrifier-denitrification—are currently under discussion [8]. Since all processes of N_2O production in soils rely on mineral N, the input of mineral or organic fertilization provides the substrates (nitrate (NO_3^-) and ammonium (NH_4^+) for these processes and thus fuels N_2O emission from soils (e.g., [9]).

Crop residues constitute a substantial input of mainly organic bound N and, hence, may also contribute to N_2O emissions from arable soils after mineralization. Lal [10] estimated a global emergence of 3.8×10^9 Mg crop residues with 74% from cereals, 8% from legumes, 3% from oil crops, 10% from sugar crops, and 5% from tuber crops. Depending mainly on the chemical properties of these crops, the mineralization of the residues may affect the mineral N pool in soils. Easily decomposable crop residues like cauliflower can increase the N pool between 95 and 140 kg N ha^{-1} after harvest [11,12] whereas other residues with a large C/N-ratio—e.g., wheat straw—may lead to an immobilization of mineral N [13]. Therefore, crop residues may affect N_2O emissions from soils because they increase [14,15] or decrease [16,17] the substrate availability for N_2O production. Consequently, knowledge on the effect of crop residues on N_2O emission may help to derive residue management strategies (such as removal or also the transfer of crop residues to other fields) for the reduction of N_2O emissions. Unfortunately, results from experiments on the overall effect, e.g., of removal are in part very contradicting. Guzman et al. [18] removed half or all of the corn residues. In the second experimental year, removal successfully reduced the annual N_2O emission when compared to a treatment with all crop residues. In contrast, removal did not affect the emission in their first experimental year.

Besides the chemical composition of crop residues, some studies also reported a relation between amount of crop residues and N_2O emission. Hu et al. [19] showed, that increasing the amount of crop residues (>6 Mg ha^{-1} dry matter) also increased N_2O emission from soils in tropical and subtropical regions, suggesting that the removal of the residues in turn might reduce them. In agreement, Schmatz et al. [20] reported enhanced N_2O emissions with increasing the amount of vetch residues. In contrast to the results with vetch (low C/N ratio), Schmatz et al. [20] did not find an effect of increasing the amount of wheat residues (high C/N ratio) on N_2O emissions. These results suggest that there is a close connection between quality and quantity of crop residues.

Different tillage systems may also affect the decomposition and mineralization of crop residues and thus they may also decide on the success of crop residue removal on N_2O reduction. It was shown that decomposition and mineralization of crop residues increases with increasing contact area between residues and soil [21,22], and therefore faster decomposition could be expected in conventional ploughed systems, whereas the decomposition in no tillage (NT) systems where residues remain on the soil surface is slowed down. The latter would decrease substrate availability and thus reduce N_2O emissions. This assumption was confirmed in the study of Guzman et al. [18] where the removal of 50% of the crop residues showed lower N_2O emissions in the NT treatment.

Although few studies on the effect of crop residue removal on N_2O emissions from arable fields were conducted, a more general evaluation is still missing. Therefore, we conducted a meta-analysis as one part of this study where we determined the impact of crop residues with different C/N-ratios, of varying amounts of residues and of different soil tillage on N_2O emissions after residue removal. The study was similar to the study of Hu et al. [19] who focused on soils in subtropical and tropical regions (with paddy and upland paddy as the main land use), whereas we focused mainly on arable, rain-fed crops grown world-wide. Chen et al. [23] also conducted a meta-analysis on the effect of crop residue addition on N_2O emissions. However, this meta-analysis was based mainly on laboratory measurements (86% laboratory; 14% field), in comparison to the one reported here, which is based entirely on field measurements (100% field). Shan and Yan [24] also conducted a similar meta-analysis on the effects of returning crop residues on N_2O emission. Although this study was also based entirely on field measurements, in comparison, the present meta-analysis includes 90% more studies and 57% more datasets (treatment/control observations), owing to the many studies on the effect of crop residues on N_2O emissions that have been conducted and published since Shan and Yan [24] executed their meta-analysis.

Some former work in our study region with vegetables showed extremely high N_2O emissions over winter when the N-rich residues from Broccoli (*Brassica oleracea* var. *italica* P.) or cauliflower (*Brassica oleracea* var. *botrytis* L.) were left in the field. Removal of the residues after harvest resulted in a reduction in N_2O emissions down to the same level as in an unfertilized control [15]. In a current project with sugar beet (*Beta vulgaris* L.), we are again confronted with crop residues with a narrow C/N-ratio, similar to the ones from the vegetables and potentially high emissions during winter. Thus, we tested the effect of sugar beet residue removal and application depth in an additional field experiment and we present these results together with the meta-study.

The working hypothesis of our field experiment and/or of our meta-study were: (1) Removal of crop residues generally reduces N_2O emissions from arable fields because it reduces substrate availability for N_2O production in soils, (2) N_2O reduction through crop residue removal increases with decreasing C/N-ratio of the residues because of the mineralization and, therefore, NH_4^+ and NO_3^- supply increase with decreasing C/N-ratio, (3) N_2O reduction increases with rising dry matter removal, and (4) residue removal in conventional tillage systems (CT) shows higher N_2O reduction than in reduced (RT) or no-tillage systems (NT).

2. Materials and Methods

2.1. Field Experiment

2.1.1. Study Site

The field experiment was conducted at the experimental farm "Ihinger Hof" which belongs to the University of Hohenheim in southern Germany. The farm is located 483 m above sea level (48°44′41′′ N, 8°55′26′′ E) in the "Heckengäu" region where agriculture is dominated by arable farming. The temperate climate in this region is characterized by a mean annual air temperature of 7.9 °C and by a mean annual precipitation of 690 mm. Soil type at the study site was a Luvisol, the main physical and chemical soil properties are shown in Table 1.

Table 1. Chemical and physical soil characteristics of the experimental field.

Soil Depth [m]	Clay [%]	Silt [%]	Sand [%]	C_{org} [%]	N_t [%]	pH [1]
0–0.3	25.5	71.4	3.1	1.53	0.15	7.5
0.3–0.6	31.8	66.6	1.6	–	–	7.1
0.6–0.9	34.9	60.5	4.6	–	–	6.9

C_{org} = organic carbon; N_t = total nitrogen, [1] measured in 0.01 *M* $CaCl_2$ solution.

2.1.2. Field Experiment and Experimental Setup

The field experiment was integrated in a randomized complete block design with four replications established in 2018. The field experiment was part of the project "Reduction of greenhouse gas emissions in plant production with optimized catch crop systems". Prior to our measurements, oil radish (*Raphanus sativus L.*, var. "Defender") was seeded as catch crop on 12 September 2018. Sugar beet (*Beta vulgaris L.*, var. "Lisanna KWS", 107,000 plants ha^{-1}) was seeded on 16 April and harvested on 24 October 2019. Split into two doses, total N fertilization of the sugar beets was 160 kg N ha^{-1}. To quantify the effect of the crop residues on N_2O emissions, we demarcated subplots with an area of 3 m^2 each (1.5 × 2 m) where the plots were calibrated using a portable GPS (Nomad, Trimble, Sunnyvale, CA, USA). After sugar beet harvest, we established the following treatments:

1. Sugar beet residues remained on the plots and were ploughed (depth 0.03 m) on 27 September (+CR:D);
2. Sugar beet residues were removed before and surface applied after ploughing (+CR:S);
3. Sugar beet residues were removed before ploughing (−CR).

Soil tillage increases C turnover and potential nitrification and denitrification [25,26] and consequently, it was shown that tillage can enhance N_2O emissions from arable soils [27,28]. Therefore, we decided to plough each treatment on 27 October to avoid superimposing crop residue effects with tillage effects.

During harvest of the main experiment, we headed approximately 130 sugar beets in each main plot and determined the fresh matter of sugar beet residues. In total, 90% of the residues were leaves and 10% stemmed from the beet crowns. In the following, we consider both leaves and crowns as one fraction. A homogenized aliquot of the sugar beet residues was dried at 60 °C for 48 h to quantify dry matter contents. A further aliquot was ground and C- and N- contents were determined with a CN analyzer (VarioMax, Elementar Analysensysteme, Hanau, Germany). Fresh and dry matter contents and C- and N- contents of the sugar beet residues (mixture of 90% leaves and 10% crowns) are given in Table 2.

Table 2. Mean values (n = 4 subsamples) of fresh matter (FM), dry matter (DM), total C (C_t), total N (N_t) and C/N-ratio (C/N) of sugar beet residues (leaves and crowns together).

FM [Mg ha^{-1}]	DM [Mg ha^{-1}]	C_t [Mg ha^{-1}]	N_t [Mg ha^{-1}]	C/N
26.401	4.947	1.824	0.112	16.3

Based on the fresh matter yield in Table 2, we applied 7.95 kg of fresh homogenized sugar beet residues per subplot. On 28 October, winter wheat (*Triticum aestivum* L., var. "Nordkap") was sown in all treatments.

2.1.3. Trace Gas Measurements, Soil Sampling and Laboratory Analysis

Trace gas measurements were performed with the closed chamber method [29]. We used dark, vented polyvinyl chloride chambers with an inner diameter of 0.3 m as described in detail by Flessa et al. [30]. One base frame was installed in the center of each subplot directly after sowing of the winter wheat (one day after ploughing). Flux measurements were conducted at least once a week between 9:00 and 11:00 AM. In the first three weeks after the application of sugar beet residues gas samples were taken twice a week. Additional measurements were performed when increased flux rates were expected (after heavy rainfall or during soil thaw).

During flux determination, four gas samples were taken periodically out of the chambers atmosphere within a total enclosure time of 45 min through a sampling port with a septum using a syringe and transferred into evacuated glass vials (12 mL Exetainer, Labco Limited, Lampeter, UK).

N_2O- and CO_2- concentrations in the glass vials were determined using a gas chromatograph with a Ni^{63} electron capture detector (GC 450 Greenhouse Gas Analyzer, Bruker Daltonic, Bremen, Germany) coupled with an autosampler (GX-271 LH, Gilson, Limburg, Germany). The separation of the trace gases was carried out using a Hayesep D column (80–10 mesh), with the oven temperature set at 80°C. Chromatograms were integrated using Bruker Compass CDSTM 2012 software.

Simultaneously to each gas sampling, temperature in 0.05 m soil depth and in the chamber was measured using portable thermometers. At the same time, soil samples were taken from the A_p-horizon (0−0.3 m depth). For the determination of soil moisture and mineral N, we took two samples per plot and pooled the samples over the four replicated plots. This procedure unfortunately yielded only one non-replicated sample per treatment and date, but it allowed for a high temporal resolution of sampling in the small subplots.

The samples were stored frozen until extraction with 0.0125 M $CaCl_2$ solution [1:5 weight by weight] [31]. The extracts were filtered and analyzed for ammonium (NH_4^+-N) and nitrate (NO_3^--N) using a continuous flow injection analyzer (3 QUAAtro, SEAL Analytical, Norderstedt, Germany).

Gravimetrical soil moisture was determined by drying at least 25 g of fresh soil at 105 °C for 24 h.

Soil bulk density (0−0.3 m) was determined four weeks after ploughing using 100 mL cylinders in 0.05 m increments. The soil cores were dried at 105 °C until constant weight.

Water-filled pore space (WFPS) was than calculated as follows:

$$\text{WFPS} = \text{gravimetric soil moisture} \times \text{soil bulk density} \times \text{total porosity}^{-1}, \quad (1)$$

with soil porosity calculated as

$$\text{Soil porosity} = 1 - \text{soil bulk density} \times 2.65^{-1}, \quad (2)$$

with 2.65 Mg m^{-3} (particle density of quartz) being the assumed particle density of the soil.

2.1.4. Calculations and Statistical Analysis for the Field Study

Trace gas fluxes were calculated using the package "gasfluxes" [32] for R software [33]. Based on the Akaike information criterion (AIC) and the kappa value, the package selects the most suitable model for calculating trace gas fluxes (linear model, nonlinear HMR model) [34], or robust linear regression model [35]. More details for the calculation of the fluxes was given by Ruser et al. [36].

Cumulative N_2O emission was calculated assuming constant flux rates between two sampling dates.

Statistical analyses were carried out using the statistical software package SigmaStat 3.5. We performed a one way ANOVA to detect differences between the cumulative N_2O emissions. Cumulative N_2O emissions were Ln transformed in order to ensure normal distribution. Significant differences were determined using a pairwise multiple comparison procedure (Student–Newman–Keuls, $p < 0.05$).

The relation between soil factors (soil moisture, NO_3^--N, NH_4^+-N, respiration, and soil temperature) and the mean flux rates of N_2O were analyzed by applying a stepwise multiple linear regression. Before these analyses, frequency distributions of the dependent and independent variables were tested for normality using the Kolmogorov–Smirnov test ($p > 0.05$) and Log_{10} transformed if the data were not normally distributed.

2.2. Meta-Analysis

2.2.1. Data Source and Approach for Meta-Analysis

The present meta-analysis focuses on N_2O emission from arable land and how it is influenced by the removal of crop residues compared to a treatment without residue removals. Between April and August 2020, we searched exclusively for peer-reviewed literature with the engines Scopus, Google Scholar, and HohSearch, an electronic literature tool of the University of Hohenheim that employs the EBSCO Discovery Service (EDS), thus covering databases such as ScienceDirect, CAB Abstracts, JSTOR, and Scopus, among many others. In our search, we used combinations of keywords from the following groups: N_2O emission: "nitrous oxide" or "N_2O" and "emission(s)", "field"; crop residue: "residue", "straw", "stubble", "stover" and "removal", "retained", "returned", "incorporated"; Tillage system: "conventional tillage", "CT", "no till", "NT", "reduced tillage", "RT". Results from lab studies and lysimeter studies were excluded as well as studies from rice paddies.

We included the results of our field experiment described above (treatments: +CR:D and –CR) as well as two additional datasets that are not yet published by our working group [37]. Due to the difference in the ploughing method before surface application, we did not include our treatment +CR:S in the meta-analysis.

Data were included in the meta-analysis database if the publication met the following four criteria:

1. Peer-reviewed publication
2. Field study
3. N_2O flux measurements conducted for at least 60 days
4. At least one treatment in which crop residues were retained on or returned to the experimental plot (control, C)

If necessary, N_2O emission from these data sets was transferred to kg N_2O-N ha^{-1}.

2.2.2. Performing Meta-Analysis

The collected data sets (observations) were used to assign them to three grouping variables, within the grouping variables they were assigned to subgroups (Table 3). The data sets could be compared based on their effect size.

Table 3. Grouping variables and their subgroups used in meta-analysis focusing on crop residues removals effects on N_2O emission.

Grouping Variables	Subgroups					Studies	Observations
	1	2	3	4	5		
C/N ratio	< 25	25– < 50	50– < 75	75– < 100	≥ 100	36	173
Residue quantity [Mg DM ha^{-1}]	< 4	4–< 6	≥ 6			22	92
Tillage system	NT	CT	RT			36	174

DM = dry matter; NT = zero or no tillage; CT = conventional tillage; RT = reduced tillage.

The subgroups of tillage system were classified according to the keywords for: (1) CT: conventional tillage, plowing, ploughing, 25 cm depth, 30 cm depth; (2) RT: reduced tillage, rotary tillage, strip till, harrowing, 10 cm depth, 15 cm depth; and (3) NT: no-tillage, zero tillage, direct drilling, mulching, spreading on soil surface. The classification of the subgroups for the quantity of residues was based on Hu et al. [19], who used the same ranking in their meta-analysis, which focused on the retention of residues as the main treatment. The categorization of the subgroup C/N ratio was based on Harmsen and Kolenbrander [38], and Seneviratne [39], who assumed N-mineralization at a C/N of less than 20–25 and 27, respectively, and N-immobilization from a C/N above. For simplicity, a value of <25 was chosen as the lowest category, and the other categories were increased by this value by a factor of two, three and four up to a C/N of ≥100. If the C/N ratio of a crop residue was not reported in a publication, we used the values provided in Table 4.

Table 4. C/N ratios of crop residues of broccoli, lettuce, cauliflower, pea, soy, oilseed rape, barley, winter wheat, and maize straw and their allocation into subgroups.

Crop	C/N Ratio	C/N Ratio Subgroup	Source
Broccoli (*Brassica oleracea* var. *italica* L.)	13.7	<25	Velthof et al. [40]
	10		Congreves et al. [41]
	9–23		De Ruijter et al. [42]
Lettuce (*Lactuca sativa* var. capitata L.)	10.3–18.7	<25	Pfab et al. [43]
	7.5		Baggs et al. [44]
Cauliflower (*Brassica oleracea* var. *botrytis* L.)	8.2–17.1	<25	Pfab et al. [43]
	11.6–18.6		Chaves et al. [45]
	11		Rezaei Rashti et al. [46]
Pea (*Pisum sativum* L.)	26.4	25– < 50	Achilles et al. [47]
Soy (*Glycine max* L.)	41.1	25– < 50	Achilles et al. [47]
Oilseed rape (*Brassica napus* L.)	73.9	50– < 75	Achilles et al. [47]
	61.9		Ruser et al. 2017 [1]
Barley (*Hordeum vulgare* L.)	87.9	75– <100	Achilles et al. [47]
Winter wheat (*Triticum aestivum* L.)	87.9	75– <100	Achilles et al. [47]
	82.8		Guzman-Bustamante et al. [28]
Maize (*Zea mays* L.)	49–65	50– <75	Ruser et al. [48] [1]
	49.6		Achilles et al. [47]
	65.1		Mean data meta-analysis [2]

[1] Raw data from the study site Ihinger Hof, a research station of the University of Hohenheim (treatment: 180 kg N ha^{-1} a^{-1}; mean of 3 years and 4 replicates). [2] Mean of all datasets from this meta-analysis where C/N ratios for maize straw were provided.

We used the *baseline contrasts* method which "expresses treatment effects in each trial as a contrast relative to a baseline or control treatment in the respective trial" [49,50]. Based on the assumption that there is variability between observations due to differences in experimental conditions (sites, years, precipitation among other environmental factors), the *continuous random effects* method with a 95% confidence interval was chosen to analyze the data [51] and ran with the basic univariate meta-regression for continuous and categorical covariates "metafor" [52,53].

The meta-analysis was conducted with the software OpenMEE [53]. The following formula was used to calculate effect sizes (natural log-transformed response ratios, lnRR) of the experimental treatment "residue removed" (E) in relation to the control or baseline treatment "residue retained or returned" (C):

$$lnRR = \ln\left(\frac{X_E}{X_C}\right), \quad (3)$$

The variance (V_{lnRR}) of effect sizes was calculated using the following formula:

$$V_{lnRR} = \frac{(S_E)^2}{N_E * (X_E)^2} + \frac{(S_C)^2}{N_C * (X_C)^2}, \quad (4)$$

X_E S_E N_E: mean value, standard deviation and sample size of residue removed
X_C S_C N_C: mean value, standard deviation and sample size of residue retained or returning

If a standard deviation (STD), variance or standard error of the mean (SEM) was not reported in a study, we calculated a conservative and reliable estimate of STD with the two-tailed inverse of the Student's t-distribution using p-values or t-values, the number of replicates (n) and the difference of means between treatment and control. If neither STD nor p values were provided, we imputed them using estimates from STD reported in the remaining studies used the meta-analysis. As shown by Furukawa et al. [54], the imputation of missing STDs leads to reliable estimates of effect sizes in meta-analyses. Imputation was performed within the OpenMEE software with the function "Impute missing Data" [53]. Using the default settings, for both control and treatment the missing standard deviations were imputed, selecting the first choice displayed. These were noted as fixed and used equally for all performed meta-analyses. As a sensitivity analysis for the effect of STD imputation on overall effect sizes, we compared the overall effect size of a meta-analysis containing imputed STD to one without imputed STDs.

The overall mean effect size (E) was calculated by:

$$E = \frac{\sum(lnRR_i * W_i)}{\sum W_i}, \quad (5)$$

$lnRR_i$ = effect size of the ith data set with W_i.

$$W_i = \frac{1}{V_{lnRR}} \quad (6)$$

W_i = weight of ith data set.

For reporting, data were back-transformed from the natural ln to actual response ratios. Consequently, the labels on the x-axes of the forest plots show the relative N_2O emissions of treatment (E) to control (C). Effect sizes and 95% confidence intervals (CIs) below 1, therefore, indicate a lower mean N_2O emission from the treatment (E) than from the control (C). Conversely, effects sizes and CIs higher than 1 indicate higher N_2O emissions from the treatment (E) than from the control (C). Effect sizes equal to 1 or CIs including 1 indicate no difference between the N_2O emissions of the treatment (E) and the control (C).

Heterogeneity was analyzed with Q-statistic [55] and estimated with I^2 [56].

The presence of publication bias, a likelihood that more studies with statistically significant effects are published than studies without significant effects, was investigated firstly by visually inspecting the funnel plots of effect sizes. In the absence of publication bias, the individual values should be arranged symmetrically in the form of a funnel around the overall mean effect size, whereas an asymmetrical arrangement indicates a possible publication bias [57]. Secondly, the numerical fail-safe N-test [58] was used to confirm the absence of publication bias. The number N indicates the number of unpublished non-significant studies that would be required to nullify a statistically significant difference between treatment (E) and the control (C) [59]. Jennions et al. [60] proposed an N-value of "5 (N) + 10" as a lower limit, at which the significant meta-analytical result can be considered robust despite possible publication bias, where N represents the number of studies used to estimate the overall effect size.

3. Results

3.1. N_2O Flux Rates and Cumulative N_2O Emission as Affected by Sugar Beet Residue Management in the Field Experiment

The N_2O fluxes in our field trial showed a high temporal variability over the entire experimental time with flux rates ranging between −1 and 277 µg N_2O-N m^{-2} h^{-1} (Figure 1). Except for one sampling date in early December 2019, N_2O fluxes in the period between residue application and mid-January 2020 were always highest in the treatment with ploughing of the sugar beet residues. The lowest flux rates were measured in the treatment with removal of the residues. The highest flux in this treatment (−CR) was 10 µg N_2O-N m^{-2} h^{-1} on 7 November 2019.

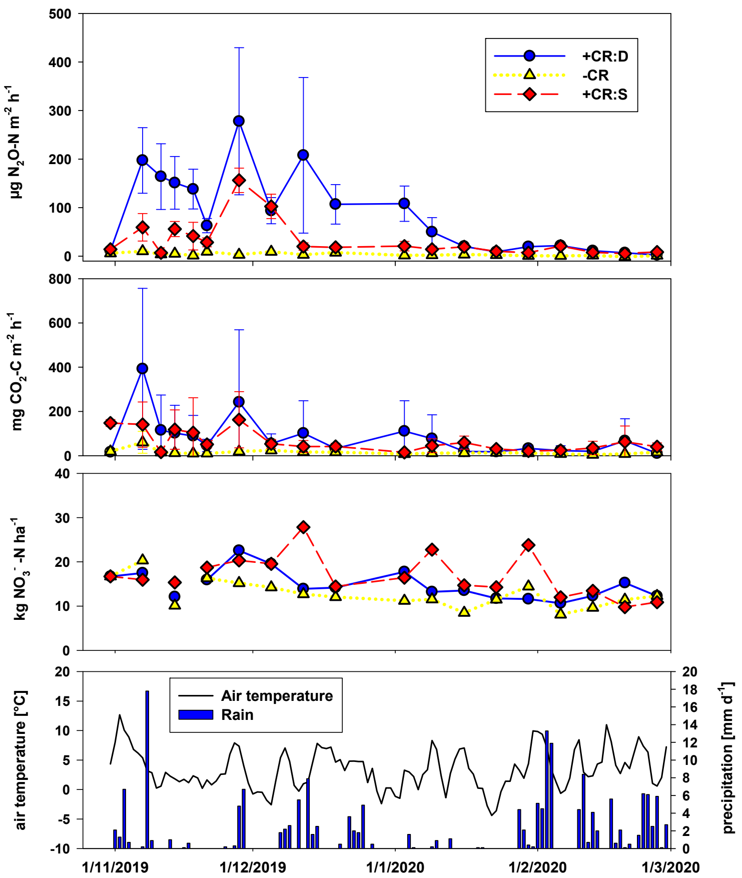

Figure 1. Mean N_2O flux rates (n = 4 ± standard error), mean CO_2 flux rates (±standard error), and soil nitrate contents (0–0.3 m depth) as affected by sugar beet residue management and mean daily air temperature in 2 m height (black line) and daily precipitation (blue bars). +CR:D = residues ploughed in, −CR = residues removed from the field and +CR:S = residues surface applied after ploughing.

Besides crop residues application, increased N_2O fluxes were also measured after 11.5 mm rainfall on 28 and 29 November 2019, as well as after several smaller rainfall events in the second December week 2019 (Figure 1). Shorter periods with frost and thaw did not affect N_2O flux rates at all.

The CO_2 flux rates varied between 4 mg CO_2−C m^{-2} h^{-1} in the removal treatment and 393 mg CO_2-C m^{-2} h^{-1} on 7th November in the treatment where residues were ploughed in (Figure 1). Removal of the sugar beet residues strongly decreased CO_2 fluxes when compared to the treatments where the crop residues remained in the field. Similarly, the removal treatment also showed the lowest soil nitrate contents in the period with the highest N_2O emission activity. The CO_2 flux rates and the soil nitrate contents were highly correlated with the N_2O flux rates (Pearson Product Moment Correlation, $p < 0.001$). CO_2 flux was the first independent variable entering the stepwise linear regression model explaining 43.8% of the variability of the $\log_{10}$ transformed N_2O flux rates. Log_{10} transformed soil nitrate-N was the second and last independent variable entering the model accounting for a further 10.5% of the N_2O flux variability ending up in a total coefficient of determination of 54.3% (not shown). All other independent variables (NH_4^+−N contents, WFPS, soil temperature in 0.05 m depth) did not render the regression model more accurate.

The mean cumulative N_2O emission over the entire field experiment (31 October 2019 until 28 February 2020) ranged between 0.12 and 2.39 kg N_2O-N ha^{-1} and it decreased in the order +CR:D > +CR:S > −CR (Figure 2). Cumulative N_2O emission over the entire experimental period differed significantly between all treatments ($p < 0.05$).

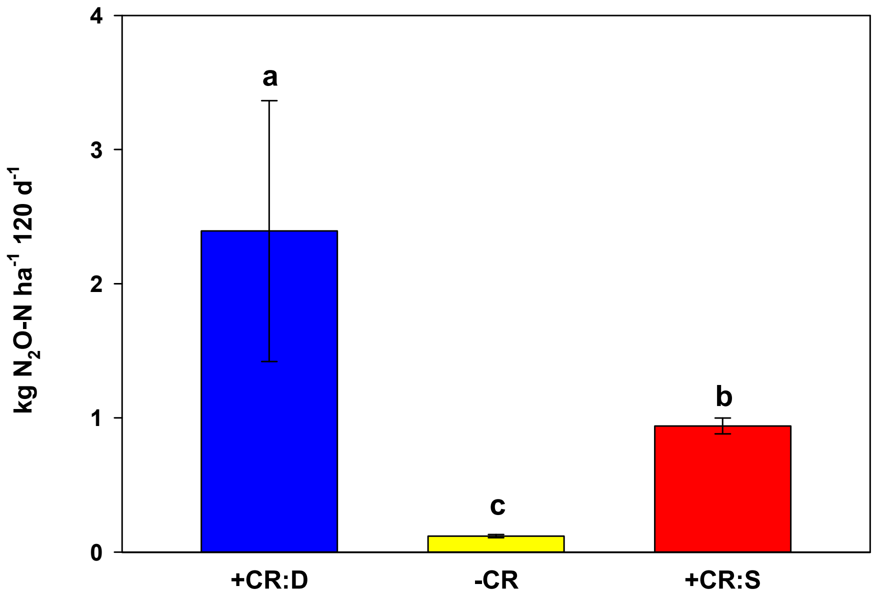

Figure 2. Mean cumulative N_2O emission (n = 4 ± standard error) over the experimental period of 120 days as affected by sugar beet residue management. +CR:D = residues ploughed in, −CR = residues removed from the field and +CR:S = residues surface applied after ploughing. Means followed by a common letter refer to Log_{10} transformed data and are not significantly different by the Student–Newman–Keuls Test at the 5% level of significance.

3.2. Meta-Analysis

3.2.1. Overall Results

The literature search using keywords and their combinations in various scientific literature databases as described in Section 2.2.1 produced 57 peer-reviewed publications. A description of the selection process is given in Figure S1. Of these, nine were discarded for the following reasons: meta-analysis (3), laboratory study (2), no treatment with residue removal (4). Of the remaining 48 studies, 12 where discarded because they were investigations on paddy rice. To the remaining

36 publications, we added data from the field experiment described above and data from a study in our own working group, which has not yet been published. Finally, 38 studies were included in the meta-analysis. A comprehensive list of all datasets showing the number of replicates, mean and standard deviation of N_2O emissions for the treatment (E) and the control (C) are provided as supplementary materials (Table S1). These generated 176 individual datasets of treatment (E)/control (C) observations. Information about C/N ratio group variable was available for 173 datasets: <25 (n = 8), 25− >50 (n = 22), 50− <75 (n = 83), 75− <100 (n = 50), ≥100 (n = 10). For the moderator quantity of crop residue, 92 datasets were available, which were arranged in the following categories: <4 Mg DM ha^{-1} (n = 15), 4− <6 Mg DM ha^{-1} (n = 31), ≥6 Mg DM ha^{-1} (n = 46). In total, 174 datasets could be organized in three categories according to the moderator tillage system: conventional tillage (CT, n = 80), not-till (NT, n = 80) and reduced tillage (RT, n =14).

For studies that did not report a measure of variance, or for which a measure could not be reliably estimated, we imputed the missing standard deviations (STDs). Results from the sensitivity analysis showed an overall effect size of −0.83 ($p < 0.001$, CIs: 0.782–0.875, n = 144) obtained for datasets with reported STDs only, which was not different from the overall effect size of all datasets including reported and imputed STDs, 0.89 ($p < 0.001$, CIs:0.854–0.924, n = 176). Therefore, the imputation of missing STDs did not alter the outcome of the meta-analysis.

Risk for publication bias was checked by visual inspection of funnel plots and by the numerical fail-safe N-test [61]. Funnel plots showed good symmetry of effect sizes of individual datasets around the overall mean effect size Figure S2. The resulting fail-safe number N = 393, which is less than the critical lower limit of 200 (5 × (n = 38 studies) + 10), was in line with the symmetry of effects sizes observed in the funnel plot. All in all, these showed that there was no risk of publication bias associated with the selected peer-reviewed publications.

Overall, the meta-analysis revealed that the effect size of removing crop residues in comparison to retaining them on the field N_2O emission was 0.89 ($p < 0.001$, CIs: 0.854–0.924, n = 176). This showed that the removal of crop residues led to 11% lower N_2O emissions in comparison to retaining or returning crop residues on the field.

3.2.2. Effect on C/N Ratio and the Quantity of Crop Residues on the Effect Size

The effect size of the subgroup C/N ratio <25 was significantly higher than those in subgroups with higher C/N ratio (Figure 3). The removal of crop residues with a low C/N ratio (<25) led to 76% lower N_2O emissions in comparison to the control (effect size: 0.24; CIs: 0.140–0.414).

The relative N_2O emissions of the remaining groups (all groups C/N-ratio >25) were distinctively less (between 6 and 9% lower than in the control treatment). For the groups with C/N ratios between 25 and 100, the effect sizes varied between 0.91 and 0.94. For the subgroup C/N ratio 25− <50, 75− <100 and ≥100, relative N_2O emission of residue removal was not different from 1.

Since the data used for the calculation of the effect sizes based on the C/N ratio categories (n = 173) were almost the same as that used to estimate effects sizes based on soil tillage systems (n = 174), the overall effect size according to C/N ratio was nearly identical to the overall effect size according to soil tillage system. For the C/N ratio, the overall effect size was 0.89 (CIs: 0.856–0.926).

Although the removal of 4− < 6 Mg ha^{-1} crop residue dry matter resulted in a significant reduction in N_2O emissions when compared to the control treatment, there was no significant difference between the effect size of this category and the effects sizes of < 4 and ≥ 6 Mg ha^{-1} (Figure 3). Even though only 92 datasets containing data on the quantity of crop residues were used for this analysis, the overall effect size of 0.89 (CIs: 0.842–0.940) was in complete accordance with the overall effect sizes, with a larger number of observations for soil tillage (174) and C/N ratio (173).

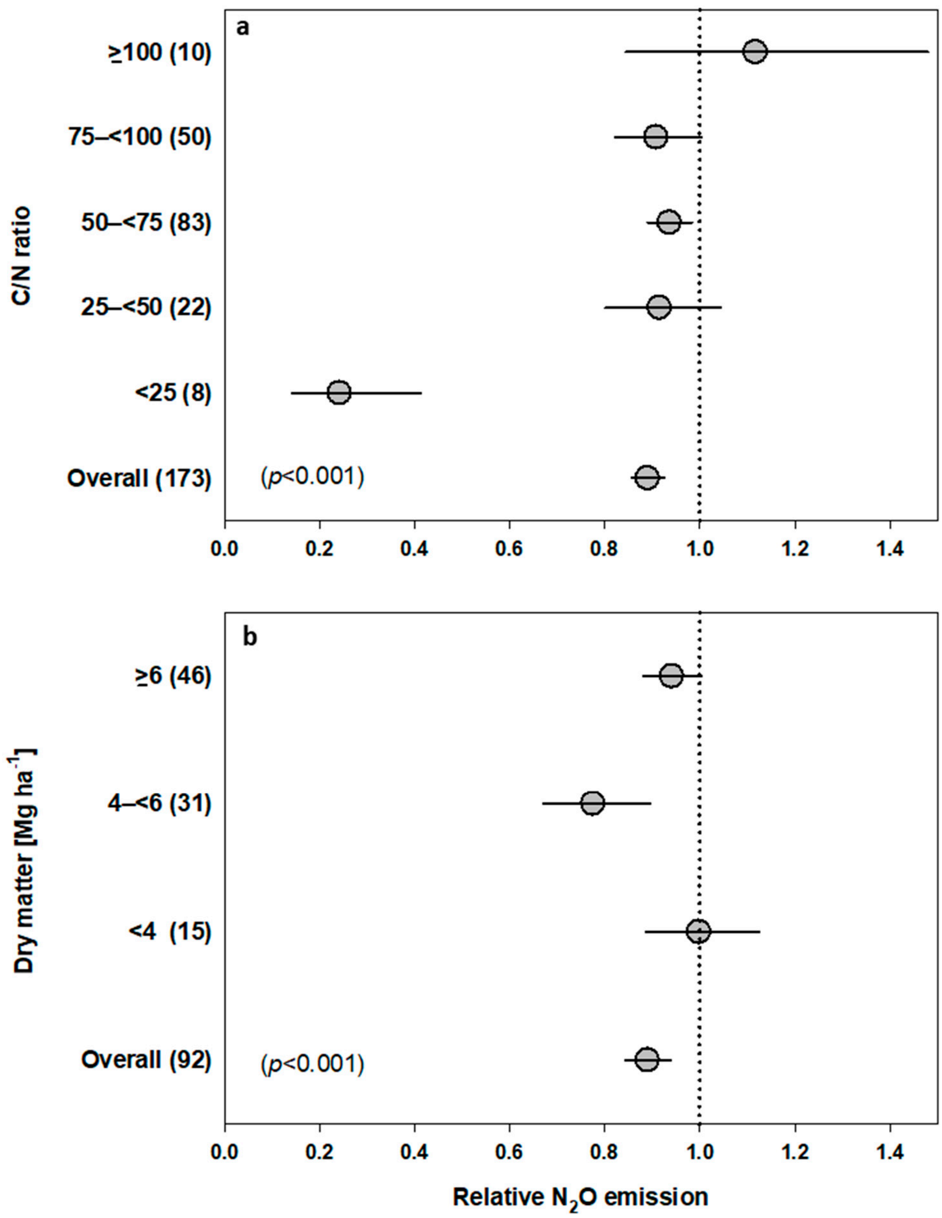

Figure 3. The effect crop residue removal on N_2O emissions as affected by C/N-ratio (**a**) and quantity of aboveground crop residues (**b**). N_2O emissions from control treatments with crop residues = 1. Mean effect sizes (circle) and 95% confidence intervals (CIs, error bars) are shown. The number of observations is given in parentheses.

3.2.3. Effect of Tillage System on Effect Size

When compared to the control treatments, all types of tillage systems showed significantly lower N_2O emissions when crop residues were removed (Figure 4). Reduced tillage (RT) showed a tendency to lead to the highest effect size with a reduction in N_2O emissions by 31% (effect size: 0.69, CIs: 0.543–0.874). However, the effect size of RT did not differ significantly from those of conventional tillage (CT) and no-till (NT) due to the overlapping of their CIs. These were 0.87 (CIs: 0.817–0.925) for CT and 0.93 (CIs: 0.873–0.991) for NT. Overall, the removal of crop residues reduced the N_2O emission by 11% (effect size: 0.89; CIs: 0.856–0.926).

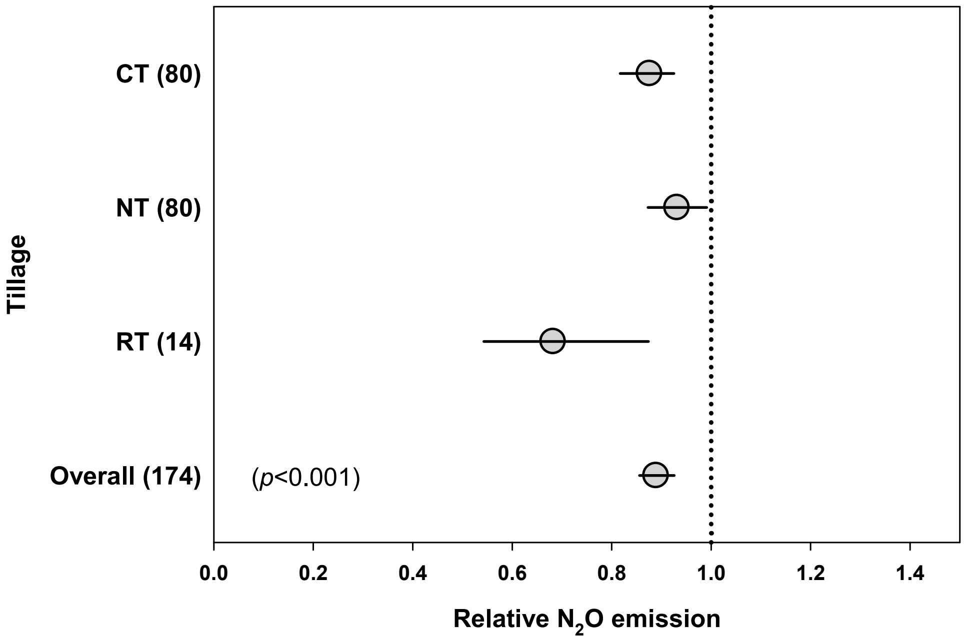

Figure 4. The effect crop residue removal on N_2O emissions as affected by soil tillage. N_2O emissions from control treatments with crop residues = 1. Mean effect size (circle) and 95% confidence intervals (CIs, error bars) are shown. CT = conventional tillage, RT = reduced tillage, NT = no or zero tillage. The number of observations is given in parentheses.

4. Discussion

4.1. N_2O Flux Rates and Emissions in the Field Experiment

Increased N_2O flux rates were measured after the application of the sugar beet residues and after periods with larger amounts of rainfall between beginning December 2019 and mid-January 2020. The significant positive correlations between the N_2O flux rates and the CO_2 flux rates as well as between N_2O flux rates and the soil nitrate contents clearly hint at heterotrophic denitrification as the main source for N_2O production in the experimental soil. Soil moisture (WFPS) did not correlate with the N_2O flux rates which might be explained mostly with the low fluxes in the −CR treatment even on sampling dates with a high soil moisture.

Rainfall increases soil moisture and thus decreases air-filled porosity. The diffusion coefficient for oxygen (O_2) is by factor 10^4 lower in soil water when compared to air [61] and consequently rainfall constrained O_2 diffusion into the soil. The microbial turn-over of fresh organic matter as well as the oxidation of NH_4^+ released from the mineralization of organically bound N requires O_2 [62,63] and might have, under these conditions of low O_2 delivery through diffusion from the atmosphere, resulted in the development of anaerobic conditions, thus favoring denitrification and N_2O release. This causal chain was supported by a microcosm study conducted by Flessa and Beese [62]. They incorporated sugar beet leaves into a silty clay soil and measured N_2O fluxes and the redox potential in different soil depths. Incorporation of the leaves decreased the redox potential already in well aerated soil columns distinctively below 500 mV to values necessary for beginning microbial nitrate reduction [64,65]. Increasing soil moisture from 63% in the treatment with good aeration to approximately 85% WFPS drastically decreased redox potential down to values below −100 mV, with this decrease being accompanied by a strong increase in N_2O release [62].

As summarized by Granli and Bøckman [66], organic carbon (C) as electron donator is a prerequisite for denitrification in soils. For similar soil and climate conditions as in the present study, C limitation resulted in a decreased N_2O release from a vegetable field [43] and from a wheat field [39]. In both studies, the authors reported enhanced N_2O emissions after glucose addition, indicating the presence of sufficient NO_3^- for N_2O production from denitrification.

Simultaneously to O_2 depletion, the turn-over of the sugar beet residues in the treatments +CR:D and +CR:S increased NO_3^- contents in the top soil and thus also substrate availability for denitrification.

In contrast to the treatments +CR:D and +CR:S, N_2O flux rates and the resulting cumulative N_2O emission of the −CR treatment was significantly lower. As indicated by the low CO_2 flux rates in this treatment, and based on the positive correlation between N_2O and CO_2 flux rates, it seems plausible that C-limitation was the main factor restricting N_2O release from denitrification in −CR.

Summarizing data published by Jungkunst et al. [67], the median annual N_2O emission from 50 measurements at arable sites in Germany was 3.40 kg N_2O-N ha^{-1} a^{-1}. Our measurements covered only 120 days or roughly 1/3 year. Therefore, the N_2O release from the +CR:D treatment (2.39 kg N_2O-N ha^{-1} 120 $days^{-1}$) can be assessed as high. This valuation was also strengthened by the fact that the data with high annual emissions reported by Jungkunst et al. [67] were driven by high N_2O pulses during frost/thaw (approximately 50% of the annual emissions occurred during frost/thaw periods). In contrast, frost/thaw, which would have increased our N_2O emissions additionally, did not contribute to the N_2O emissions in our study.

Even though information on N_2O fluxes from sugar beet fields during winter is scarce, it seems that sugar beet residues have a high potential for the induction of high N_2O emissions. Comparing the effect of different crop residues (winter wheat (*Triticum aestivum L.*), soybean (*Glycine max L.*), green manure oats (*Avena sativa L.*) and sugar beet) at two different residue quantities, Koga [68] reported highest N_2O fluxes of his entire measurements when sugar beet residues were ploughed in a conventionally tilled system. He explained the highest N_2O fluxes and the resulting high emission factor from sugar beet residues with the highest amount of N returned into soil.

The mean N_2O emission from +CR:S was lower (0.94 kg N_2O-N ha^{-1} 120 $days^{-1}$) than from +CR:D and well within the range of trace gas measurements with not frost/thaw affected winter emission [67,69]. Ambus and Jensen [21] showed that the decomposition of crop residues essentially depends on the contact area between soil and crop residues. Incorporated crop residues have a higher contact area with the soil than surface applied residues and thus they might be mineralized faster [22]. The higher O_2 demand in the +CR:D treatment with a higher contact area and a consequent stronger O_2 depletion might have been one reason for the higher mean N_2O emission in this treatment.

As a result of C-limitation and lower NO_3^- contents when compared to the treatments where crop residues remained in the field, the cumulative N_2O emission from −CR (0.12 kg N_2O-N ha^{-1} 120 $days^{-1}$) was very low.

4.2. Effect of Removing Crop Residues on N_2O Emissions from Soils: Results of the Meta-Analysis

The overall result of our meta study showed that removal of crop residues lowered N_2O emissions from arable soils by approximately 11%. The turn-over of fresh crop residues releases mineral N as substrate for N_2O production in soils, it supplies microorganisms with electrons and it enhances anaerobiosis through O_2 depletion thus fueling denitrification. The latter, especially, was shown to be the main reason for considerably high Q_{10} values (>5) for N_2O emission after the application of fresh organic matter [44,70]. Consequently, removing crop residues reduces N substrate availability for N_2O production and it maintains aeration in soil. Therefore, our first hypothesis can be confirmed, removal of crop residues decreases post-harvest N_2O emission.

The C/N-ratio showed the highest effect on N_2O emissions after crop residue removal. Compared to the control treatment, N_2O emission after residue removal in the subgroup with C/N-ratios below 25 was reduced by 76% whereas the reduction in the subgroups with wider C/N-ratios varied only between 6% and 9%. Although the breakeven C/N-ratio of crop residues or organic amendments for N immobilization or mineralization varied widely between 15 and approximately 35 [39,71–73] it seems most likely, that in the subgroup with a C/N-ratios <25, intense mineralization occurred and this might have led to increased O_2 depletion and enhanced mineral N availability for N_2O production if crop residues remained in the field. Kaiser et al. [74] reported increasing N_2O winter emissions with a decreasing crop residue dry matter-to-N content ratio with the latter being generally positively related with the C content. In their study, Kaiser et al. [74] included measurements from a field with differently fertilized sugar beet (with the lowest C/N-ratio), wheat, barley and oilseed rape treatments. Highest emission in the experimental consortium of Kaiser et al. [74] was measured in the plots where sugar beet residues were ploughed in which might also explain the high N_2O emission in the +CR:D treatment in our field study. Increased N_2O fluxes from crop residues with a low C/N-ratio have also been reported by Toma and Hatano [75], who similarly explained this phenomenon with the rapid decomposition of the crop residues.

The similar response of the relative N_2O emissions in the subgroups with C/N-ratios above 25 suggests only moderate turn-over of the crop residues in these subgroups. The relative emission higher than 1 in the subgroup with C/N-ratios ≥100 (meaning that the N_2O emission from the control plots with crop residues was lower than in the treatment with residue removal) could be the result of N immobilization in the treatment with residues remaining in the field [76] whereas mineralization in the removal treatment enlarged the mineral N pools and thus increased substrate availability for N_2O production. Another explanation for higher N_2O emissions from the removal treatment was given by Pitombo et al. [77] who reported higher soil temperatures in the removal treatment after removal of intense soil shading sugarcane residues thus increasing process rates of N_2O production. A rise in soil temperature can promote mineralization and nitrification [78,79] promoting N_2O emissions in the crop removal treatment. The effect of the removal of crop residues with different C/N-ratios on N_2O emissions over the whole data set was manifested by a trend showing increasing relative N_2O emission reduction with decreasing C/N-ratios (Figure 3). The significant highest N_2O reduction in the subgroup with a C/N-ratios <25 and the observed trend of lower reduction with increasing C/N-ratio confirmed our second hypothesis, although the differences between the groups with a C/N-ratios >25 were not statistically confirmed.

The overall significant reduction of N_2O emission for the grouping variable "residue quantity" was 11% when crop residues were removed, and it was the same reduction as observed for the grouping variable "C/N-ratio". Data set for the grouping variable "residue quantity" contained approximately half of the observations used for the grouping variable "C/N-ratio" (n = 92 vs. n = 173). Furthermore, half of the data sets with a C/N-ratio <25 (n = 4) was included in the grouping variable "residue quantity" spread over two categories. Therefore, it was not surprising, that both grouping variables ("C/N-ratio" and "amount removed") yielded in the same overall N_2O reduction potential.

The fact that we did not find differences between the subgroup within the grouping variable "residue quantity" clearly indicates, that chemical properties of the residues as the C/N-ratio was more decisive for the reduction of the N_2O emission than the total amount of residues removed. The reports on the effects of crop residue amounts on N_2O emission are in part contradicting. In comparison to treatments with low amounts of different crop residues, Koga [68] reported significantly higher N_2O emissions in the treatments with high amounts of the same crop residues. In contrast, no effect on the N_2O emission was measured for increased amounts of crop residues and explained with the high C/N-ratio of winter wheat [20] or maize straw [18].

Surey et al. [80] investigated the effect of water-extractable C and N from different crop residues on potential denitrification. Total gaseous N release from denitrification was highly correlated with the amount of extractable C and N from the residues. Moreover, the amount of water-extractable C and N was negatively correlated with the ratio of organic C to organic N. They concluded, that "the potential to release water-extractable organic matter is closely linked to the plant residues' chemical composition, which, in turn, reflects the residues' source and degradation stage". Müller et al. [81] showed that water-extractable C and N contents may vary widely between different crops types. Within the six crops of their investigation, water-extractable C ranged between 3.7% and 35.0% of total C, the corresponding range for water-extractable N was between 16.4% and 67.2% of total N. It seems likely that, in experiments with different amounts of the same crop residues with the same chemical properties, the effect on N_2O emission will be apparent (e.g., [82]), whereas it may be overwritten when, as in our meta-analysis, data of several crop residues with strongly differing chemical characteristics are pooled. Therefore, we had to reject our third hypothesis, N_2O reduction potential through crop residue removal was not affected by the quantity of the crop residues.

The overall N_2O reduction through residue removal in the grouping variable "tillage" was the same as in grouping variable "C/N-ratio" because it was mainly the same data set used here. Soil tillage subgroups did not show any difference in N_2O reduction through residue removal, indicating that it was not affected by soil tillage and consequently, we had to reject our fourth hypothesis.

Several studies reported higher N_2O emissions in RT or NT systems than in ploughed systems [83–85]. The higher N_2O emission (often measured during the cropping season) was mainly explained with the higher water-filled porosity due to lower pore volume under NT or RT. Petersen et al. [86] compared the effects of different tillage systems (RT, CT, NT) on N_2O emission from treatments with and without crop residues. N_2O emission did not show any differences between soil tillage treatments without crop residues whereas CT showed higher emissions with crop residues. They concluded that soil moisture was more important for N_2O release than soil structure. The time slot for removal or returning of crop residues may vary with the crop and this might affect N_2O emissions [82]. However, most crop residues come up in autumn, hence in a period with increasing rainfall and potentially high soil moisture over winter. The meta-analysis probably did not reveal differences between soil tillage categories, because the main effects of residue removal or returning occurred predominantly in these periods with high soil moisture.

5. Conclusions

Our results clearly reveal that the C/N-ratio of crop residues is a main driver for post-harvest N_2O emissions from arable soils. Especially, removal of crop residues with a C/N-ratio <25 was shown to be a very efficient measure to reduce N_2O emissions. The high reduction potential for the effect of removing crop residues with a low C/N-ratio on N_2O emission (calculated with the meta-analysis; 76%) seems to be a promising tool to reduce N_2O emissions through residue management. Our data also hint on the need for measurements where organic material with a high C/N ratio (e.g., cereal straw) is supplemented to crop residues with low C/N ratio in order reduce N mineralization over autumn and winter.

Deriving the removal of crop residues with a low C/N-ratio as a recommendation for farmers, further questions should be clarified. The first question concerns the usage of the removed residues. The most suitable utilization of N-rich crop residues, e.g., from vegetable or from sugar beet production seems to be composting because the usage as feedstock for biogas plants is declined by plant operators due to the in part high portion of adhesive soil particles. Second, composting is also afflicted with the release of greenhouse gases (GHG) and consequently further GHG measurements from the compost process, including NH_3 flux measurements (as a source for indirect N_2O emissions), are needed for an overall assessment of the environmental effect of residue removal. Third, removal of C with the residues also means the removal of humus-reproductive organic matter implying the need of additional investigations focusing on organic carbon (C_{org}) dynamics and potential C_{org} loss through crop residue removal.

When compared to the conventional treatment with ploughing of the sugar beet residues, the extremely high N_2O reduction potential of 95% achieved through the removal of the residues in our field experiment suggests the need of further studies in our experimental region focusing on the post-harvest period especially in sugar beet production. So far, information on N_2O emission from sugar beet fields including the post-harvest period is scarce. Realization of this claim would also increase the probability of conducting trace gas measurements in winter periods with more intense frost/thaw cycles which were shown to double annual N_2O emission. Results from Seiz et al. [15] with a 74% reduction in N_2O emissions through the removal of vegetable crop residues with narrow C/N-ratios seem to confirm this claim.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-0472/10/11/546/s1, Figure S1: Flow chart for the selection process of the meta-analysis, Figure S2: Funnel plot of effect size distribution around the overall mean effect size, Table S1: Observations used in the meta-analysis with corresponding values and subgroups.

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