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Effectiveness of soil management strategies for mitigation of N_2O emissions in European arable land: A meta-analysis

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Abstract

Soil management strategies involving the application of organic matter (OM) inputs (crop residues, green and livestock manure, slurry, digestate, compost and biochar) can increase soil carbon storage but simultaneously lead to an increase in non-CO_2 greenhouse gas (GHG) emissions such as N_2O. Although multiple meta-analyses have been conducted on the topic of OM input impacts on GHG, none has focused specifically on European arable soils. This study plugs this gap and can assist policymakers in steering European agriculture in a more sustainable direction. The objective of this meta-analysis was to quantify how OM inputs of different nature and quality, but also the application strategy, can mitigate soil N_2O emissions in different pedoclimatic conditions in Europe. We quantitatively synthesised the results of over 50 field experiments conducted in 15 European countries. Diverse arable crops, mainly cereals, were cultivated in monoculture or in crop rotations on mineral soils. Cumulative N_2O emissions were monitored during periods of 30–1070 days in treatments, which received OM inputs, alone or in combination with mineral N fertiliser; and in controls fertilised with mineral N. The overall effect of OM inputs had a slight tendency to reduce N_2O emissions by 10% ($n = 53$). With the increasing carbon-to-nitrogen ratio of the OM inputs, this mitigation effect became more pronounced. In particular, compost and biochar significantly reduced N_2O emissions by 25% ($n = 6$) and 33% ($n = 8$) respectively. However, their effect strongly depended on pedoclimatic characteristics. Regarding the other types of OM inputs studied, a slight N_2O emission reduction can be achieved by their application alone, without mineral N fertiliser (by 16%, $n = 17$). In contrast, their co-application with mineral N fertiliser elevated emissions to some extent compared to the control (by 14%, $n = 22$). We conclude that amongst the seven OM inputs studied, the application of compost and biochar are the most promising soil management practices, clearly demonstrating N_2O emission reduction compared to mineral

N fertiliser. In contrast, other OM inputs had a small tendency to mitigate N_2O emissions only when applied without mineral N fertiliser.

KEYWORDS

climate change mitigation, effect size, EJPSOIL, nitrous oxide, organic matter inputs, pedoclimatic characteristics

1 | INTRODUCTION

Approximately 6.2 Tg N_2O-N a^{-1}, or 35% of the annual worldwide emission, comes from agricultural soils (Kroeze et al., 1999). Following the application of chemical or organic fertiliser to the field, microbial processes (known as nitrification and denitrification) are the primary sources of nitrous oxide (N_2O) in soils. Soil management strategies involving the application of organic matter (OM) inputs such as crop residues, green manure, livestock manure, slurry, digestate, compost and biochar have been shown to increase soil carbon (C) storage, as documented by several global meta-analyses and reviews (Bai et al., 2019; Bolinder et al., 2020; Gross et al., 2021; Jian et al., 2020; Siedt et al., 2021; Tiefenbacher et al., 2021; Xia et al., 2018). However, the mitigation effects of agricultural practices enhancing C sequestration can be offset if N_2O emissions increase (Lugato et al., 2018; Zhou et al., 2017). The complex processes of N_2O loss from soil can also be affected by many environmental and crop management factors such as soil organic C (SOC) content, nitrate and ammonium concentrations in soil solution, N application rate, fertiliser type and application technique, soil oxygen status, microbial abundance and activity, soil pH, soil drainage and moisture, and crop species (Butterbach-Bahl et al., 2013; Thangarajan et al., 2013). In contrast, soil management practices enhancing C sequestration and reducing N_2O emissions may imply a "double-win" situation, with synergetic mitigation effects on climate change.

1.1 | Crop residues

The return of crop residues to the soil is an agricultural nutrient-conserving practice that effectively increases soil fertility and crop nutrition. When added to the soil, they are subject to microbial N mineralisation and nitrification, which results in N_2O production. This process, however, relies on the N content of crop residues (Frimpong & Baggs, 2010; Garcia-Ruiz & Baggs, 2007; Millar & Baggs, 2005; Miller et al., 2008). Crop residues also stimulate microbial N assimilation through the development of an organic C substrate for microbial growth. Hence, heterotrophic microorganisms may compete with autotrophic nitrifiers for NH_4^+ (Burger & Jackson, 2003), leading to a reduction of N_2O production. However, crop residues may serve as an energy provider for denitrifiers, enhancing denitrification and consequently N_2O production under anaerobic conditions. Moreover, it is after the incorporation of crop residues that peaks in N_2O emissions are expected, also driven by the soil compaction status (Pulido-Moncada et al., 2022).

Highlights

- The first meta-analysis focused on mitigating N_2O emissions in European arable land.
- The effect of seven different organic matter (OM) inputs were synthesised in over 50 field experiments.
- The overall effect of OM inputs had a slight tendency to reduce N_2O emissions, by 10%.
- Compost and biochar mitigated N_2O emissions by 25% and 33% respectively.

The impact of crop residues on N_2O emissions was studied in five global meta-analyses. However, in four, most of the studies originated from China and India, and the number of European studies included was scarce (Table 1). Field studies demonstrated a large variation in response to crop residue inputs, depending on the soil water regime: either (i) emission stimulation for upland crops; or (ii) emission reduction and a negligible impact for paddy crops. Furthermore, crop residue effects on soil N_2O emissions depended greatly on soil properties, specifically soil moisture content and soil texture (Chen et al., 2013), and clay content (Xia et al., 2018). Crop residue quality such as biochemical and physical characteristics is also an important factor controlling N_2O emissions (Olesen et al., 2023). These quality factors control the balance between N mineralisation and immobilisation (due to microbial assimilation) during decomposition (Mary et al., 1996), as well as residue C dynamics and partitioning between mineralisation and stabilisation (Lashermes et al., 2016). Although Chen et al. (2013) highlighted the necessity of connecting the quantity and quality of crop residues with soil properties for predicting soil N_2O emissions, in two later meta-analyses, the authors did not

TABLE 1 Global meta-analyses on the impact of organic matter inputs on N_2O emissions, the main effect sizes, number of independent studies and main moderators studied.

Author	Origin of the most studies	Organic matter type	Study type	Main results	Crops	Effect size (% change from control)[a]	Total number of studies (in parenthesis number in Europe)	Main moderators
Chen et al. (2013)[b]	Global	Crop residues	Laboratory, field	Figure 2	Vegetables, legume, cereals	167% (lab), 47% (field)	28 (n.a.)	Soil moisture, texture, C/N ratio of crop residues, amounts of residue C input
C. Liu et al. (2014)[c]	China, India	Crop residues	Field	Figure 2	Upland	8.3%	11 (6)	Not studied
					Paddy	−15.2%	40 (0)	
Wang et al. (2018)[c]	China	Crop residues	Field	Figure 2	Upland	16.6%	14 (3)	Crop residue amount
					Paddy	Negligible	16 (2)	
Xia et al. (2018)[b]	China	Crop residues	Field	Figure 3	Upland	21.5%	n.a.	C/N ratio of crop residues; clay content
					Paddy	−17.3%		
Fan et al. (2023)[c,d]	China, India	Crop residues	Field	Figure 10	Upland and paddy	*−8%*	18 (n.a)	Not studied
Basche et al. (2014)[c]	USA	Green manure	Field	Figure 4	Legume	490%	26 (6)	Type of green manure, residue management, measurement period
					Non-legume	*7%*		
Muhammad et al. (2019)[c]	Global	Green manure	Field	Figure 2	Legume	61%	41 (13)	Quality and quantity of green manure, residue management, soil texture
					Non-legume	−36%		
Han et al. (2017)[b,d]	Global	Green manure	Field	Figure 1	Mainly non-legume	*−6%*	21 (5)	Measurement period
Li et al. (2023)[c]	USA, South Korea, China, Brazil	Green manure	Field	Figure 2	Legume and non-legume	*3.3%*	19 (4)	Soil pH, soil total N, soil organic C
Zhou et al. (2017)[c,d]	Global	Livestock manure	Field	Figure 2b	Upland and paddy	46.9%	36 (7)	Clay content, soil pH, soil texture
Han et al. (2017)[b,d]	Global	Livestock manure, slurry	Field	Figure 1	Mainly maize and wheat	*12%*	23 (9)	Clay content
Wei et al. (2020)[c,d]	China	Mainly livestock manure, slurry	Field	Figure 2b	Maize	*−12.7%*	36 (1)	OM amount, study duration, replacement rate of chemical fertiliser with OM
Fan et al. (2023)[c,d]	China, India	Livestock manure	Field	Figure 9a	Upland and paddy	*−15.3%*	45 (11)	Not studied

(Continues)

TABLE 1 (Continued)

Author	Origin of the most studies	Organic matter type	Study type	Main results	Crops	Effect size (% change from control)[a]	Total number of studies (in parenthesis number in Europe)	Main moderators
Zhou et al. (2017)[c,d]	Global	Compost, digestate	Field	Figure 2b	Upland and paddy	*2.8%*	12 (3)	Clay content, soil pH, soil texture
Kong et al. (2023)[c,d]	China	Digestate	Field, greenhouse	Figure 2a	Upland and paddy	negligible	n.a.	Replacement rate of chemical fertiliser with digestate
Cayuela et al. (2014)[c]	–	Biochar	Mostly laboratory and greenhouse	Figure 1	–	−54%	30 (n.a.)	Soil pH, soil texture, biochar amount
Verhoeven et al. (2017)[c]	Global	Biochar	Field	Figure 2	Upland Paddy	−11.5% −14%	43 (6)	Biochar amount, biochar pH, field site, measurement period
Liu et al. (2018)[c]	Global	Biochar	Laboratory, greenhouse, field	Figure 5c	Various	−32%	70 (n.a)	Soil texture, biochar amount
Borchard et al. (2019)[c]	Global	Biochar	Laboratory, field	Figure 1	Cereals, maize, rice, vegetables, perennials and others	−38%	10 (n.a.)	Pedo-climatic characteristics, biochar properties

Abbreviation: n.a., not available.

[a] Italic indicates statistically non-significant effect.

[b] Unweighted meta-analysis. Weighting by sample size is considered as unweighted.

[c] Weighted meta-analysis by the inverse of variance (Hedges et al., 1999).

[d] OM inputs were compared to mineral fertiliser.

consider these moderators (Fan et al., 2023; C. Liu et al., 2014).

1.2 | Cover crop/green manure

Green manure is a term used to describe crops that are grown in and incorporated into the soil to improve its fertility and OM content. Green manuring can have different impacts on N_2O emissions, depending on the type of crop, the method of incorporation and the rate of mineral N fertilisation. Legume crops such as clover or alfalfa, tend to increase N_2O emissions compared to non-legume crops such as grass or rye because they fix more N from the atmosphere and release it into the soil (Carter et al., 2014). Non-legume cover crops that mediate the trapping of nitrate in arable fields can reduce the indirect N_2O emissions (Constantin et al., 2010).

Composting green manure with straw before soil application can reduce N_2O emissions compared to ensiling or fresh incorporation because composting reduces N availability and increases the carbon-to-nitrogen (C/N) ratio of the OM. Incorporating green manure by ploughing can increase N_2O emissions compared to harrowing because ploughing promotes anaerobic conditions near the decomposing OM, which favours denitrification (Carter et al., 2014). Green manure can therefore have both positive and negative effects on N_2O emissions, depending on how it is managed.

Four meta-analyses have studied the effect of cover crops/green manure on N_2O emissions based on field data (Basche et al., 2014; Han et al., 2017; Li et al., 2023; Muhammad et al., 2019). There was a clear difference between non-legume and legume cover crops in terms of their effect on N_2O emissions: non-legume cover crops had either a negligible effect or reduced the emissions, whilst legumes typically stimulated N_2O emissions (Table 1). Han et al. (2017) found that with increasing N inputs from cover crops, N_2O emissions also increased. Both environmental and farm management factors modified the impact of cover crops on N_2O emissions, including fertiliser N rate, precipitation and the period of measurement (Basche et al., 2014). Furthermore, the incorporation of cover crop residues contributed to an increase in N_2O emissions, whilst a surface-placed residue resulted either in an emission reduction or had a negligible effect (Basche et al., 2014; Muhammad et al., 2019). However, when measured for periods of 1 year or longer, cover crops on average lead to a small or negligible increase in N_2O emissions.

1.3 | Livestock manure, slurry, compost and digestate

Globally, the application of animal manure to arable land as organic fertiliser enhances SOC stocks compared to synthetic N fertiliser alone (e.g. Maillard & Angers, 2014). However, the potential of manure application for climate change mitigation by increasing SOC stocks can be attenuated by enhanced N_2O emissions. The magnitude and duration of N_2O emissions from manure depend on its composition and quality, including its total N, ammonium-N, organic N, C/N ratio, pH and water content (Zhou et al., 2017).

The method and timing of manure application can also influence N_2O emissions. For example, the surface application or incorporation of manure can reduce N_2O emissions compared to injection or band spreading because it diminishes anaerobic conditions and denitrification potential in the soil (Thorman et al., 2020). Matching manure application with crop N demand can also reduce N_2O emissions, for example, in the spring or summer (the beginning of the crop season) compared to the autumn (end of season) to reduce N losses (Thorman et al., 2020).

Two global meta-analyses have summarised the effects of manure and slurry on N_2O emissions in comparison with mineral fertilisers in fields (Han et al., 2017; Zhou et al., 2017), and two meta-analyses have included mostly studies in China (Wei et al., 2020) or in China and India (Fan et al., 2023). Zhou et al. (2017) showed that the application of raw manure strongly increased soil N_2O emissions, but with increasing soil clay content and pH, the effect sizes of manure application on N_2O emissions decreased. Three other meta-analyses demonstrated overall small and non-significant effects of manure and slurry, ranging from −15.3% to 12% (Fan et al., 2023; Han et al., 2017; Wei et al., 2020) but also showed a negative correlation between clay content and the effect sizes (Han et al., 2017). In coarser soils, manure and slurry slightly increased N_2O emissions compared to mineral fertiliser, whilst in finer soils, they tended to have similar or lower N_2O emissions than mineral fertiliser (Han et al., 2017). The replacement rate of mineral fertiliser with organic fertiliser was another crucial factor, explaining the variability in effect sizes. The full substitution of mineral fertiliser with organic fertiliser decreased N_2O emissions by 25% (Wei et al., 2020).

Two meta-analyses showed small and statistically non-significant effects of compost and digestate on N_2O emissions (Kong et al., 2023; Zhou et al., 2017). The effect sizes of N_2O emissions depended primarily on the replacement ratio, and the full substitution of mineral fertiliser with digestate slurry increased N_2O emissions by 26% (Kong et al., 2023).

1.4 | Biochar

Biochar, the product obtained after pyrolyzing biomass, potentially contributes to climate change mitigation (Smith, 2016; Woolf et al., 2010). During pyrolysis, biomass is subjected to high heat and low O_2 conditions, resulting in about a quarter of its mass being converted to biochar. The process rearranges C into strongly bonded aromatic molecules which are more difficult for microbes to access and metabolise. Biochar C can remain unmineralised in the soil for hundreds to thousands of years, depending on the feedstock from which it is made, the temperature at which it is produced, and the soil and climate systems to which it is added (Lehmann et al., 2015; Lehmann et al., 2006).

In addition to its C sequestration potential, many studies have reported that biochar can help reduce soil N_2O emissions. Four global meta-analyses synthesised the effect of biochar on N_2O emissions in laboratory, greenhouse and field experiments with various crops (Borchard et al., 2019; Cayuela et al., 2014; Liu et al., 2018; Verhoeven et al., 2017). Cayuela et al. (2014) included studies conducted mainly in laboratories and greenhouses and demonstrated the largest overall reduction in N_2O emissions by about 50% (Table 1). The biochar feedstock, pyrolysis conditions and C/N ratio were shown to be key factors influencing N_2O emissions, whilst a direct correlation was found between the biochar application rate and N_2O emission reductions. Indeed, Liu et al. (2018) demonstrated that along with the biochar addition rate, the magnitude of emissions reduction increased, reaching the maximum when the biochar addition rate was higher than 40 t ha^{-1}. The chemical form of N fertiliser applied with biochar and the interaction between soil texture and biochar were also found to have a major influence on soil N_2O emissions.

Another global meta-analysis by Verhoeven et al. (2017) showed much lower reductions of N_2O emissions due to biochar under field conditions (Table 1). This meta-analysis consisted of 43 studies, of which only 6 were conducted in Europe. Liu et al. (2018) showed the intermediate effects of biochar addition to soils resulting in a reduction of N_2O emissions by 32%. The authors pointed out that the effect of biochar was largest in loam soils, but small and non-significant for soils with low organic carbon content ($\leq$5 g kg^{-1}). Biochar made from manure or pyrolyzed at temperatures lower than 350°C showed a weak and insignificant reduction of soil N_2O emissions. Verhoeven et al. (2017) demonstrated there was a trend of reduced N_2O mitigation in longer-term studies. Borchard et al. (2019) also stressed that although the overall effect of biochar was statistically significant (−38%), N_2O emission reductions tended to be negligible after 1 year. The use of biochar reduced N_2O emissions in arable farming and horticulture, but not in grassland or perennial crops.

To summarise, during the last decade, several meta-analyses have been published to quantify the impact of OM inputs on N_2O emissions at the global scale (Table 1). These global meta-analyses showed inconsistent results even for the same OM type. In addition, none of these global meta-analyses focused on European agricultural soils, with most studies originating from China, India and United States, or in some cases, the countries of origin were not reported. These facts may prompt scepticism concerning the straightforward applicability of the results for European pedoclimatic zones. Moreover, many EU science policy practitioners may not be convinced when recommendations are based on the synthesis of non-European studies, which may inadequately reproduce agricultural management practices and pedoclimatic conditions in Europe.

Although there were some attempts to harmonise the results of European field experiments on the effect of crop residues, green manure and slurry on N_2O emissions (Lehtinen et al., 2014; Sandén et al., 2018), the scarce data collected were a barrier to conducting a reliable research synthesis. Our study is the first European meta-analysis to summarise the effect of soil management strategies, involving the application of a wide range of OM inputs (crop residues, green manure, livestock manure, slurry, digestate, compost and biochar), on N_2O emissions in arable land.

We hypothesised that soil management strategies involving the application of OM inputs would mitigate soil N_2O emissions in European arable land. The objective of this meta-analysis was to quantify the effectiveness of OM inputs with contrasting nature and quality, as well as the effectiveness of the application strategy for mitigating soil N_2O emissions in different pedoclimatic conditions in Europe.

2 | MATERIALS AND METHODS

To assure high quality, we followed a checklist for quality criteria specifically compiled for a meta-analysis in soil and agricultural sciences (Fohrafellner et al., 2023).

2.1 | Studies collection

The research question was structured according to the PICO framework (population, intervention, comparator and outcome):

Population: European arable land.

Intervention: Organic matter inputs (green manure, crop residues, livestock manure, slurry, digestate, biochar, compost), alone or in combination with mineral N fertiliser.

Comparator: Mineral N fertiliser.

Outcome: Cumulative N_2O emissions per unit land area for a period.

We found the articles by searching for the keywords "soil*" AND ("agr*" OR "farm*" OR "field") AND ("Europe" OR Name of European country) AND ("crop residue*" OR "cover crop*" OR "green manure" OR "livestock manure" OR "slurry" OR "compost" OR "biochar" OR "digestate") AND ("N_2O" OR" nitrous oxide"), using Web of Science, Scopus, Agricola (USDA National Agricultural Library), ScienceDirect, the AGRIS International System for Agricultural System and Technology and Google Scholar. The outcome from the first search was a large number of studies that were later refined by selecting European research organisations with the assumption that only European research organisations had the ability to conduct field experiments in Europe. At least one (co-) author needed to be affiliated with these institutes.

The screening was conducted in two stages:

1. The title of each study was examined for relevance. If at this stage it did not indicate the presence of exclusion criteria (Table 2), the abstract was screened.
2. All studies that passed the abstract screening were checked for suitability in the form of a full text screening.

We also screened the references of global N_2O meta-analyses and reviews on the effect of biochar (Borchard et al., 2019; Cayuela et al., 2014; Verhoeven et al., 2017), crop residues (Abalos et al., 2022; Chen et al., 2013; Wang et al., 2018; Xia et al., 2018), green manure, cover crops (Abdalla et al., 2019; Basche et al., 2014; Muhammad et al., 2019; Muhammad et al., 2021), manure (Sandén et al., 2018; Shakoor, Shahzad, et al., 2021; Shakoor, Shakoor, et al., 2021; Zhou et al., 2017), compost, slurry (Sandén et al., 2018) and their databases if available. The article search was completed in November 2022.

2.2 | Inclusion criteria

To be included in the database, a study had to meet the inclusion criteria listed in Table 2. About 200 screened articles contained exclusion criteria, amongst which the most common were laboratory studies and zero N fertilisation.

2.3 | Data extraction

The data extraction method is crucial for dealing with the non-independence of the observations that can lead to underestimations of the standard error of the mean effect and therefore liberal evaluations of the statistical significance of effects (Nakagawa et al., 2017).

To avoid problems with the non-independence of the effect sizes, only one pair comparison corresponding to the longest period of N_2O measurements was extracted from an article. If an article reported results for several OM inputs, a treatment was randomly selected, taking care that the number of studies for each OM type was comparable. If an article reported results from different experimental sites with different pedoclimatic characteristics or from the same site but with different soil characteristics, those sites were considered as independent studies and were included in the database. If several articles referred to the same experimental site with the same pedological characteristics, the article with the longest experimental duration was selected. However, when different articles reported the results from the same site such as El Encín (Spain), Berge (Germany), Cascina Baroncina (Italy), but experiments were conducted in different decades or/and with different OM inputs, we included them in the database as independent studies.

The data were extracted from tables and digitised from figures using the ImageJ 1.37 program (Schneider et al., 2012). Standard errors (SE) were converted to standard deviations (SD) where necessary ($SD = SE * \sqrt{n}$, where n is the number of replicates). When no measure of variability was provided, we extracted the SD from the ANOVA table using the EX-TRACT tool (Acutis et al., 2021, 2022). This tool allows the estimation of the experimental error (i.e. standard deviation and standard error of treatments mean) associated with the statistical analysis results of published articles (i.e. estimated from the LSD, P(F) values or even from the assignment of letters indicating differences amongst means based on the results of a multiple comparison test).

2.4 | Database creation

We collected 46 articles published between 1993 and 2022 in peer-reviewed scientific journals, as well as a project report and a PhD thesis (Table 3; Appendix in Data S1). The database consists of 53 field studies, located in 46 sites with mostly loamy soil textures, across 15 European countries covering all European climate zones, from Alpine North to Mediterranean South (Table 3, Figure 1). A total of 13 studies was conducted in Spain, 11 in Germany, 4 in Italy, 3 in Denmark, England, Finland,

TABLE 2 Inclusion and exclusion criteria for the literature screening process.

Criteria	Inclusion	Exclusion
Language	English	Other than English language
Study location	Europe, including non-EU, and part of Turkey	Other regions of the world
Soil	Mineral	Organic
Study type	Field study	Laboratory, greenhouse, modelling studies (unless primary data from field studies presented as well)
Land use	Arable land	Permanent crops (vineyard; fruit trees; berry plantation; olive grove); Pastures, rice field; forests and semi-natural areas; wetlands
Cropping system	Monoculture, crop rotation, intercropping	Agroforestry
Control 1 (except for crop residues studies)	No OM inputs, no animal- or fish-based organic fertiliser, no other organic amendments (sphagnum peat, wood chips, grass clippings, biosolids, sawdust and wood ash). Doses of mineral N fertilisation within the range used in EU. Conventional tillage (up to 30 cm soil depth) Crop residues incorporated or removed.	Any OM inputs, animal- or fish-based organic fertiliser organic amendments (sphagnum peat, wood chips, grass clippings, biosolids, sawdust and wood ash). Doses of mineral N fertilisation higher or lower than used in EU Zero N fertilisation. Conventional tillage deeper than 30 cm soil depth, minimum or no-tillage
Control 2 (for crop residues studies only)	As control 1, but crop residues removed	Crop residues incorporated
Treatment	OM inputs (crop residues, green manure, livestock manure, slurry, digestate, biochar, compost) applied either solely or in combination with mineral N fertiliser. Conventional tillage, minimum or no-tillage Crop residues incorporated to soil or retained on soil surface.	Other OM inputs, not in the list
Means	Reported cumulative N_2O emissions for a period for treatment and control in text, tables and figures, or means can be calculated	Not reported and cannot be calculated, or results expressed as a daily flux
Standard deviation or standard error	Reported for treatment and control or can be calculated from statistics by using EX-TRACT tool (Acutis et al., 2021, 2022)	Not reported and cannot be calculated by using EX-TRACT tool (non-available statistics or experimental design)
Sample size (number of replicates)	Reported in tables, figures, or methods	Not reported

Abbreviation: OM, organic matter.

France and Norway, 2 in Scotland, Switzerland and the Netherlands, and 1 in Greece, Cyprus, Slovakia and Sweden. The entire database for the meta-analysis is available in Zenodo (https://zenodo.org/doi/10.5281/zenodo.10907111).

Two studies on the effect of crop residues (Essich et al., 2020; Nett et al., 2016) were not included in the database due to extremely large effect sizes, ln $R = 1.8$ (500%) and 2.05 (680%) respectively, which violated the normal distribution of effect sizes.

All calculated cumulative N_2O emissions were estimated from chamber measurements in the fields during periods from 30 to 1070 days, throughout the growing season (31 studies), outside growing season (3 studies), or throughout the year (19 studies). The types of OM inputs included 10 studies of crop residues, 10 of slurry, 9 of green manure, 8 of biochar, 7 of digestate, 6 of compost and 3 of livestock manure. Total N supply due to OM inputs ranged between 20 and 418 kg ha^{-1} a^{-1}, and the C/N ratio ranged between 2.7 and 390. In 32 field studies, organic materials were added to soils in combination with mineral N fertiliser, resulting in total N amounts more than in the control (26 studies), equal to the control (5 studies), or less (1 study). In the other studies, OM

TABLE 3 Studies included in the meta-analysis.

ID	Authors[a]	Country	Site	Soil texture	Environmental zone	OM type
1	Abalos et al. (2013)	Spain	El Encín	Silty clay loam	Mediterranean South	Crop residues
2	Alluvione et al. (2010)	Italy	Turin	Silt loam	Mediterranean Mountains	Green manure
3	Autret et al. (2019)	France	La Cage	Silt loam	Atlantic Central	Green manure
4	Baggs et al. (2000)	Scotland	Mosstowie	Sandy loam	Alpine North	Crop residues
5	Baral et al. (2017)	Denmark	Foulumgaard	Loamy sand	Alpine North	Slurry
6	Bosco et al. (2019)	Italy	Pisa	Loamy sand	Mediterranean North	Green manure
7	Calleja-Cervantes et al. (2017)	Spain	Arazuri	Silty clay loam	Lusitanian	Digestate
8–1	Dambreville et al. (2008)	France	Champ Noël	Silt loam	Atlantic Central	Slurry
8–2	Dambreville et al. (2008)	France	Le Rheu	Silt loam	Atlantic Central	Livestock manure
9	Dicke et al. (2015)	Germany	Berge	Sandy loam	Alpine North	Digestate
10	Franco-Luesma et al. (2022)	Spain	Aula Dei	Silt loam	Mediterranean South	Green manure
11	Guardia et al. (2017)	Spain	El Encín	Sandy clay loam	Mediterranean South	Compost
12	Hagemann et al. (2017)	Germany	Goldener Acker	Silty clay loam	Atlantic Central	Biochar
13	Hansen et al. (1993)	Norway	Surnadal	Sandy loam	Alpine North	Slurry
14	Herr et al. (2019)	Germany	Heidfeldhof	Silt loam	Alpine North	Slurry
15	Horák et al. (2017)	Slovakia	Malanta	Loam	Pannonian	Biochar
16	Hüppi et al. (2015)	Switzerland	Zurich	Clay loam	Continental	Biochar
17	Kesenheimer et al. (2019)	Germany	Ihinger Hof	Silt loam	Alpine North	Crop residues
18	Köbke et al. (2022)	Germany	Reinshof	Silt loam	Alpine North	Crop residues
19	Kontopoulou et al. (2015)	Greece	Agrinio	Clay loam	Mediterranean South	Compost
20	Lagomarsino et al. (2022)	Italy	Cascina Baroncina	Sandy loam	Mediterranean North	Digestate
21	Louro et al. (2015)	Spain	Mabegondo	Silty clay loam	Lusitanian	Slurry
22	Ludwig et al. (2011)	Germany	Darmstadt	Loamy sand	Pannonian	Livestock manure
23	Maris et al. (2018)	Spain	Almacelles	Clay loam	Mediterranean South	Crop residues
24	Mateo-Marín et al. (2020)	Spain	Soto Lezcano	Silt loam	Mediterranean South	Slurry
25	Meijide et al. (2007)	Spain	La Poveda	Sandy loam	Mediterranean South	Compost
26	Meijide et al. (2009)	Spain	El Encín	Sandy clay loam	Mediterranean South	Compost
27	Nadeem et al. (2012)	Norway	Østrevoll	Silty clay loam	Nemoral	Digestate
28	O'Toole (2021)	Norway	NMBU field station	Silty clay loam	Boreal	Biochar
29	Olofsson and Ernfors (2022)	Sweden	Lönnstorp	Loam	Continental	Green manure
30	Omirou et al. (2020)	Cyprus	Acheleia Paphos	Clay	Mediterranean South	Compost
31	Perälä et al. (2006)	Finland	Vihti	Clay	Boreal	Slurry
32	Plaza-Bonilla et al. (2014)	Spain	Senés de Alcubierre	Silty clay loam	Mediterranean North	Slurry

(Continues)

TABLE 3 (Continued)

ID	Authors[a]	Country	Site	Soil texture	Environmental zone	OM type
33–1	Regina et al. (2021)	Finland	Jokioinen	Loamy sand	Boreal	Green manure
33–2	Regina et al. (2021)	Finland	Jokioinen	Sand	Boreal	Green manure
34	Rothardt et al. (2021)	Germany	Hohenschulen	Sandy clay loam	Alpine North	Crop residues
35	Sanchez-Martin et al. (2010)	Spain	El Encín	Sandy clay loam	Mediterranean South	Livestock manure
36	Sánchez-García et al. (2020)	Spain	Campus of Espinardo	Sandy loam	Mediterranean South	Biochar
37	Sanz-Cobena et al. (2014)	Spain	la Chimenea	Silty clay loam	Mediterranean South	Green manure
38	Sarkodie-Addo et al. (2003)	England	Wye	Silt loam	Atlantic Central	Green manure
39	Scotti et al. (2022)	Italy	Cascina Baroncina	Sandy loam	Mediterranean North	Biochar
40–1	Senbayram et al. (2014)	Germany	Karkendamm	Sand	Alpine North	Digestate
40–2	Senbayram et al. (2014)	Germany	Hohenschulen	Sandy loam	Alpine North	Digestate
41	Skinner et al. (2019)	Switzerland	Therwil	Silt loam	Atlantic Central	Compost
42	Sun et al. (2017)	Germany	Berge	Sandy loam	Alpine North	Biochar
43–1	Sylvester-Bradley et al. (2015)	England	Gleadthorpe	Sandy loam	Atlantic Central	Crop residues
43–2	Sylvester-Bradley et al. (2015)	Scotland	Edinburgh	Clay loam	Alpine North	Crop residues
43–3	Sylvester-Bradley et al. (2015)	England	Terrington	Clay loam	Alpine North	Crop residues
44	Taghizadeh-Toosi et al. (2022)	Denmark	Foulum	Loamy sand	Alpine North	Crop residues
45	Thers et al. (2020)	Denmark	Askov Experimental Station	Sandy loam	Alpine North	Biochar
46	van Groenigen et al. (2004)	The Netherlands	Leeuwarden	Silty clay loam	Atlantic Central	Slurry
47	Velthof and Mosquera (2011)	The Netherlands	Wageningen	Sand	Atlantic Central	Slurry
48	Wolf et al. (2014)	Germany	Braunschweig	Sandy loam	Alpine North	Digestate

Abbreviation: OM, organic matter.

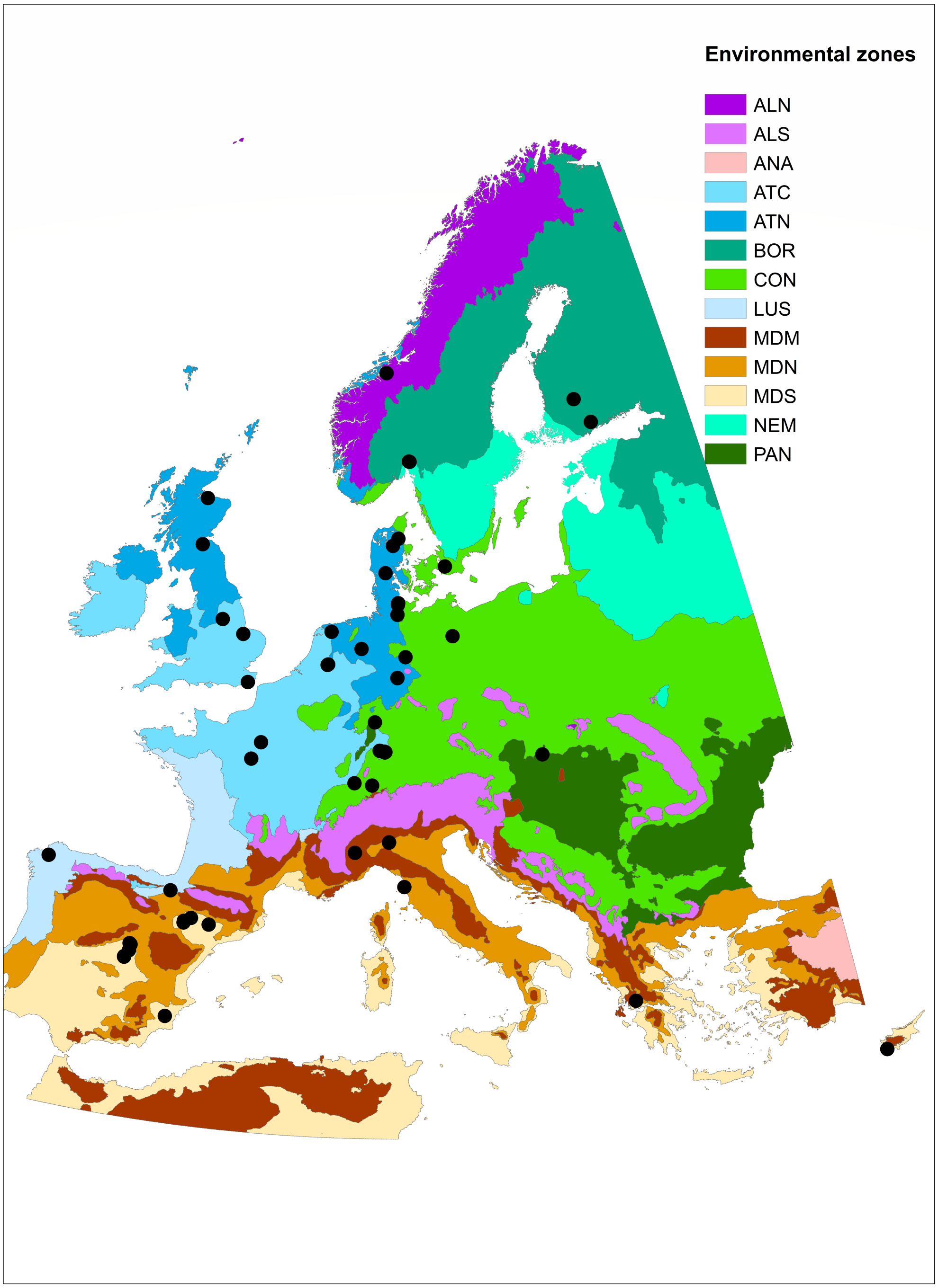
[a] Reference list of articles appears in Appendix in Data S1.

inputs were applied solely at the N amounts either more than in the control (nine studies), equal to the control (seven studies), or less (four studies) or an unknown amount (one study).

The annual average precipitation and average annual temperature measured on the experimental sites that are included in this meta-analysis ranged between 250 and 1300 mm, and between 4.5 and 19.6°C respectively. The studies included in this meta-analysis cultivated diverse arable crops in the field experiments, mainly cereals (maize, spring wheat, winter wheat and spring barley). In 47 of these studies, arable crops were cultivated in monoculture or in crop rotations in a conventional farming system on the treatment plot, and in only six studies, an organic farming system was used on the treatment plots (control plots were always conventional).

The soil management of the treatments included conventional tillage at a soil depth of 20–30 cm in 42 studies, minimum tillage in 5 studies and no-tillage in 1 study, whilst 5 studies did not report soil tillage management. No cover crops were used in 41 studies, non-legume cover crops in 9 studies and legumes in 3 studies.

FIGURE 1 The location of 46 experimental sites used for meta-analysis and related environmental zones of Europe (Metzger et al., 2005). ALN, Alpine North; ALS, Alpine South; ANA, Anatolian; ATC, Atlantic Central; ATN, Atlantic North; BOR, Boreal; CON, Continental; LUS, Lusitanian; MDM, Mediterranean Mountains; MDN, Mediterranean North; MDS, Mediterranean South; NEM, Nemoral; PAN, Pannonian.



Fields were not irrigated in 37 studies, whilst they were irrigated in 16 studies.

2.5 | Explanatory variables (moderators)

To explain the variation in the N_2O changes due to OM inputs, we included 19 explanatory variables derived from the database and grouped them into five categories, namely, study characteristics, OM input characteristics, climate, soil and agronomic management (Table 4). Tillage practices were not included in the list of explanatory variables, as the fields were conventionally tilled in most studies, and there was a lack of studies with minimum tillage or no tillage. A Spearman rank order correlation (r_s) was run between soil characteristics and climate to assess their intercorrelation.

2.6 | Meta-analysis

Meta-analysis was conducted using Meta Win 2.0 statistical software (Rosenberg et al., 2000) and IBM SPSS Statistics 29.

TABLE 4 Categorical and continuous explanatory variables (moderators) included in the meta-analysis.

Variable category	Explanatory variables	Group or range
Study characteristics	Duration of experiments (years)	0.3–35
	Measurement period (days)	30–1069
	Season of N_2O measurements	All year, in growing season, outside of growing season
OM input characteristics	Type	Green manure, crop residues, livestock manure, slurry, digestate, biochar, compost
	OM input strategy	OM applied alone (OM alone); OM applied in combination with mineral N fertiliser (OM + N)
	C/N ratio	2.7–390
	Total N supply in OM (kg ha^{-1} a^{-1})	20–418
Climate	Annual precipitation (mm)	275–1300
	Average annual temperature (°C)	4.5–19.6
Soil	SOC (%)	0.69–4.5
	Clay (%)	1–52
	Sand (%)	2–91
	Soil C/N ratio	7–21
	pH	4.8–8.4
Agronomic management	Total N supply as sum of mineral N and OM (kg ha^{-1} a^{-1})	25–613
	Farming system	Conventional, organic
	Cropping system	Monoculture, crop rotation, intercropping
	Cover crops	Non-legume, legume, no cover crops
	Irrigation	Irrigation, no irrigation

Abbreviation: OM, organic matter.

A quantitative meta-analysis involves calculating an effect size (i.e. the magnitude of the treatment effect) that can be averaged across independent studies. As two experimental groups were compared, the response ratio (R) was computed for the response variables as an index of the effect size:

$$R = \frac{\overline{X}_{OM}}{\overline{X}_C}, \tag{1}$$

where $\overline{X}_{OM}$ and $\overline{X}_C$ represent the means for cumulative N_2O emissions (kg N_2O-N ha^{-1}) in treatments (OM input solely or in combination with mineral N fertiliser) and in controls (mineral N fertiliser) respectively, averaged for experimental replicates.

As the distribution of R is skewed, performing statistical analyses in the metric of the natural logarithm of R is usually preferred due to its much more normal distribution in small samples than that of R (Hedges et al., 1999):

$$\ln(R) = \ln\left(\frac{\overline{X}_{OM}}{\overline{X}_C}\right) = \ln\left(\overline{X}_{OM}\right) - \ln\left(\overline{X}_C\right). \tag{2}$$

A normal distribution for $\ln R$ was tested by Shapiro–Wilk test in SigmaPlot15.

We calculated the variance of $\ln(R)$ (Hedges et al., 1999):

$$V_{\ln(R)} = \frac{(SD_{OM})^2}{n_{OM}\left(\overline{X}_{OM}\right)^2} + \frac{(SD_C)^2}{n_C\left(\overline{X}_C\right)^2}, \tag{3}$$

where SD_{OM} and SD_C are the corresponding standard deviations and n is the sample size (number of replicates).

We assumed that studies did not share the same effect sizes, and we therefore used a random effects model to combine estimates across the studies. The application of this kind of model accounts for experimental method differences between studies (that are considered only a random sample of possible effect sizes) which may introduce variability ("heterogeneity", τ^2) amongst the true effects.

We calculated the weighted mean of the log response ratio for all studies as:

$$\overline{\ln(R)} = \frac{\sum_{i=1}^{n} w_i \ln R_i}{\sum_{i=1}^{n} w_i}, \tag{4}$$

where $\ln R_i$ is the log response ratio for study i, n is the number of studies and w_i is the weight for study i, defined as (Borenstein et al., 2009):

$$w_i = \frac{1}{V_i + \tau^2}, \tag{5}$$

where V_i is the variance of the study i and τ^2 denotes the amount of residual heterogeneity (between-study variance). Because the variance of the effect sizes is a function of the sample size (Equation 3), studies with a larger sample size had lower variances and received heavier weights.

The τ^2 parameter is considered the variance of the true effect size. As it is impossible to compute it from the entire population of the effect size, τ^2 is an estimation of the observed effect by using DerSimonian and Laird method (Borenstein et al., 2009):

$$\tau^2 = \frac{(Q - df)}{C}, \tag{6}$$

where $Q = \sum_{i=1}^{k} w_i (Y_i - M)^2$; $df = n - 1$; $C = \sum w_i - \frac{\sum W_i^2}{\sum W_i}$, where w_i is the study weight, Y_i is the study effect size, M is the summary effect and n is the number of studies.

A random effects model served to combine estimates across the studies, assuming that the studies in each subgroup did not share the same effect size. Because meta-analytic data often have small sample sizes and may violate basic distributional assumptions (such as normality), resampling techniques can be important to accurately determine the significance of meta-analytic metrics (Rosenberg et al., 2000). We used a bootstrap statistical method (Efron & Tibshirani, 1986) to generate bias-corrected 95% confidence intervals (CIs) around the log response ratios from 4999 iterations. To test whether ln R differed between the groups of categorical explanatory variables, we used the χ^2 test to examine the between-group heterogeneity (Q_B). To study the effect of continuous explanatory variables, we ran weighted meta-regressions, with ln R as the dependent variable, and the continuous variables as independent ones. We also used the χ^2 test to examine the model heterogeneity (Q_M), which describes the amount of heterogeneity explained by the regression models. The significant level of Q_M indicates that an independent variable (a moderator) explains a significant amount of variability in effect sizes (ln R).

To identify the outliers, we used the backward search algorithm specifically developed for meta-analysis (Mavridis et al., 2017). Backward search algorithms start with the full data set and remove sequentially outlying observations until all outliers have been removed. This method can be useful when there are a few outlying studies (Mavridis et al., 2017).

Results were back transformed, except for meta-regression, and reported in the text and figures as percentage changes from the controls:

$$N_2O \text{ emission change } (\%) = [\text{EXP}(\ln(R)) - 1] \times 100\%. \tag{7}$$

The OM input effects on the N_2O emissions were considered to be significantly different from the controls if the 95% CIs did not overlap with zero.

2.7 | Sensitivity analysis

Funnel plot asymmetry, which may indicate publication bias in meta-analysis, was examined by plotting ln R against its SE (Sterne & Egger, 2001). Moreover, Egger's regression-based test was conducted, enabling the detection of funnel plot asymmetry. A statistically non-significant p-value of Egger's test indicates no publication bias.

To estimate the magnitude of the file-drawer problem a fail-safe number (Nfs) was calculated. A fail-safe number is the number of non-significant, unpublished or missing studies that need to be added to a meta-analysis to change its results from significant to non-significant. Specifically, we used Rosenthal's method that estimates how many missing studies we would need to retrieve and incorporate in the analysis before the p-value became non-significant (Borenstein et al., 2009).

Trim-and-fill analysis was performed to allow one to enter values for "missing" studies to generate a symmetric funnel plot from which a new mean effect size can be estimated (Duval & Tweedie, 2000).

3 | RESULTS

This meta-analysis summarised the results of 53 field studies on the effect of seven different types of OM inputs added to soils on cumulative N_2O emissions, covering

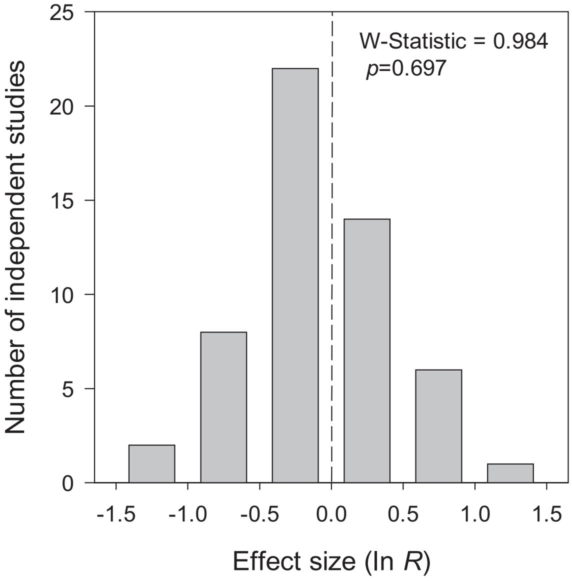


FIGURE 2 The distribution of effect sizes for 53 studies examining the effect of organic matter inputs on cumulative N_2O emissions. The dashed line indicates the control (mineral N fertiliser). The result for the normality test (Shapiro–Wilk) is shown.

European climate zones from the Alpine North to the Mediterranean South. These studies were published mainly in peer-reviewed scientific journals between 1993 and 2022. The impacts of pedoclimatic characteristics, agricultural management practices and the nature and quality of OM inputs on N_2O emissions were also studied.

3.1 | Overall effect

The effect sizes for 53 studies examining the effect of OM inputs on cumulative N_2O emissions were normally distributed (W-statistic $= 0.984$, $p = 0.697$; Figure 2). The forest plot indicates the large variability of effect sizes, ranging from −75% ($\ln R = -1.35$) to +200% ($\ln R = 1.10$) (Figure 3). The overall effect across all studies had a slight tendency to emissions reduction by 10% ($\ln R = -0.12$) compared to the control, that is mineral N fertiliser (median of 1.8 kg N_2O-N ha^{-1}). Since the 95% CI (−20%; 0%) overlapped with zero (the control), this indicates that the overall effect of OM inputs on N_2O emissions was not statistically significant.

3.2 | OM input characteristics

3.2.1 | C/N ratio

There was a statistically significant positive relationship between the C/N ratio of OM inputs and N_2O emission reduction (Figure 4). According to the meta-regression, OM with C/N ratio < 20 had a risk for increased N_2O emissions, whilst OM with C/N ratio of 20, 30, 50 and 100 reduced N_2O by 1%, 4%, 11% and 25% respectively, for example. OM inputs with the C/N ratio of 300, such as biochar, may have a potential to reduce emissions by up to 65% ($\ln R = -1.01$).

3.2.2 | Type of OM and N amount

The subgroup analysis showed that seven studied OM types had somewhat different effects ($Q_B = 12.3$, $df = 6$, 52, $p = 0.056$; Figure 5a). The effect of OM types such as green manure, crop residues, livestock manure, slurry and digestate ranged from −18% to +15%, but their 95% CIs overlapped with zero, indicating non-significant effects (Figure 5a). In contrast, compost and biochar significantly reduced N_2O emissions by 25% (95% CI: −36% to −18%, $n = 6$) and 33% (95% CI: −48% to −14%, $n = 8$) respectively compared to mineral N fertiliser (Figure 5a).

For the further moderator analyses, based on the similarity of effect sizes, the OM inputs were merged into two larger groups, namely OM_1 (green manure, crop residues, livestock manure, slurry and digestate) and OM_2 (biochar and compost). This allowed us to obtain enough studies per group. The response of N_2O emissions was statistically different between the groups ($Q_B = 10.5$, $df = 1$, 52; $p = 0.001$; Figure 5b): OM_1 had no effect on N_2O emissions compared to mineral N fertiliser (0%, 95% CI: −14% to 15%, $n = 39$), whilst OM_2 reduced N_2O emissions by 29% (95% CI: −40% to −18%, $n = 14$).

Finally, the total N supply in OM, ranging from 20 to 418 kg ha^{-1} a^{-1}, did not relate to effect sizes for both OM_1 ($Q_M = 0.00$, df = 1, 21; $p = 0.944$) and OM_2 ($Q_M = 0.82$, df = 1, 13; $p = 0.364$).

3.2.3 | OM input strategy

The impact of green manure, crop residues, livestock manure, slurry and digestate (OM_1) on N_2O emissions change depended on input strategy ($Q_B = 5.53$, $df = 1$, 38; $p = 0.019$; Figure 5b). In combination with mineral N fertiliser, they tended to increase emissions by 14% (95% CI: −3% to 41%, $n = 22$). When the experiments with crop residues ($n = 10$) were excluded from the previous subgroup analysis, the impact of organic fertilisers in combination with mineral N fertiliser increased N_2O emissions by 30% (95% CI: 2%–74%, $n = 12$) compared to control. In contrast, the application of organic fertilisers alone showed a declining trend by 16% (95% CI: −35% to 2%, $n = 17$).

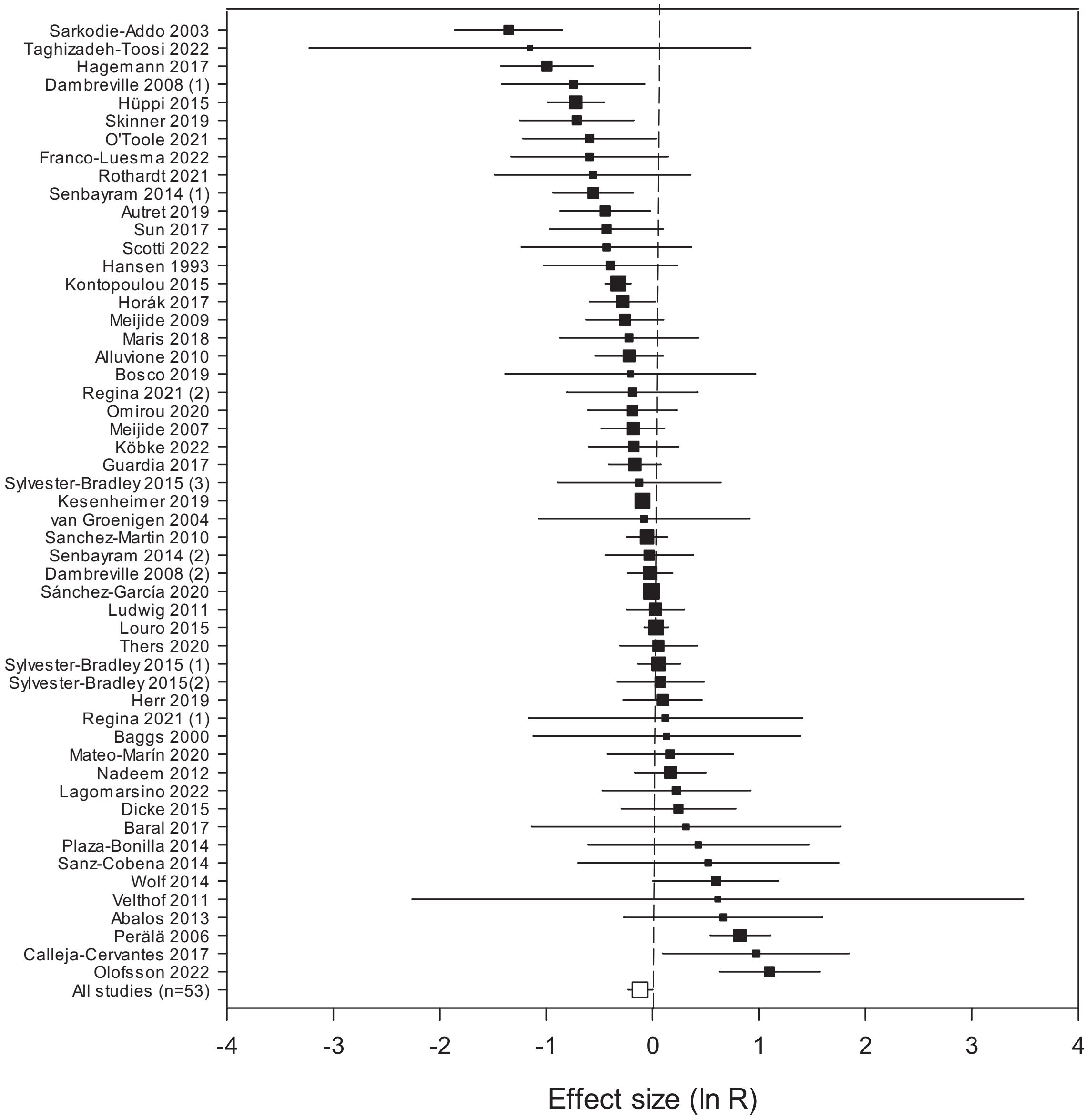


FIGURE 3 Forest plot showing effect sizes for 53 independent studies examining the effect of organic matter inputs on N_2O emissions compared to mineral N fertiliser (control). Black squares are summary effect estimates for each study with lower and upper 95% CIs. The square size corresponds to study weight, the white square indicates the weighted average with 95% CIs across all studies and the dashed vertical line indicates the control (mineral N fertiliser).

Unlike OM_1, biochar and compost reduced N_2O emissions statistically significantly, regardless of the input strategy (Figure 5b).

3.3 | Pedoclimatic factors

The meta-regressions indicated no statistically significant relationships between climatic characteristics and N_2O emission change due to the inputs of green manure, crop residues, livestock manure, slurry and digestate (Figure 6a,b). In addition, soil characteristics such as the content of sand, clay or SOC, soil pH and soil C/N ratio was unrelated to N_2O emission changes (Table S1 in Data S1). This suggests that the impact of these OM inputs on N_2O emissions is similar for all European pedoclimatic zones.

In contrast, the annual average temperature and annual precipitation was correlated with the efficiency of biochar and compost to mitigate N_2O emissions (Figure 6c,d). A smaller efficiency was observed under warmer or drier climatic conditions such as in the Mediterranean South than that in a temperate or boreal climate. For example, increasing the annual average temperature

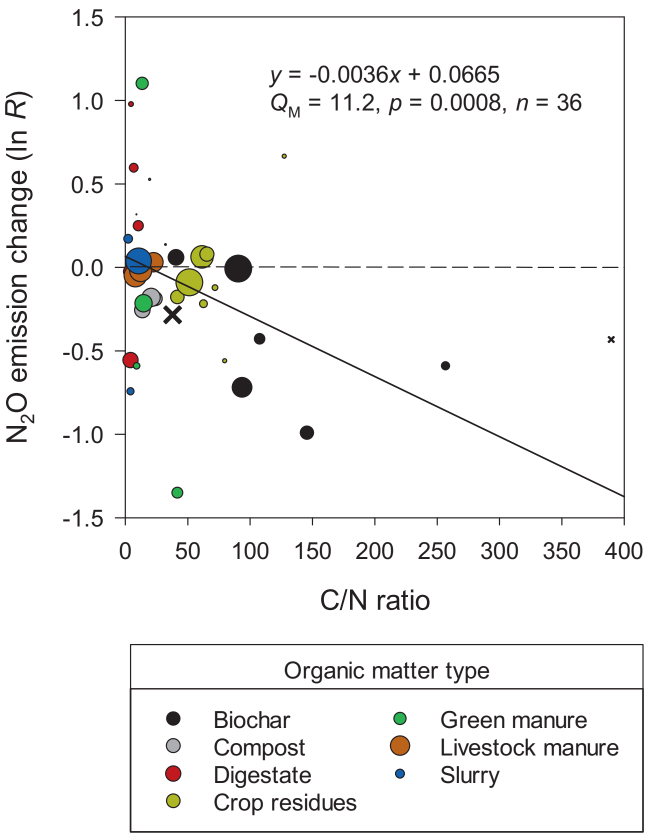


FIGURE 4 The relationship between the C/N ratio of organic matter inputs and N_2O emission change compared to mineral N fertiliser (control). The symbol size represents the study weight. The dashed line indicates the control (mineral N fertiliser) and the crosses indicate the outliers (ID38, ID39, ID40-1). For the back-transformation of ln *R*, see Equation (7). *n*, number of independent studies; Q_M, model heterogeneity.

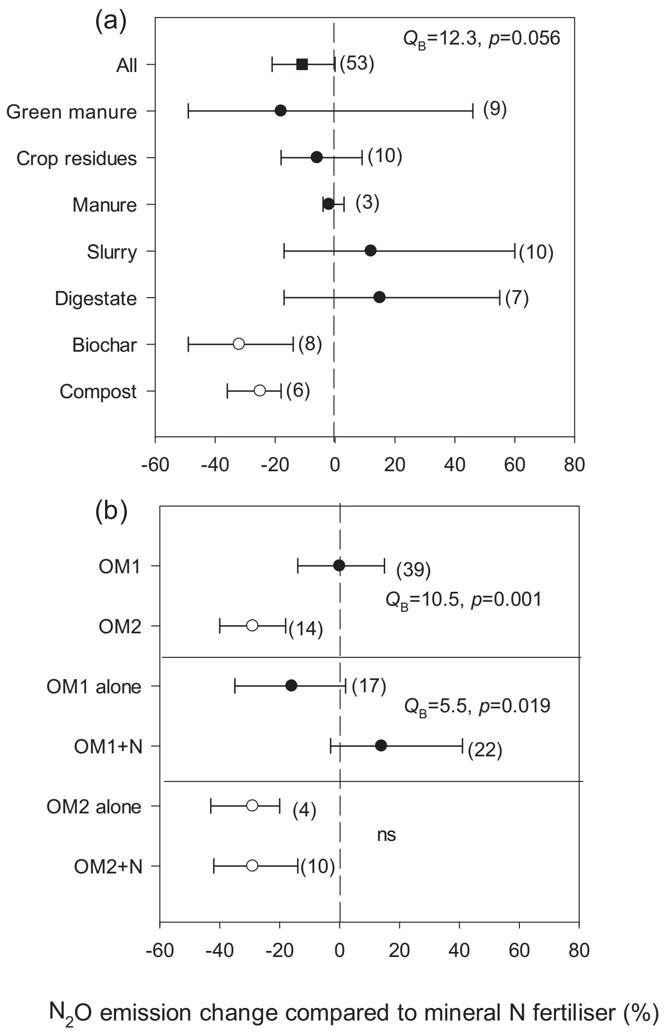


FIGURE 5 N_2O emission change due to organic matter (OM) types (a) individually and (b) clustered to the larger groups (OM_1; OM_2), and separated by input strategy (OM alone, OM applied alone; OM + N, OM applied in combination with mineral N fertiliser). The filled circles indicate OM_1 (green manure, crop residues, livestock manure, slurry and digestate), and the open circles indicate OM_2 (biochar, compost). The square corresponds to the overall effect. The dashed vertical line indicates the control (mineral N fertiliser). The numbers in parentheses indicate the number of independent studies. The N_2O emission changes were considered significantly different from the controls if the 95% CIs did not overlap with zero. Q_B is the between-group heterogeneity test.

from 5°C (boreal) to 15°C (Mediterranean South) reduced the efficiency of biochar and compost to mitigate N_2O from 55% to 23%. With a further temperature increase to 20°C, the efficiency of biochar and compost to mitigate N_2O emissions dropped to zero.

Moreover, increasing soil pH and sand content was related to a decline of the mitigation effect of biochar and compost (Figure 7). According to the meta-regression, in soil with high sand content (70%, e.g. sandy loam), the efficiency of biochar and compost was low, and it dropped twice in alkaline soils (−7%) compared to neutral soils (−15%). In contrast, in soil with low sand content (20%, e.g. silt loam), the efficiency was as high as −43% in neutral soils, and it dropped slightly to −37% in alkaline soils.

Several confounding factors such as the intercorrelation between soil pH and both annual average temperature ($r_s = 0.781$, $p < 0.001$, $n = 14$) and annual precipitation ($r_s = -0.673$, $p < 0.001$, $n = 14$) should be interpreted with care. For example, studies in the Mediterranean South had alkaline soils, with pH ranging between 7.4 and 8.4, whilst studies in temperate and boreal zones had acidic soil, with pH ranging between 5.7 and 6.5. This does not allow us to draw a clear conclusion on which factor, soil pH or climate, is the most important in terms of driving N_2O emissions reduction by biochar and compost.

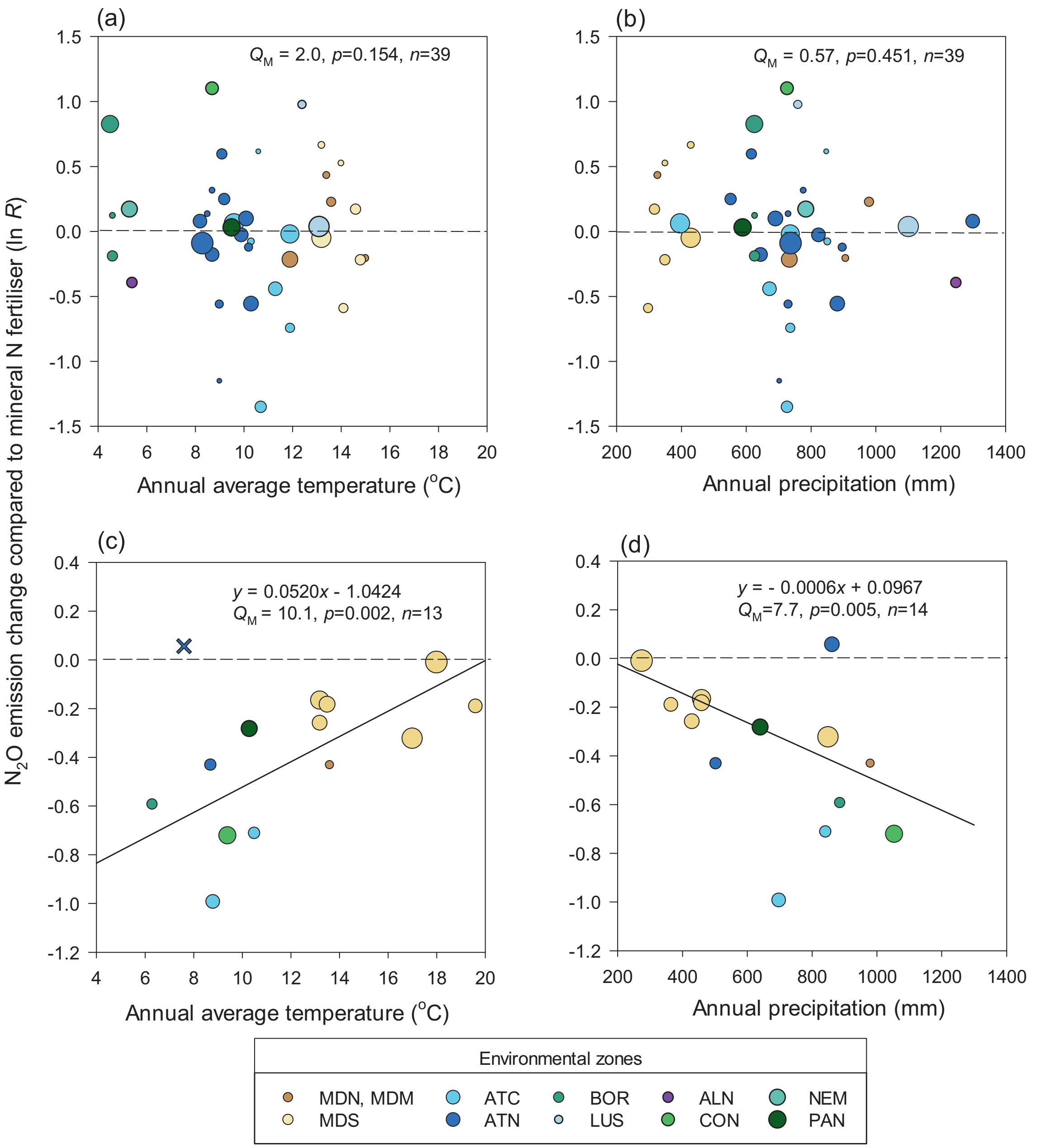


FIGURE 6 (a and b) Scatter plots between N_2O emission change due to green manure, crop residues, livestock manure, slurry and digestate and annual average temperature and annual precipitation. (c and d) Weighted meta-regressions (solid lines) between N_2O emission change due to biochar and compost and annual average temperature and annual precipitation. The symbol size represents the study weight. The dashed line indicates the control (mineral N fertiliser), whilst the cross indicates the outlier (ID45 Thers et al., 2020). For the back-transformation of ln R, see Equation (7). For abbreviations for environmental zones, see Figure 1. n, number of independent studies; Q_M, model heterogeneity.

3.4 | Management practices and study characteristics

There were no statistically significant relationships between total N supply (mineral N + OM) and effect sizes (Table S2 in Data S1). Agronomic management practices (farming systems, cropping systems, the presence of cover crops or irrigation) did not modify the effect sizes (Table S2 in Data S1). This indicates that N_2O emission changes due to OM inputs were independent of the management practices studied here. Finally, the effect sizes were not related to the duration of experiments, the measurement period (covering a period from 1 month to 3 years) or to the season of N_2O measurement (Table S2 in Data S1).

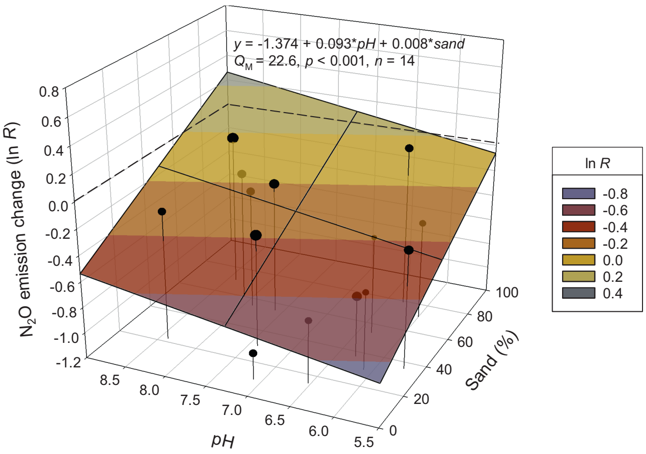


FIGURE 7 Weighted meta-regressions between N_2O emission change due to biochar and compost and the combination of soil pH and sand content. The symbol size represents the study weight. The dashed line indicates the control (mineral N fertiliser). For the back-transformation of ln *R*, see Equation (7). *n*, number of independent studies; Q_M, model heterogeneity.

3.5 | Sensitivity analysis

The funnel plot for N_2O emissions studies showed no asymmetry (Figure S1 in Data S1). In addition, no publication bias was detected by the Egger's regression-based test ($p = 0.896$; Table S3 in Data S1). The trim-and-fill analysis of publication bias for meta-analysis was also implemented. The imputed five “missing” studies shifted ln *R* slightly from −0.12 (−11%) to −0.17 (−16%) (Figure S1 in Data S1). However, the adjusted estimate is close to the original.

For studies on biochar and compost, a fail-safe number is 77, indicating that the results are robust. A consistent number of unpublished or missing studies would need to be added (that is 5.5 times more than in the present meta-analysis) to change the results from significant to non-significant.

4 | DISCUSSION

We hypothesised that soil management strategies involving the application of OM inputs would mitigate soil N_2O emissions. Indeed, the results of meta-analysis showed that the overall effect of OM inputs had a slight tendency to reduce N_2O emissions by 10% ($n = 53$). One of the important factors related to the N_2O emission reduction was the C/N ratio of OM inputs as indicated by meta-regression (Figure 4). However, it should be noted that amongst all OM types, biochar with high C/N ratio was the major contributor to this strong relationship. The threshold of emissions reduction was set at the C/N ratio of 20–30, which is commonly considered a threshold for net N immobilisation (Mooshammer et al., 2014). Similarly, the meta-analysis by Cayuela et al. (2014) showed that biochar with a C/N ratio higher than 30 decreased N_2O emissions but not for biochar characterised by ratios lower than 30 C/N. Meta-analyses on the effect of crop residues amendments also demonstrated that the C/N ratio was one of the main factors determining the variability of N_2O emission response (Chen et al., 2013; Xia et al., 2018).

In our meta-analysis, we clearly demonstrated a statistically significant reduction of N_2O emissions by 33% due to biochar and by 25% due to compost (Figure 5a). The result of biochar effect was in accordance with the global meta-analysis by Liu et al. (2018) and by Borchard et al. (2019), who estimated emissions cutting by 32% and 38% respectively. The meta-analysis by Cayuela et al. (2014) demonstrated an even larger reduction effect (−54%), which can probably be attributed to the experiment type, as the experiments were conducted in laboratory and greenhouse conditions but not in the field. The results of our study contrasted with the meta-analyses by Verhoeven et al. (2017) and Zhou et al. (2017), who showed minor effects of biochar (for upland −11.5%) and compost (+2.8%). The inconsistency between the outcomes of different meta-analyses may have been driven by the locations considered, and the variability in pedoclimatic conditions of the experiments may therefore have been included in both meta-analyses.

Our study demonstrates that the effect of biochar and compost depended on climate, with less emissions reduction in warmer or drier climatic conditions such as in the Mediterranean South than in temperate climates (Figure 6c,d). However, due to intercorrelation, it is difficult to confidently conclude which factor, soil pH or climate, was the most important moderator in terms of driving N_2O emission reduction by biochar and compost. In line with our results, Sánchez-García et al. (2014) showed that the dominant soil microbial community, usually characterised by pedoclimatic conditions, strongly influences the dominant N_2O pathway (denitrification vs nitrification), and that biochar can both increase and decrease N_2O emissions in different climates or soils.

Indeed, our meta-analysis confirmed that the mitigation effect of biochar and compost declined with an increasing soil pH or sand content (Figure 7) and became zero in soils with a sand content ranging from 80% to 95%, depending on soil pH. N_2O emissions are more likely to be higher in acidic soils due to the suppression in the production of the N_2O reductase enzyme (NosZ) at lower pH (B. Liu et al., 2014). Sandy soils will normally have a lower incidence of waterlogging compared to clay soils and thus lower anaerobic sites where denitrification can take place. The mitigation effect of biochar and compost may therefore be less pronounced in these conditions.

Several mechanisms may contribute to the N_2O emission reduction after compost application, as observed in our study. The typically lower availability of mineral N compounds in compost (Omirou et al., 2020; Zhou et al., 2017) may have limited the denitrification process (Zhou et al., 2017). Furthermore, the addition of carbon associated with compost application may stimulate microbial respiration resulting in anaerobic microsites, where complete denitrification to N_2 can take place (Omirou et al., 2020), reducing the emissions of N_2O. Dalal et al. (2010) suggested that the reduction of N_2O emissions due to compost may be explained by its chemical properties. The typically high C/N ratios favour the immobilisation of mineral N, whilst high lignin concentrations and high lignin/N ratios slow down organic N decomposition. Both processes result in reduced mineral N levels in the soil, limiting denitrification.

Although high biochar C/N ratios are correlated with lower N_2O emissions, the immobilisation of N in microbial biomass is not the main reason biochar reduces N_2O. Biochar with high C/N ratio is typically produced at higher temperatures (>500°C), whereby N is driven off, and the remaining solid product is enriched in C, with higher alkalinity, increased porosity and surface area (Mukherjee et al., 2011). Several controlled experiments have concluded that biochar reduced N_2O through the entrapment and sorption of N_2O in biochar pore space (Cornelissen et al., 2013), slowing of the N_2O diffusion to the surface in water saturated biochar pores (Harter et al., 2016), greater alkalinity (supporting complete denitrification to N_2) (Weldon et al., 2019), abiotic reduction of N_2O to N_2 on redox active biochar surfaces (Quin et al., 2015) and immobilisation of N, which limits N substrate access to denitrifying bacteria (Singh et al., 2010; Spokas et al., 2009). In summary, whilst the C/N ratio for both compost and biochar was correlated with reduced N_2O emissions, the mechanisms for reduction due to compost were mostly due to biotic factors, whilst the reasons for reduction due to biochar were mostly abiotic.

It should be noted that the extensive use of biochar in European agriculture is scant, and N_2O reductions from biochar observed in research experiments (also in the studies included in this meta-analysis) have mostly been achieved when high dose rates have been used (>10 t ha^{-1}). It is unrealistic to expect these high dose rates in broadacre agriculture due to the current high market price for biochar (€800 t^{-1}, Garcia et al., 2022). Furthermore, the N_2O suppression effect from biochar has been shown to abate with time as it ages and loses its alkalinity (O'Toole, 2021; Thers et al., 2020). However, more long-term field experiments are needed to assess this effect in a European meta-analysis.

The effect of other OM types (green manure, crop residues, livestock manure, slurry and digestate) on N_2O emissions ranged from −18% to +15% compared to mineral N fertiliser, but not statistically significantly (Figure 5a). Inputs of crop residues tended to decrease N_2O emissions per unit area, but not significantly. This contradicts the general statements of previous meta-analyses, where crop residues in upland soils reported stimulation of N_2O emissions, but with large variability in the effects (Table 1). However, this is mainly because the N_2O stimulation was significant for vegetables and legumes, but not for cereals (Abalos et al., 2022; Chen et al., 2013). This pattern is also confirmed by the results of other incorporated plant residues such as green manures (Basche et al., 2014), where the stimulation by legumes was many times higher than by non-legume plants (+490% and +7% respectively, Table 1), arguably due to the N content of the residues, that is low C/N ratio.

In the European studies included in our database, there were mainly non-legume crops, whilst the scarce data on legumes were reflected in the knowledge gap on the effect of legume residue incorporation/removal on N_2O emissions. Compared to other OM types, most cereal crop residues (except crops for silage) are already drier and more depleted in N content compared to green residues, as they are incorporated after the grain harvest. Another factor is the biochemical composition of the crop residues (Abalos et al., 2022), as the more lignin or cellulose content in the incorporated aboveground biomass at the time of application may tend to reduce cumulative N_2O emissions after incorporation. The yield-scaled N_2O emissions have been proposed as a suitable metric for the evaluation of N_2O mitigation by considering the crop productivity (Van Groenigen et al., 2010). Van Groenigen et al. (2010) observed a negative correlation between the nutrient use efficiency and yield-scaled N_2O emissions on the basis of a global meta-analysis but due to shortage of data, did not quantify the effect of organic amendments. Original field experiments showed inconsistent results for the yield-scaled N_2O emissions due to crop residues: either increased N_2O emissions due to non-legume cover crops (Taghizadeh-Toosi et al., 2022) and their mixture with legumes (Kim et al., 2017), or decreased N_2O emissions by the incorporation of legume residues (Sanz-Cobena et al., 2014), whilst no changes by incorporation of cereal residues (Rahman et al., 2024; Sanz-Cobena et al., 2014).

Our results for livestock manure and slurry were consistent with the global meta-analyses by Han et al. (2017), Wei et al. (2020) and Fan et al. (2023), who demonstrated statistically non-significant effects on N_2O emissions (−15% to +12%, Table 1). In their meta-analysis, Zhou et al. (2017) observed some differences in effect sizes between manure types ($p = 0.087$), with the largest stimulation of N_2O emissions due to the application of poultry manure (+45.4%), whilst there was a statistically non-significant emission reduction (−21.4%) due to farmyard manure compared to mineral N fertiliser. The variation in the extent of emissions from different types of manure demonstrates the effects of manure properties such as moisture content, total N and available N content on emission generation (Bell et al., 2016). In our meta-analysis, however, we were unable to address the effect of manure types due to the limited number of studies ($n = 3$ for livestock manure and $n = 10$ for slurry).

This meta-analysis revealed that neither soil characteristics nor climate impacted N_2O emission changes due to inputs of green manure, crop residues, livestock manure, slurry and digestate, suggesting that the results were valid for all European environmental zones. In contrast, several global meta-analyses demonstrated the importance of pedoclimatic characteristics in the regulation of N_2O emissions due to manure (Han et al., 2017; Zhang et al., 2022; Zhou et al., 2017), cover crops (Muhammad et al., 2019) and straw return (Xia et al., 2018). For example, the significant stimulatory effects on N_2O emissions due to manure were observed for warm temperate climates, acid soils ($pH < 6.5$) and the soil texture classes of sandy loam and clay loam, as shown in the global meta-analysis by Zhou et al. (2017). Zhang et al. (2022) concluded the greater power of key abiotic factors (annual precipitation, soil pH and soil C/N ratio) in explaining N-induced changes in soil N_2O emission, since there was no clear relationship between changes in soil N_2O emission and shifts in ammonia oxidizer and denitrifier abundances, which are the main producers of N_2O.

Here, we stress the importance of the input strategy for organic fertilisers (green manure, livestock manure, slurry and digestate), as their addition to soils in combination with mineral N fertiliser increased N_2O emissions by 30%, whilst their inputs alone showed a decline trend by 16%. This can be attributed by the lower availability or the slower release of mineral N compounds from OM compared to the application from mineral N fertiliser, as was also suggested by Zhou et al. (2017) for N_2O emission reductions after compost application. In the meta-analysis by Wei et al. (2020), it was shown that the organic substitution of mineral fertiliser non-significantly decreased N_2O emissions by about 13%, whilst at the high fertilisation rate, N_2O emissions were significantly decreased by about 37%. Similarly, the meta-analysis by Kong et al. (2023), who mainly summarised Chinese studies, demonstrated that the partial replacement of mineral N fertiliser by biogas slurry (a liquid with a high moisture content and a low C/N ratio) reduced N_2O emissions by 16%.

5 | CONCLUSION

The major challenge of conducting this meta-analysis was the ambitious goal of synthesising the effects of seven OM inputs, which had a different nature and quality (i.e. plant- or animal-based, raw or pre-treated), on N_2O emissions in the European field experiments.

Amongst the seven types of OM inputs studied, only biochar and compost application to soils reduced N_2O emissions statistically significantly compared to mineral N fertiliser. Other OM inputs (green manure, livestock manure, slurry and digestate) added solely to soils tended to reduce N_2O emissions. In contrast, the addition of OM inputs to soils in combination with mineral N fertiliser entailed a risk of increasing N_2O emissions.

Although the total number of independent experiments included in the database exceeded 50, which is considered as a large number of studies for a meta-analysis (Hedges et al., 1999), the availability of field experiments for each OM type was relatively small. This impeded a detailed study on the role of pedoclimatic factors and management practices in relation to a specific OM type. There is therefore a need for more European studies that monitor N_2O emissions in the field.

AUTHOR CONTRIBUTIONS

Elena Valkama: Conceptualization; data curation; formal analysis; methodology; supervision; visualization; writing – original draft; writing – review and editing. **Domna Tzemi:** Data curation; visualization; writing – original draft; writing – review and editing. **Ulises Ramon Esparza-Robles:** Data curation; writing – original draft; writing – review and editing. **Alina Syp:** Data curation; writing – original draft. **Adam O'Toole:** Writing – original draft; data curation; writing – review and editing. **Peter Maenhout:** Conceptualization; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at https://zenodo.org, reference number https://doi.org/10.5281/zenodo.10907112.

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REFERENCES

Abalos, D., Rittl, T. F., Recous, S., Thiébeau, P., Topp, C. F. E., van Groenigen, K. J., Butterbach-Bahl, K., Thorman, R. E., Smith, K. E., Ahuja, I., Olesen, J. E., Bleken, M. A., Rees, R. M., & Hansen, S. (2022). Predicting field N_2O emissions from crop residues based on their biochemical composition: A meta-analytical approach. *Science of the Total Environment*, *812*, 152532. https://doi.org/10.1016/j.scitotenv.2021.152532

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R. M., & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology*, *25*, 2530–2543. https://doi.org/10.1111/gcb.14644

Acutis, M., Tadiello, T., Perego, A., Di Guardo, A., Schillaci, C., & Valkama, E. (2021). Ex-tract tool_1.0.xlsm. An excel tool for the estimation of standard deviations from published articles. *Figshare Software*. https://doi.org/10.6084/m9.figshare.14987130.v6

Acutis, M., Tadiello, T., Perego, A., Di Guardo, A., Schillaci, C., & Valkama, E. (2022). EX-TRACT: An excel tool for the estimation of standard deviations from published articles. *Environmental Modelling and Software*, *147*, 105236. https://doi.org/10.1016/j.envsoft.2021.105236

Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P.-A., Tao, B., Hui, D., Yang, J., & Matocha, C. (2019). Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. *Global Change Biology*, *25*, 2591–2606. https://doi.org/10.1111/gcb.14658

Basche, A. D., Miguez, F. E., Kaspar, T. C., & Castellano, M. J. (2014). Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis. *Journal of Soil and Water Conservation*, *69*, 471–482. https://doi.org/10.2489/jswc.69.6.471

Bell, M. J., Hinton, N. J., Cloy, J. M., Topp, C. F. E., Rees, R. M., Williams, J. R., Misselbrook, T. H., & Chadwick, D. R. (2016). How do emission rates and emission factors for nitrous oxide and ammonia vary with manure type and time of application in a Scottish farmland? *Geoderma*, *264*, 81–93. https://doi.org/10.1016/j.geoderma.2015.10.007

Bolinder, M. A., Crotty, F., Elsen, A., Frac, M., Kismányoky, T., Lipiec, J., Tits, M., Tóth, Z., & Kätterer, T. (2020). The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: A synthesis of reviews. *Mitigation and Adaptation Strategies for Global Change*, *25*, 929–952. https://doi.org/10.1007/s11027-020-09916-3

Borchard, N., Schirrmann, M., Luz Cayuela, M., Kammann, C., Wrage-Moennig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Sigua, G., Spokas, K., Ippolito, J. A., & Novak, J. (2019). Biochar, soil and landuse interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis. *Science of the Total Environment*, *651*, 2354–2364. https://doi.org/10.1016/j.scitotenv.2018.10.060

Borenstein, M., Hedges, L., Higgins, J., & Rothstein, H. (2009). *Introduction to meta-analysis*. John Wiley & Sons, Ltd..

Burger, M., & Jackson, L. E. (2003). Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. *Soil Biology and Biochemistry*, *35*, 29–36. https://doi.org/10.1016/S0038-0717(02)00233-X

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., & Zechmeister-Boltenstern, S. (2013). Nitrous oxide emissions from soils: How well do we understand the processes and their controls? *Philosophical Transactions of the Royal Society, B: Biological Sciences*, *368*, 20130122. https://doi.org/10.1098/rstb.2013.0122

Carter, M. S., Sørensen, P., Petersen, S. O., Ma, X., & Ambus, P. (2014). Effects of green manure storage and incorporation methods on nitrogen release and N_2O emissions after soil application. *Biology and Fertility of Soils*, *50*, 1233–1246. https://doi.org/10.1007/s00374-014-0936-5

Cayuela, M. L., van Zwieten, L., Singh, B. P., Jeffery, S., Roig, A., & Sánchez-Monedero, M. A. (2014). Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment*, *191*, 5–16. https://doi.org/10.1016/j.agee.2013.10.009

Chen, H., Li, X., Hu, F., & Shi, W. (2013). Soil nitrous oxide emissions following crop residue addition: A meta-analysis. *Global Change Biology*, *19*, 2956–2964. https://doi.org/10.1111/gcb.12274

Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., & Beaudoin, N. (2010). Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agriculture, Ecosystems and Environment*, *135*, 268–278. https://doi.org/10.1016/j.agee.2009.10.005

Cornelissen, G., Rutherford, D. W., Arp, H. P. H., Dörsch, P., Kelly, C. N., & Rostad, C. E. (2013). Sorption of pure N_2O to biochars and other organic and inorganic materials under anhydrous conditions. *Environmental Science and Technology*, *47*, 7704–7712. https://doi.org/10.1021/es400676q

Dalal, R. C., Gibson, I., Allen, D. E., & Menzies, N. W. (2010). Green waste compost reduces nitrous oxide emissions from feedlot manure applied to soil. *Agriculture, Ecosystems & Environment*, *136*, 273–281. https://doi.org/10.1016/j.agee.2009.06.010

Duval, S., & Tweedie, R. (2000). Trim and fill: A simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*, *56*, 455–463. https://doi.org/10.1111/j.0006-341X.2000.00455.x

Efron, B., & Tibshirani, R. (1986). Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. *Statistical Science*, *1*, 54–77. https://doi.org/10.1214/ss/1177013815

Essich, L., Nkebiwe, P. M., Schneider, M., & Ruser, R. (2020). Is crop residue removal to reduce N_2O emissions driven by quality or quantity? A field study and meta-analysis. *Agriculture*, *10*, 546. https://doi.org/10.3390/agriculture10110546

Fan, X., Chen, X., Chen, T., Liu, X., Song, Y., Tan, S., Chen, Y., Yan, P., & Wang, X. (2023). Effects of substituting synthetic nitrogen with organic amendments on crop yield, net greenhouse gas emissions and carbon footprint: A global meta-analysis. *Field Crops Research*, *301*, 109035. https://doi.org/10.1016/j.fcr.2023.109035

Fohrafellner, J., Zechmeister-Boltenstern, S., Murugan, R., & Valkama, E. (2023). Quality assessment of meta-analyses on soil organic carbon. *The Soil*, *9*, 117–140. https://doi.org/10.5194/soil-9-117-2023

Frimpong, K. A., & Baggs, E. M. (2010). Do combined applications of crop residues and inorganic fertilizer lower emission of N_2O from soil? *Soil Use and Management*, *26*, 412–424. https://doi.org/10.1111/j.1475-2743.2010.00293.x

Garcia, B., Alves, O., Rijo, B., Lourinho, G., & Nobre, C. (2022). Biochar: Production, applications, and market prospects in Portugal. *Environments*, *9*, 95. https://doi.org/10.3390/environments9080095

Garcia-Ruiz, R., & Baggs, E. M. (2007). N_2O emission from soil following combined application of fertiliser-N and ground weed residues. *Plant and Soil*, *299*, 263–274. https://doi.org/10.1007/s11104-007-9382-6

Gross, A., Bromm, T., & Glaser, B. (2021). Soil organic carbon sequestration after biochar application: A global meta-analysis. *Agronomy*, *11*, 2474. https://doi.org/10.3390/agronomy11122474

Han, Z., Walter, M. T., & Drinkwater, L. E. (2017). N_2O emissions from grain cropping systems: A meta-analysis of the impacts of fertilizer-based and ecologically-based nutrient management strategies. *Nutrient Cycling in Agroecosystems*, *107*, 335–355. https://doi.org/10.1007/s10705-017-9836-z

Harter, J., Guzman-Bustamante, I., Kuehfuss, S., Ruser, R., Well, R., Spott, O., Kappler, A., & Behrens, S. (2016). Gas entrapment and microbial N_2O reduction reduce N_2O emissions from a biochar-amended sandy clay loam soil. *Scientific Reports*, *6*, 39574. https://doi.org/10.1038/srep39574

Hedges, L. V., Gurevitch, J., & Curtis, P. S. (1999). The meta-analysis of response ratios in experimental ecology. *Ecology*, *80*(4), 1150–1156. https://doi.org/10.2307/177062

Jian, J., Du, X., Reiter, M. S., & Stewart, R. D. (2020). A meta-analysis of global cropland soil carbon changes due to cover cropping. *Soil Biology and Biochememistry*, *143*, 107735. https://doi.org/10.1016/j.soilbio.2020.107735

Kim, G. W., Das, S., Hwang, H. Y., & Kim, P. J. (2017). Nitrous oxide emissions from soils amended by cover-crops and under plastic film mulching: Fluxes, emission factors and yield-scaled emissions. *Atmospheric Environment*, *152*, 377–388. https://doi.org/10.1016/j.atmosenv.2017.01.007

Kong, F., Li, Q., Yang, Z., & Chen, Y. (2023). Does the application of biogas slurry reduce soil N_2O emissions and increase crop yield? A systematic review. *Journal of Environmental Management*, *342*, 118339. https://doi.org/10.1016/j.jenvman.2023.118339

Kroeze, C., Mosier, A., & Bouwman, L. (1999). Closing the global N_2O budget: A retrospective analysis 1500–1994. *Global Biogeochemical Cycles*, *13*(1), 1–8. https://doi.org/10.1029/1998GB900020

Lashermes, G., Gainvors-Claisse, A., Recous, S., & Bertrand, I. (2016). Enzymatic strategies and carbon use efficiency of a litter-decomposing fungus grown on maize leaves, stems, and roots. *Frontiers in Microbiology*, *7*, 1315. https://doi.org/10.3389/fmicb.2016.01315

Lehmann, J., Abiven, S., Kleber, M., Pan, G., Singh, B. P., Sohi, S. P., & Zimmerman, A. R. (2015). Persistence of biochar in soil. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science, technology and implementation* (pp. 236–282). Earthscan.

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems – A review. *Mitigation and Adaptation Strategies for Global Change*, *11*, 395–419. https://doi.org/10.1007/s11027-005-9006-5

Lehtinen, T., Schlatter, N., Baumgarten, A., Bechini, L., Krüger, J., Grignani, C., Zavattaro, L., Costamagna, C., & Spiegel, H. (2014). Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils. *Soil Use and Management*, *30*, 524–538. https://doi.org/10.1111/sum.12151

Li, Y., Chen, J., Drury, C. F., Liebig, M., Johnson, J. M., Wang, Z., Feng, H., & Abalos, D. (2023). The role of conservation agriculture practices in mitigating N_2O emissions: A meta-analysis. *Agronomy for Sustainable Development*, *43*, 63. https://doi.org/10.1007/s13593-023-00911-x

Liu, B., Frostegård, Å., & Bakken, L. R. (2014). Impaired reduction of N_2O to N_2 in acid soils is due to a posttranscriptional interference with the expression of nosZ. *MBio*, *5*, e01383-14. https://doi.org/10.1128/mbio.01383-14

Liu, C., Lu, M., Cui, J., Li, B., & Fang, C. (2014). Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. *Global Change Biology*, *20*, 1366–1381. https://doi.org/10.1111/gcb.12517

Liu, Q., Zhang, Y., Liu, B., Amonette, J. E., Lin, Z., Liu, G., Ambus, P., & Xie, Z. (2018). How does biochar influence soil N cycle? A meta-analysis. *Plant and Soil*, *426*, 211–225. https://doi.org/10.1007/s11104-018-3619-4

Lugato, E., Leip, A., & Jones, A. (2018). Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions. *Nature Climate Change*, *8*, 219–223. https://doi.org/10.1038/s41558-018-0087-z

Maillard, É., & Angers, D. A. (2014). Animal manure application and soil organic carbon stocks: A meta-analysis. *Global Change Biology*, *20*, 666–679. https://doi.org/10.1111/gcb.12438

Mary, B., Recous, S., Darwis, D., & Robin, D. (1996). Interactions between decomposition of plant residues and nitrogen cycling in soil. *Plant and Soil*, *181*, 71–82. https://doi.org/10.1007/BF00011294

Mavridis, D., Moustaki, I., Wall, M., & Salanti, G. (2017). Detecting outlying studies in meta-regression models using a forward search algorithm: Forward search in meta-analysis. *Research Synthesis Methods*, *8*, 199–211. https://doi.org/10.1002/jrsm.1197

Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Mücher, C. A., & Watkins, J. W. (2005). A climatic stratification of the environment of Europe. *Global Ecology and*

Biogeography, *14*, 549–563. https://doi.org/10.1111/j.1466-822X.2005.00190.x

Millar, N., & Baggs, E. M. (2005). Relationships between N_2O emissions and water-soluble C and N contents of agroforestry residues after their addition to soil. *Soil Biology and Biochemistry*, *37*, 605–608. https://doi.org/10.1016/j.soilbio.2004.08.016

Miller, M. N., Zebarth, B. J., Dandie, C. E., Burton, D. L., Goyer, C., & Trevors, J. T. (2008). Crop residue influence on denitrification, N_2O emissions and denitrifier community abundance in soil. *Soil Biology and Biochemistry*, *40*, 2553–2562. https://doi.org/10.1016/j.soilbio.2008.06.024

Mooshammer, M., Wanek, W., Hämmerle, I., Fuchslueger, L., Hofhansl, F., Knoltsch, A., Schnecker, J., Takriti, M., Watzka, M., Wild, B., & Keiblinger, K. M. (2014). Adjustment of microbial nitrogen use efficiency to carbon: Nitrogen imbalances regulates soil nitrogen cycling. *Nature Communications*, *5*, 3694. https://doi.org/10.1038/ncomms4694

Muhammad, I., Sainju, U. M., Zhao, F., Khan, A., Ghimire, R., Fu, X., & Wang, J. (2019). Regulation of soil CO_2 and N_2O emissions by cover crops: A meta-analysis. *Soil and Tillage Research*, *192*, 103–112. https://doi.org/10.1016/j.still.2019.04.020

Muhammad, I., Wang, J., Sainju, U. M., Zhang, S., Zhao, F., & Khan, A. (2021). Cover cropping enhances soil microbial biomass and affects microbial communitystructure: A meta-analysis. *Geoderma*, *381*, 114696. https://doi.org/10.1016/j.geoderma.2020.114696

Mukherjee, A., Zimmerman, A. R., & Harris, W. (2011). Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma*, *163*, 247–255. https://doi.org/10.1016/j.geoderma.2011.04.021

Nakagawa, S., Noble, D. W., Senior, A. M., & Lagisz, M. (2017). Meta-evaluation of meta-analysis: Ten appraisal questions for biologists. *BMC Biology*, *15*, 18. https://doi.org/10.1186/s12915-017-0357-7

Nett, L., Sradnick, A., Fuß, R., Flessa, H., & Fink, M. (2016). Emissions of nitrous oxide and ammonia after cauliflower harvest are influenced by soil type and crop residue management. *Nutrient Cycling in Agroecosystems*, *106*, 217–231. https://doi.org/10.1007/s10705-016-9801-2

Olesen, J. E., Rees, R. M., Recous, S., Bleken, M. A., Abalos, D., Ahuja, I., Butterbach-Bahl, K., Carozzi, M., De Notaris, C., Ernfors, M., & Haas, E. (2023). Challenges of accounting nitrous oxide emissions from agricultural crop residues. *Global Change Biology*, *29*, 6846–6855. https://doi.org/10.1111/gcb.16962

Omirou, M., Anastopoulos, I., Fasoula, D. A., & Ioannides, I. M. (2020). The effect of chemical and organic N inputs on N_2O emission from rain-fed crops in eastern Mediterranean. *Journal of Environmental Management*, *270*, 110755. https://doi.org/10.1016/j.jenvman.2020.110755

O'Toole, A. (2021). *The agronomic and environmental effects of biochar under field conditions in Norway*. Norwegian University of Life Sciences, Faculty of Environmental Sciences and Natural Resource Management, Ås, PhD thesis. https://static02.nmbu.no/mina/forskning/drgrader/2021-Otoole.pdf

Pulido-Moncada, M., Petersen, S. O., & Munkholm, L. J. (2022). Soil compaction raises nitrous oxide emissions in managed agroecosystems. A review. *Agronomy for Sustainable Development*, *42*, 38. https://doi.org/10.1007/s13593-022-00773-9

Quin, P., Joseph, S., Husson, O., Donne, S., Mitchell, D., Munroe, P., Phelan, D., Cowie, A., & Van Zwieten, L. (2015). Lowering N_2O emissions from soils using eucalypt biochar: The importance of redox reactions. *Scientific Reports*, *5*, 16773. https://doi.org/10.1038/srep16773

Rahman, M. S., Ferdous, J., Mumu, N. J., Kamruzzaman, M., Eckhardt, C., Zaman, M., Müller, C., & Jahangir, M. M. R. (2024). Crop residues integration with nitrogen rates reduces yield-scaled nitrous oxide emissions and improves maize yield and soil quality. *Journal of Integrative Environmental Sciences*, *21*, 2310856. https://doi.org/10.1080/1943815X.2024.2310856

Rosenberg, M. S., Adams, D. C., & Gurevitch, J. (2000). *Metawin: Statistical software for meta-analysis, version 2.1*. Sinauer Associates, Inc.

Sánchez-García, M., Roig, A., Sánchez-Monedero, M. A., & Cayuela, M. L. (2014). Biochar increases soil N_2O emissions produced by nitrification-mediated pathways. *Frontiers in Environmental Science*, *2*, 25. https://doi.org/10.3389/fenvs.2014.00025

Sandén, T., Spiegel, H., Stüger, H. P., Schlatter, N., Haslmayr, H. P., Zavattaro, L., Grignani, C., Bechini, L., D'Hose, T., Molendijk, L., & Pecio, A. (2018). European long-term field experiments: Knowledge gained about alternative management practices. *Soil Use and Management*, *34*, 167–176. https://doi.org/10.1111/sum.12421

Sanz-Cobena, A., García-Marco, S., Quemada, M., Gabriel, J. L., Almendros, P., & Vallejo, A. (2014). Do cover crops enhance N_2O, CO_2 or CH_4 emissions from soil in Mediterranean arable systems? *Science of the Total Environment*, *466*, 164–174. https://doi.org/10.1016/j.scitotenv.2013.07.023

Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH image to ImageJ: 25 years of image analysis. *Nature Methods*, *9*(7), 671–675. https://doi.org/10.1038/nmeth.2089

Shakoor, A., Shahzad, S. M., Chatterjee, N., Arif, M. S., Farooq, T. H., Altaf, M. M., Tufail, M. A., Dar, A. A., & Mehmood, T. (2021). Nitrous oxide emission from agricultural soils: Application of animal manure or biochar? A global meta-analysis. *Journal of Environmental Management*, *285*, 112170. https://doi.org/10.1016/j.jenvman.2021.112170

Shakoor, A., Shakoor, S., Rehman, A., Ashraf, F., Abdullah, M., Shahzad, S. M., Farooq, T. H., Ashraf, M., Manzoor, M. A., Altaf, M. M., & Altaf, M. A. (2021). Effect of animal manure, crop type, climate zone, and soil attributes on greenhouse gas emissions from agricultural soils—A global meta-analysis. *Journal of Cleaner Production*, *278*, 124019. https://doi.org/10.1016/j.jclepro.2020.124019

Siedt, M., Schäffer, A., Smith, K. E., Nabel, M., Roß-Nickoll, M., & van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of the Total Environment*, *751*, 141607. https://doi.org/10.1016/j.scitotenv.2020.141607

Singh, B. P., Hatton, B. J., Singh, B., Cowie, A. L., & Kathuria, A. (2010). Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. *Journal of Environmental Quality*, *39*, 1224–1235. https://doi.org/10.2134/jeq2009.0138

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, *22*, 1315–1324. https://doi.org/10.1111/gcb.13178

Spokas, K. A., Koskinen, W. C., Baker, J. M., & Reicosky, D. C. (2009). Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. *Chemosphere*, *77*, 574–581. https://doi.org/10.1016/j.chemosphere.2009.06.053

Sterne, J. A. C., & Egger, M. (2001). Funnel plots for detecting bias in meta-analysis: Guidelines on choice of axis. *Journal of Clinical Epidemiology*, *10*, 1046–1055. https://doi.org/10.1016/s0895-4356(01)00377-8

Taghizadeh-Toosi, A., Hansen, E. M., Olesen, J. E., Baral, K. R., & Petersen, S. O. (2022). Interactive effects of straw management, tillage, and a cover crop on nitrous oxide emissions and nitrate leaching from a sandy loam soil. *Science of The Total Environment*, *828*, 154316. https://doi.org/10.1016/j.scitotenv.2022.154316

Thangarajan, R., Bolan, N. S., Tian, G., Naidu, R., & Kunhikrishnan, A. (2013). Role of organic amendment application on greenhouse gas emission from soil. *Science of the Total Environment*, *465*, 72–96. https://doi.org/10.1016/j.scitotenv.2013.01.031

Thers, H., Abalos, D., Dörsch, P., & Elsgaard, L. (2020). Nitrous oxide emissions from oilseed rape cultivation were unaffected by flash pyrolysis biochar of different type, rate and field ageing. *Science of the Total Environment*, *724*, 138140. https://doi.org/10.1016/j.scitotenv.2020.138140

Thorman, R. E., Nicholson, F. A., Topp, C. F., Bell, M. J., Cardenas, L. M., Chadwick, D. R., Cloy, J. M., Misselbrook, T. H., Rees, R. M., Watson, C. J., & Williams, J. R. (2020). Towards country-specific nitrous oxide emission factors for manures applied to arable and grassland soils in the UK. *Frontiers in Sustainable Food Systems*, *4*, 62. https://doi.org/10.3389/fsufs.2020.00062

Tiefenbacher, A., Sandén, T., Haslmayr, H.-P., Miloczki, J., Wenzel, W., & Spiegel, H. (2021). Optimizing carbon sequestration in croplands: A synthesis. *Agronomy*, *11*, 882. https://doi.org/10.3390/agronomy11050882

Van Groenigen, J. W., Velthof, G. L., Oenema, O., Van Groenigen, K. J., & Van Kessel, C. (2010). Towards an agronomic assessment of N_2O emissions: A case study for arable crops. *European Journal of Soil Science*, *61*, 903–913. https://doi.org/10.1111/j.1365-2389.2009.01217.x

Verhoeven, E., Pereira, E., Decock, C., Suddick, E., Angst, T., & Six, J. (2017). Toward a better assessment of biochar-nitrous oxide mitigation potential at the field scale. *Journal of Environmental Quality*, *46*, 237–246. https://doi.org/10.2134/jeq2016.10.0396

Wang, M., Pendall, E., Fang, C., Li, B., & Nie, M. (2018). A global perspective on agroecosystem nitrogen cycles after returning crop residue. *Agriculture, Ecosystems & Environment*, *266*, 49–54. https://doi.org/10.1016/j.agee.2018.07.019

Wei, Z., Ying, H., Guo, X., Zhuang, M., Cui, Z., & Zhang, F. (2020). Substitution of mineral fertilizer with organic fertilizer in maize systems: A meta-analysis of reduced nitrogen and carbon emissions. *Agronomy*, *10*, 1149. https://doi.org/10.3390/agronomy10081149

Weldon, S., Rasse, D. P., Budai, A., Tomic, O., & Dörsch, P. (2019). The effect of a biochar temperature series on denitrification: Which biochar properties matter? *Soil Biology and Biochemistry*, *135*, 173–183. https://doi.org/10.1016/j.soilbio.2019.04.018

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*, 56. https://doi.org/10.1038/ncomms1053

Xia, L., Lam, S. K., Wolf, B., Kiese, R., Chen, D., & Butterbach-Bahl, K. (2018). Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. *Global Change Biology*, *24*, 5919–5932. https://doi.org/10.1111/gcb.14466

Zhang, Y., Zhang, F., Abalos, D., Luo, Y., Hui, D., Hungate, B. A., García-Palacios, P., Kuzyakov, Y., Olesen, J. E., Jørgensen, U., & Chen, J. (2022). Stimulation of ammonia oxidizer and denitrifier abundances by nitrogen loading: Poor predictability for increased soil N_2O emission. *Global Change Biology*, *28*, 2158–2168. https://doi.org/10.1111/gcb.16042

Zhou, M., Zhu, B., Wang, S., Zhu, X., Vereecken, H., & Brüggemann, N. (2017). Stimulation of N_2O emission by manure application to agricultural soils may largely offset carbon benefits: A global meta-analysis. *Global Change Biology*, *23*, 4068–4083. https://doi.org/10.1111/gcb.13648

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