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A review and meta-analysis of mitigation measures for nitrous oxide emissions from crop residues

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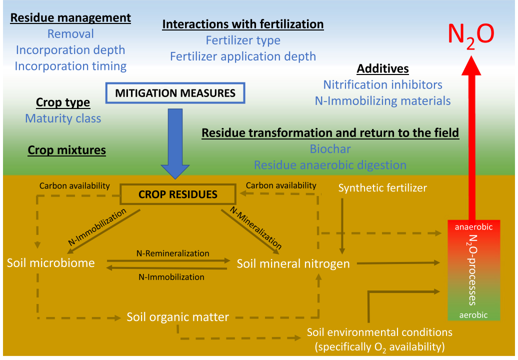
HIGHLIGHTS

- Some measures imply negative side-effects on e.g. yield, soil organic carbon storage.
- Promising mitigation measures I: conversion into biochar or digestate.
- II: co-application with nitrification inhibitors or N-immobilizing materials
- III: use of residues from crop mixtures

GRAPHICAL ABSTRACT



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ABSTRACT

Crop residues are of crucial importance to maintain or even increase soil carbon stocks and fertility, and thereby to address the global challenge of climate change mitigation. However, crop residues can also potentially stimulate emissions of the greenhouse gas nitrous oxide (N_2O) from soils. A better understanding of how to mitigate N_2O emissions due to crop residue management while promoting positive effects on soil carbon is needed to reconcile the opposing effects of crop residues on the greenhouse gas balance of agroecosystems. Here, we combine a literature review and a meta-analysis to identify and assess measures for mitigating N_2O emissions due to crop residue application to agricultural fields. Our study shows that crop residue removal, shallow incorporation, incorporation of residues with C:N ratio > 30 and avoiding incorporation of residues from crops terminated at an immature physiological stage, are measures leading to significantly lower N_2O emissions. Other practices such as incorporation timing and interactions with fertilisers are less conclusive. Several of the evaluated N_2O mitigation measures implied negative side-effects on yield, soil organic carbon storage, nitrate leaching and/or ammonia volatilization. We identified additional strategies with potential to reduce crop residue N_2O emissions without strong negative side-effects, which require further research. These are: a) treatment of crop residues before field application, e.g., conversion of residues into biochar or anaerobic digestate, b) co-application with nitrification inhibitors or N-immobilizing materials such as compost

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with a high C:N ratio, paper waste or sawdust, and c) use of residues obtained from crop mixtures. Our study provides a scientific basis to be developed over the coming years on how to increase the sustainability of agroecosystems though adequate crop residue management.

1. Introduction

Regulating atmospheric greenhouse gas (GHG) concentrations and ensuring food and nutrition for the growing world population are two of the greatest challenges facing humanity today. Crop residue application in agricultural soils has been posited as a tool to simultaneously tackle both challenges. This is because crop residues contribute to maintaining or even increasing soil carbon storage in soils while improving soil fertility, thereby enhancing sustainability of food production (Watson et al., 2002). However, the potential benefits of crop residue retention (i.e., the fraction of biomass left on the field and possibly incorporated into the soil following harvest) for C sequestration and thus, climate change mitigation could be partly or fully offset by increased emissions of the powerful greenhouse gas nitrous oxide (N_2O), as shown in several meta-analyses (Chen et al., 2013; Shan and Yan, 2013; Xia et al., 2018; Hu et al., 2019; Muhammad et al., 2019). Agricultural soils are the largest anthropogenic source of N_2O emissions, and N_2O emissions due to crop residue retention in agricultural fields account for a substantial fraction of these (EEA, 2020). Global N_2O emissions from crop residues have been estimated to increase steadily over the last decades mainly due to higher crop production, reaching approximately 0.224 Gt CO_2-eq in 2017 (FAO, 2021). To harness the benefits of crop residue retention, we must identify the conditions and residue management strategies that minimize N_2O emissions after application or incorporation, avoiding trade-offs in terms of soil C sequestration and soil fertility.

In this study, we combine a literature review and meta-analysis to identify and assess measures for mitigating N_2O emissions from crop residues. We evaluate the degree of certainty associated to their mitigation potential, the most important general conditions under which every measure is expected to be effective, and positive and negative side-effects. We also propose future research avenues to address the knowledge gaps precluding effective implementation of these measures. These knowledge gaps include the interactions between management, climate and residue composition that make emissions difficult to predict at regional and global scales. While there are other meta-analyses focused on the effect of crop residues on N_2O emissions (Chen et al., 2013; Shan and Yan, 2013; Xia et al., 2018; Hu et al., 2019; Muhammad et al., 2019; Abalos et al., 2022), our study is the first one evaluating the residue management measures that may be able to mitigate such emissions, while considering potential impacts on other ecosystem services.

2. Materials and methods

2.1. Literature review

Mitigation measures for N_2O emissions from crop residues were collated from the literature using ISI Web of Science, SCOPUS and Google Scholar. The search terms were: “residue” OR “straw” OR “stubble” AND “nitrous oxide” OR “N2O” OR “greenhouse gas” OR “GHG” OR “emission factor” AND “measure” OR “strategy”. After screening the literature, the measures were categorized according to: residue physical management, residue incorporation timing, interactions with fertilisation, additives and crop residue modifications, crop type, and edaphoclimatic conditions (Table 1). Information from the articles was used to present and discuss the individual factors (e.g., precipitation, tillage) determining the effectiveness of each measure. A comprehensive literature review (or purposive review following Cook (2019)) was used as a basis to assess the positive and negative side-effects of the mitigation measures in relation to crop yields, soil organic carbon (SOC), nitrate leaching and ammonia (NH_3) volatilization, among others.

2.2. Database

To gain a quantitative understanding of the potential of every residue management measure to mitigate N_2O emissions from crop residues, we conducted a meta-analysis using an extended version (as described below) of the database compiled by Rittl et al. (2022). Briefly, this database contains data from field studies across the world investigating the impact of crop residues on N_2O emissions. Crop residues are considered as any above-ground plant component of a crop returned to the soil. The database consisted of 367 selected pairwise comparisons reported in 78 studies, which met predetermined quality criteria (only studies with replication, with detailed information, and performed under realistic field conditions) (Rittl et al., 2022). Pairwise comparisons only included observations where a treatment (i.e., with crop residue retention) and a control (i.e., with crop residue removal) could be compared with all other factors unchanged.

The database provides information about the management, site, and experimental factors from each study, which allowed us to test the effect of several mitigation measures identified through the literature review. To do so, we extended the database in this study creating additional variables that categorize the available information into moderators for a meta-analysis. For example, according to the crop residue application method, observations were categorized as incorporated (when crop residues were mechanically incorporated into the soil) or surface applied (when residues were retained at the soil surface without incorporation, e.g., via mulching). The specific information about crop residue incorporation depth was categorized into deep (≥ 15 cm) and shallow (<15 cm). Information about fertilisation at the time when the residues were incorporated was coded as in combination with and without fertiliser application. Moreover, for studies assessing residue management in combination with fertiliser applications, we categorized studies according to the type of fertiliser applied (synthetic, organic, or combination of synthetic and organic). The timing of residue incorporation was grouped as autumn incorporation versus spring incorporation.

For the measures that could not be analysed with the database, the quantitative N_2O mitigation potential was derived from a literature review based on individual studies for novel measures such as anaerobic digestion of crop residues or crop residue mixtures, for which the empirical evidence is more limited (Table 1). Certain management strategies, such as liming in combination with residue application were not included because there were not enough observations in the database, and because the available information did not attribute the effect of the mitigation measure to N_2O emissions from crop residues (most available strategies are focused on fertiliser-derived N_2O emissions). Due to limited data availability, the main edaphoclimatic drivers potentially regulating each mitigation measure are discussed qualitatively based on the literature review, and not quantitatively through statistical tools.

2.3. Meta-analysis

The effect of mitigation measures for crop residues on soil N_2O emission was assessed by calculating the natural logarithmic response ratio (lnR) as an effect size for each observation (J. Chen et al., 2020; X. Chen et al., 2020; Hedges et al., 1999):

$$lnR = ln\left(\frac{\overline{x_t}}{\overline{x_c}}\right)$$

with $\overline{x_t}$ and $\overline{x_c}$ being the mean cumulative N_2O emissions from a treatment with crop residue retention, and from a control with crop residue removal,

Table 1
Overview of mitigation measures for N_2O emissions from crop residues.

Categorization	Mitigation measure	Mitigation potential	Time frame	Negative side-effects	Positive side-effects
Removal	Crop residue removal versus residue in the field	High	Short and long term	- Lower SOC, yield, and soil physical and biological quality - Higher N leaching and soil erosion	- Feedstock for biofuel and biorefinery - Lower NH_3
Crop residue type	Avoid incorporation of residues from immature crops	High	Short and long term	- Lower SOC - Higher costs, N fertiliser requirement	- Animal feed - Higher yield
Soil management	Residues left at the field surface (e.g., mulching) instead of residue incorporation	Low	Short term	- Higher NH_3 - Lower yield	- Lower N leaching, soil evaporation, and soil erosion
	Shallow instead of deep incorporation	Medium	Short and long term	- Lower yield - Higher use of pesticides, NH_3	- Higher SOC, soil fauna, water infiltration and moisture conservation - Lower costs, soil erosion
Timing of residue incorporation	Autumn instead of spring incorporation	Low	Short term	- Higher N leaching, soil erosion, P losses	- Higher yield
	Crop residue incorporation when the soil is dry instead of when the soil is wet	Medium	Short term		- Better soil structure
Interactions with fertilisation	Synthetic instead of organic fertiliser	Medium	Short term	- Lower SOC - Higher off-farm GHG emissions	- Higher yield
Residue removal, transformation, and return under other forms	Biochar	High	Short and long term	- Higher costs - Lower nutrient supply	- Higher yield, SOC, soil physical and biological quality - Lower N leaching
	Anaerobic digestion	Low to Medium	Short term	- Lower SOC	- Heat and power generation
Additives for application with crop residues	Nitrification inhibitors	Medium	Short term	- Higher costs	- Lower N leaching - Higher yield
	N-immobilizing materials with high C:N ratio	Medium	Short and long term	- Lower yield	- Lower N leaching - Higher SOC, CH_4 uptake
Crop mixtures	Crop mixtures instead of single crops	Medium	Short and long term	- Increased management complexity and costs	- Higher SOC, yield, biodiversity - Lower N leaching, soil erosion
Interactions with edaphoclimatic conditions	Crop residue incorporation in clay soils instead of incorporation in sandy soils	Medium	Long term	- Lower yield	- Lower N leaching, NH_3 - Higher SOC
	Crop residue incorporation when aridity index is <1	Medium	Long term	- Lower SOC, soil health	- Lower N leaching

respectively (Abalos et al., 2022). The variance (Var) of lnR was calculated as:

$$Var = \frac{SD_t^2}{N_t \bar{x}_t^2} + \frac{SD_c^2}{N_c \bar{x}_c^2}$$

with N_t and N_c as the replicate numbers, and SD_t^2 and SD_c^2 as the standard deviations for the treatment and control, respectively.

We conducted a weighted mixed-effects model meta-analysis using the "rma.mv" function from R package "metafor" (Viechtbauer, 2010). Since several studies contributed more than one paired observation, we considered "study" and "observation" as random factors in the mixed-effects models. For ease of interpretation, the overall effect size was converted into percentage change, i.e., $(e^{\ln R} - 1) * 100\%$. We considered the effect size to be significant (i.e., it changes N_2O emissions compared to crop residue removal) when the 95% CI of experimental classes did not include zero. To evaluate statistical differences between sub-groups within mitigation measures, we used a Wald-type test.

3. Results and discussion

In this section, for every mitigation measure we first describe the effect on N_2O emissions from crop residues based on either a meta-analysis or literature review (methodology based on the data availability), and then we present the main side-effects on ecosystem services.

3.1. Crop residue removal versus residue in the field

On average, crop residue incorporation increases soil N_2O emissions by 40–50% compared to scenarios where residues are removed from the field (Abalos et al., 2022). Accordingly, the easiest way to reduce N_2O emissions from aboveground crop residue retention in the field would be removing the crop residues, thus eliminating N and C compounds which would fuel soil microbial processes. However, crop residue removal cannot be generalized as a beneficial management practice. This is because crop residue incorporation into the soil can sometimes decrease N_2O fluxes (more details in the following sections), and because crop residues enhance other agroecosystem services that may outweigh the mitigation benefits for N_2O of removing crop residues (Table 1). For example, removing crop residues represents a substantial export of nutrients out of the field, which has negative effects on crop yields and SOC stocks in the long-term (Chowdhury et al., 2015). An increased requirement for N fertilisation will be needed in the medium to long term to partially compensate for the nutrient exports, increasing the risk for N_2O emissions. As SOC stocks may decrease, also the soil anion retention capacity decreases, which has been found to stimulate nitrate leaching from fertiliser application (Xia et al., 2018). Removal of crop residues also decreases the soil water holding capacity, soil structural stability, soil water infiltration as well as increase soil bulk density and erosion, factors that may influence negatively crop productivity and ecosystem services. Crop residues sustain decomposer food webs in arable soil; therefore, removing crop residues denies a source of energy for soil biological activity and growth with potentially negative impacts on nutrient retention and soil biodiversity (Liu et al., 2016; Drost et al., 2020). The negative aspects of removing crop residues from the field could be partially compensated if they are used for e.g., biofuel production and biorefinery, which would increase farmers´ revenue and decrease farm level GHG emissions.

3.2. Crop residue type: avoid incorporation of residues from immature crops

The effect of crop residues on soil N_2O emissions, and the potential of mitigation measures to curb N_2O emissions from crop residues, is largely driven by the type of crop residue. This is because crop residues can have large differences in biochemical characteristics. The most common biochemical property used to predict the effect of crop residues on N_2O emissions is the C:N ratio. Crop residues with a C:N ratio lower than 20–30 are expected to cause net N mineralization due to their high N concentration, while those with C:N ratios higher than 30, as is generally the case in cereal straw, were found to result in net N immobilization (Alexander, 1977; Trinsoutrot et al., 2000; Redin et al., 2014). A recent meta-analysis confirms this threshold and indicates that the balance between net N mineralization and immobilization explains the differences in N_2O emissions between crop types according to their C:N ratios (Abalos et al., 2022). Immobilization of soil N may decrease N_2O emissions due to reduced availability of ammonium and nitrate for the processes of nitrification and denitrification (Baggs et al., 2000).

Recent studies have shown that the degree of crop maturity at which the residues are generated can be a simple and robust way to integrate crop residue biochemical characteristics of importance for N_2O emissions, in addition to the C:N ratio. According to this categorization, incorporation of residues from immature crops into the soil after crop termination increases N_2O emissions compared to incorporation of residues from mature crops (Abalos et al., 2022; Janz et al., 2022; Lashermes et al., 2022). Immature residues show a specific overall composition of low C:N ratio (due to high N concentration), low cellulose content, and high soluble dry matter and water-soluble C contents. The high content of water-soluble C and easily decomposable C provide an energy source for denitrifying bacteria and for general microbial activity that deplete soil O_2 via enhanced soil respiration (Li et al., 2016; Surey et al., 2020), stimulating denitrification. Indeed, denitrification is frequently the main source of short-term N_2O emissions when organic matter containing highly degradable C is applied to soil (Köster et al., 2011; Li et al., 2016; Surey et al., 2020). When there is a high content of easily mineralizable N or even nitrate in immature residues or the ammonium present in the residue is rapidly nitrified. The risk for high N_2O emissions caused by denitrification is therefore large. Immature residues are mainly represented by green plant biomass (cover crops, vegetable residues, and grasslands), whereas mature residues are mainly straw from cereals, rice, maize or grain legumes.

Cover crops provide a wide range of ecosystem services (Haruna and Nkongolo, 2015), including reductions of N losses in the form of nitrate leaching (Abdalla et al., 2019), potentially reducing soil N_2O emissions during their growing phase due to the depletion of soil inorganic N and the absence of fertilisation. These effects may be species-specific, with legumes promoting higher emissions than non-legumes due to their lower capacity/need to acquire N from the soil (Muhammad et al., 2019). In grassland, herbage incorporation by ploughing may also strongly enhance N_2O emissions, especially legume-based herbage. Compared to roots and stubbles, herbage has a higher degradability due to its biochemical composition and lack of interaction with soil mineral particles (Rasse et al., 2005, 2006). Residues from vegetable production are particularly prone to causing high N_2O emissions due to the high input of highly degradable C and N from their residues, and due to their high requirements for fertilisers, irrigation, and tillage (Baggs et al., 2000; Nett et al., 2015; Nett et al., 2016; Qasim et al., 2021).

Alternatives to incorporation of immature crop residues may have positive side-effects. For example, immature crops can be sold as animal feed, increasing farmer's revenue. Incorporating cover crop residues into the soil may hinder rapid establishment of the succeeding crop by slow soil warming when used as mulch (O'Brien and Daigh, 2019), or due to release of growth inhibiting substances (Putnam and DeFrank, 1983). By removing crop residues, the risk for transferring residue-borne pathogens and plant diseases from one season to the next, decreases (Govaerts et al., 2007). Many of these negative aspects can be avoided or reduced if crop residues are removed from the field, or if residues are treated (biochar or digestate, see Section 3.6) before incorporation. On the other hand, there are numerous reasons to incorporate immature crop residues into the soil. They are nutrient rich, and therefore incorporation into the soil may increase nutrient supply to the succeeding crop and decrease N fertiliser requirements, which is of particular importance for organic vegetable growers. Cover crop incorporation of *Brassica* species can be used to control some soil-borne pests and diseases but may promote others. Removing cover crop, vegetable residues and surplus vegetables from fields is costly and time consuming at a time of the year with heavy workloads for the farmer.

3.3. Soil management

3.3.1. Residues left at the field surface (e.g., mulching) versus residue incorporation

The decay rate of crop residues placed on the soil surface is generally slower than if incorporated into the soil. This is because highly variable moisture conditions and N limitation at the soil surface hamper residue decomposition, and this is particularly true for mature residues having moderate to high C:N ratio (Coppens et al., 2007; Chaves et al., 2021; Chen et al., 2014). Surface-applied residues may increase the distance between C substrates and soil N, limiting N availability for decomposers and thus lowering soil N immobilization effects by residues (Coppens et al., 2007). Therefore, residues may increase mineral N, soluble C and moisture at the soil-mulch interface, representing a hot spot of denitrification (Kravchenko et al., 2018). Thus, surface application of residues could lead either to lower or higher N_2O emissions depending on the environmental conditions (rain-evaporation regime, and residue type, mulch mass and thickness). This is reflected in our meta-analysis, where N_2O emissions from surface-applied or incorporated residues are not significantly different due to the large variation within each category (Fig. 1).

There are several positive side-effects of leaving residues on the field surface. Residue surface application protects the soil surface against the erosive impacts of rainfall, and it may also reduce the formation of surface cracks and crusts (Blanco-Canqui et al., 2006). It also reduces soil evaporation, which is a critical factor for crop production in dry climates (Qin et al., 2015). A reduction in nitrate leaching and runoff can be achieved by surface crop residue application compared to soil incorporation (Xia et al., 2018). There are also some negative side-effects of leaving residues on the field surface: part of the residue N may be lost as NH_3 (Xia et al., 2018; Janz et al., 2022), and additionally the presence of mulch may enhance NH_3 volatilization of surface applied fertiliser (Pinheiro et al., 2019). This, together with slower decomposition of surface-applied plant residues, may reduce or postpone N availability to crops and therefore affect their growth and yields. Leaving plant residues on the soil surface also creates a cooler and wetter environment at the soil surface than incorporation of plant residues into the soil (Chen et al., 2014), which may delay plant growth, specifically in early growth stages in cool and wet climates.

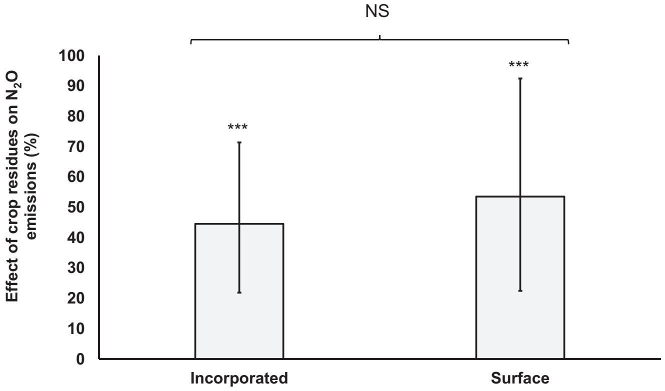

Fig. 1. Relative increase in field N_2O emission (mean ± 95% CIs) with crop residues, as affected by residue placement. The number of observations and studies were 264 and 59 for incorporated, 75 and 21 for surface. *** indicates significance at $p < 0.001$, and NS indicates not significant. Incorporated and surface applied crop residues increased N_2O emissions relative to the control (with the residues removed), whereas the difference between the two placement treatments was not significant.

3.3.2. Shallow versus deep incorporation

Although the effect was not significant, our meta-analysis indicates a trend for higher N_2O emissions when crop residues were incorporated at depth (>15 cm) as compared to a shallower incorporation (Fig. 2; $P \leq 0.10$). This is probably an interactive effect of crop residue placement and the tillage system required for such placement. Six et al. (2004) argued that long-term adoption of no-till as compared to reduced tillage (i.e., shallow incorporation) increases soil organic matter content in the upper soil layers, and results in improved soil structure. The latter may decrease the tendency for the formation of anaerobic microsites conducive to N_2O production (Malhi et al., 2006; Ussiri et al., 2009). Additionally, O_2 diffusion rates decrease with soil depth, thus crop residue decomposition is more likely to cause O_2 limitation and increase N_2O emissions if the residues are incorporated to a soil depth > 15 cm by mouldboard ploughing as opposed to a shallower incorporation (Petersen et al., 2011). These results were supported by the meta-analysis of Van Kessel et al. (2013), and this trend is also observed in our study. Shallow crop residue incorporation with reduced tillage has several advantages: it may increase SOC concentrations in the upper soil layers, save fuel and labour which lowers field management costs, preserve earthworms and other soil fauna, improve water infiltration and soil moisture conservation, prevent soil erosion and improve trafficability (Spiess et al., 2020). The negative side-effects of shallow incorporation with reduced tillage are that, depending on cropping conditions and climate, it may require increased use of herbicides, reduce crop yields and yield stability in cool and wet climates (due to e.g., soil waterlogging and/or lower soil temperature hampering crop establishment, soil compaction limiting root development), promote stratification of phosphorus and potassium in the soil profile, and may promote larger NH_3 losses (Spiess et al., 2020).

3.4. Timing of residue incorporation

3.4.1. Autumn versus spring incorporation

Our meta-analysis did not find an effect of the season in which crop residues are incorporated on the magnitude of N_2O released (Fig. 3). It is likely that the specific quality parameters of the crop residues that are incorporated in either the autumn or spring, which is determined by the interaction between crop physiology, available resources and the environmental conditions of a given geographical location, are more important drivers of the magnitude of N_2O release than the season of incorporation per se. Although farmers cannot choose the harvest time of their crops, they can manage tillage timing to some extent and therefore the timing of residue incorporation into the soil, which will influence several factors (e.g., mineral N, soil moisture, etc.) depending on the climatic conditions and risks identified. For example, ploughing in the autumn can prevent N immobilization during the plant growth period in spring/summer of a spring cereal (note that the specific seasons differ according to latitude), and therefore increase yield. This will also avoid that residue application coincides with synthetic N fertilisation, which may trigger N_2O emissions (Taghizadeh-Toosi et al., 2021). The main negative consequences of autumn incorporation are that it may increase nitrate leaching (Hansen and Djurhuus, 1997; Stenberg et al., 1999), and the risk for soil erosion and losses of phosphorus (Bechmann and Bøe, 2021). In areas prone to freezing during winter, residue incorporation in the autumn can greatly increase N_2O emissions compared to incorporation in the spring (Wagner-Riddle et al., 2017).

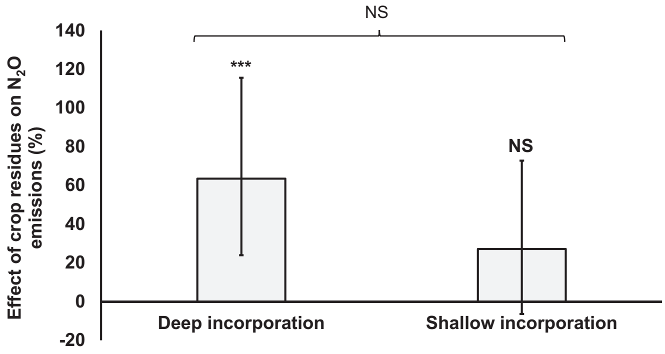

Fig. 2. Relative increase in field N_2O emission (mean ± 95% CIs) with crop residues, as affected by residue incorporation depth (deep incorporation >15 cm; shallow incorporation <15 cm). The number of observations and studies were 104 and 23 for deep incorporation, 62 and 18 for shallow incorporation. *** indicates significance at $p < 0.001$, and NS indicates not significant. Although deep residue incorporation increased N_2O emissions relative to the control (with the residues removed) and shallow incorporation did not, the difference between the two incorporation depths was not significant at $P = 0.05$ (a trend was observed; $P \leq 0.10$).

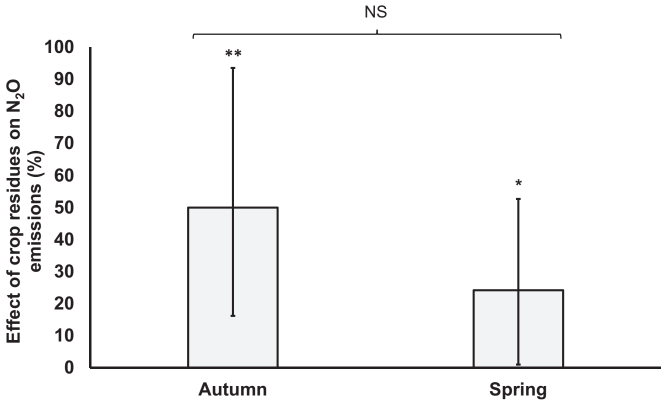

Fig. 3. Relative increase in field N_2O emission (mean ± 95% CIs) with crop residues, as affected by season of residue incorporation. The number of observations and studies were 61 and 16 for autumn incorporation, 133 and 30 for spring incorporation. *, ** indicate significance at $p < 0.05$ and $p < 0.01$, respectively, and NS indicates not significant. Crop residue retention in Spring and Autumn increased N_2O emissions relative to the control (with the residues removed), whereas the difference between the seasons was not significant.

3.4.2. Crop residue incorporation when the soil is dry versus when the soil is wet

Incorporating crop residues when the soil is wet due to rainfall or irrigation may increase N_2O emissions (Taghizadeh-Toosi et al., 2021). This is because increased litter decomposition and reduced O_2 diffusion into soils under wet conditions increase the occurrence of anaerobic microsites in soils (Kravchenko et al., 2017), which stimulates N_2O production by denitrification not only due to anaerobiosis but also by provisioning of labile C (Butterbach-Bahl et al., 2013). However, clear generalizations regarding this effect are not possible, since the outcome in terms of N_2O emissions is likely to depend on interactions between soil moisture, residue incorporation depth, soil properties including soil compaction, as well as residue properties (Kravchenko et al., 2018). Reviewing pairwise comparisons of N_2O emissions from no-till vs. ploughed systems. Rochette et al. (2008) found that higher soil water content in no-till soils usually results in lower aeration and greater N_2O emissions as compared to tilled soils. However, deeper incorporation by ploughing under wet soil conditions may result in large anaerobic zones in the soil due to reduced O_2 diffusion and stimulated microbial respiration from increased substrate availability. This may promote complete denitrification with N_2 as sole end-product and in turn decrease N_2O emissions (Paul et al., 2012). Incorporating crop residues under suitable dry soil conditions is important to maintain a good soil structure and avoid soil compaction. Ideally, residues should be incorporated when the soil is dry, but with expected rain ahead in arid and semiarid regions, as water stress at the time of residue incorporation slows down its mineralization by the soil microbial community (Manzoni et al., 2012; Thapa et al., 2021).

3.5. Interactions with fertilisation

Studies using ^{15}N-labelled fertilisers applied in combination with crop residues have found that the fertiliser is the dominant source of N_2O (Machado et al., 2021). When N fertilisers are applied with crop residues (particularly mature residues with a high C:N ratio), part of the available N from the fertiliser can be immobilized due to the supply of organic C from the residues. Accordingly, the availability of soil mineral N and the release of N_2O from the soil are reduced. This is consistent with studies that have shown a reduction in N_2O emissions if crop residues and fertiliser N are applied at the same time (Xu et al., 2019). However, other studies have shown that N_2O emissions can be increased where a combination of fertiliser and residues are applied to soil (Abalos et al., 2013). It is likely that these different outcomes are explained by the type of residues returned and associated net immobilization/mineralization processes, as explained above. Other controlling factors may be the fertiliser form (e.g., granule or liquid), and the spatial distribution of the fertiliser and the residues in the soil, as these factors determine the physical interaction between them.

We found a greater increase in N_2O emissions induced by crop residues when incorporated with organic fertilisers as compared to the joint application of residues and synthetic N fertilisers (Fig. 4). It is possible that the anaerobic environment created by organic fertilisers due to the addition of organic C and water may favour denitrification and associated N_2O emissions (Decock, 2014). However, it is also possible that this result is due to a confounding effect between fertiliser type and residue type, since most crop residues linked to organic fertiliser application in our database were immature crops (grasslands, vegetables and cover crops), which induce higher N_2O emissions. Even if organic fertilisers increase N_2O emissions from crop residues, their use is crucial for the delivery of other agroecosystem services. This is because organic fertilisers provide several nutrients (e.g., P, K) in addition to N, and may increase SOC and yield in poor soils. Using organic fertilisers avoids energy consumption and emissions of GHGs during the industrial Haber-Bosch process of N-fixation for synthetic fertiliser production and promotes circularity of nutrients at farm to regional scale.

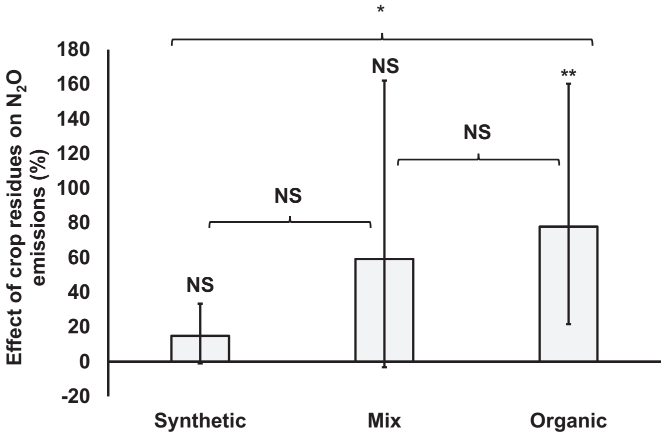

Fig. 4. Relative increase in field N_2O emission (mean ± 95% CIs) with crop residues, as affected by the type of fertiliser applied at the time when the residues were incorporated. The number of observations and studies were 154 and 51 for synthetic, 3 and 1 for mixture of synthetic and organic, 33 and 7 for organic. *, ** indicate significance at $p < 0.05$ and $p < 0.01$, respectively, and NS indicates not significant. Crop residue incorporation with organic fertilisers increased N_2O emissions relative to the control (with the residues removed), but not with synthetic N fertilisers or with a combination of organic and synthetic. The increase in N_2O emissions induced by crop residues was higher when incorporated with organic fertilisers than with synthetic N fertilisers.

3.6. Residue removal, transformation, and return under other forms

3.6.1. Biochar

A potential strategy to mitigate N_2O emissions from crop residues is to turn them into biochar, and then apply this material to the field. Biochar is the C-rich product derived from biomass pyrolysis of organic feedstocks, such as crop residues. Recent meta-analyses have shown that biochar can decrease N_2O emissions after application with an average reduction of about 20% (Shakoor et al., 2021); however, a meta-analysis of field studies across several cropping systems, including maize, wheat, rice, vegetables, and pasture showed no robust evidence for emissions reductions despite tendencies for reductions of up to 17% (Verhoeven et al., 2017). The processes by which biochar affects N_2O emissions remain poorly understood (Cayuela et al., 2014) and may, in addition to changes in chemical and physical soil structure, involve changes in the soil microbial community affecting N_2O reducers (Krause et al., 2018). The pyrolysis process will remove most of the N from the biochar, and the resulting biochar material degrades very slowly in soil and has negligible N fertilisation effects. Therefore, N in the removed crop residues needs to be substituted by other N sources, typically fertiliser N.

The use of biochar presents numerous positive side-effects. The pyrolysis process produces gas that may be used for producing fuels or heat for substituting fossil fuels. Biochar has been shown to be stable in soil, and it may also contribute to stabilisation of existing soil organic C, having overall positive effects on soil C sequestration (Wang et al., 2016). In addition, biochar application will in general improve soil physical and chemical properties such as increasing the pH of acidic soils, water and nutrient retention, and cation exchange capacity (Biederman and Harpole, 2013; Borchard et al., 2019). This may lead to improved crop yields, where such soil properties are currently limiting crop growth and yield (Majunder et al., 2019). A recent meta-analysis has shown that biochar addition reduced nitrate leaching by on average 13% (Borchard et al., 2019), but only in arable farming and vegetable cropping, with no effects in perennial cropping systems.

Barriers to the use of biochar are its production, distribution and application costs, and the fact that the process of biochar production largely removes N from the biomass, so that this needs to be substituted from other sources; however, the greater retention of nutrients in biochar amended soils may reduce the long-term effects of this reduction in N inputs (Biederman and Harpole, 2013). Another negative effect of removing crop residues for production of biochar is the lower inputs of metabolizable C that can support macro- and micro-fauna, and this may have longer term negative effects on soil biodiversity and soil functions (Tibbett et al., 2020).

3.6.2. Anaerobic digestion

Crop residues may be collected and treated by anaerobic digestion, alone or together with livestock manure, to produce biogas and (co) digestates. The specifics of biogas treatment, however, will depend on the biomass processed. Considerable efforts have been made to exploit fibre-rich crop residues such as straw from rapeseed, maize, wheat, rice, and high-yielding grasses grown for bioenergy production. Yu et al. (2019) reported that physical (e.g., milling, extrusion, and steam explosion) and chemical (various bases, acids, and hydrogen peroxide oxidation) pretreatments may increase biogas yields by 30 to 70% compared to the untreated biomass. Fibre-rich co-digestates may increase residual organic matter and add value to digestates as a soil conditioner, but not as a N fertiliser. This is different when using residues of green manure crops such as leys (Frøseth et al., 2014; De Notaris et al., 2018) or winter cover crops as co-digestates; given the higher degradability and lower C:N ratio of these immature residues, the anaerobic digestion will typically result in net N mineralization and increasing ammoniacal N availability during digestion. Thus, anaerobic digestion of grass-legume leys has been proposed as a strategy to redistribute N within crop rotations and to increase crop productivity of organic farms (Brozyna et al., 2013; Frøseth et al., 2014; Pugesgaard et al., 2014). Applying anaerobic digestates has implications for C and N turnover as the applied organic matter has a reduced availability of easily degradable C, and consequently, the stimulating effect on the soil microbial community is limited. This also means that soils stay aerobic following anaerobic digestate application, which reduces the potential to stimulate N_2O emissions (Brozyna et al., 2013). However, it should be acknowledged that residual (particulate) organic matter in digestates has a high water retention capacity compared to bulk soil and, if co-digested with livestock manure, will give N-rich organic hotspots that may still have a potential for high N_2O emissions (Baral et al., 2017). Therefore, the balance between stimulation or reduction of soil N_2O emissions will depend on the interaction between digestate quality and soil conditions (Thomsen et al., 2010; Li et al., 2016).

Heat and power generation from anaerobic digestion may partially substitute fossil fuels and thereby reduce radiative forcing from anthropogenic emissions of carbon dioxide (Don et al., 2012). Digestates normally contain a higher proportion of N in mineral form available for plant uptake (Sommer and Husted, 1995; De Vries et al., 2012), and this will also apply when immature crop residues are digested. Following biogas treatment, the digestate of crop residues can be recycled for maintenance of soil C stocks and soil quality (Thomsen et al., 2013), but the effect on the long-term stabilisation of soil C stocks (per unit of initial residue amount) remains to be clarified. Organic matter stabilisation occurs at residue-soil interfaces (Witzgall et al., 2021), and hence occlusion and stabilisation may be closely associated with the initial decomposition process that is intercepted by removal of residues for treatment, although this stabilisation mechanism may well be less important for aboveground compared to belowground residues (Rasse et al., 2005).

3.7. Additives for application with crop residues

3.7.1. Nitrification inhibitors

In recent years, the potential of nitrification inhibitors (NIs) to reduce N losses from crop residues has been explored. NIs were developed to improve the N use efficiency of synthetic and organic fertilisers. Synthetic inhibitors such as dicyandiamide (DCD), nitrapyrin, and 3,4-dimethylpyrazole phosphate (DMPP), operate by chelating Cu, which is involved in the first step of nitrification, ammonia oxidation (Subbarao et al., 2006; Corrochano-Monsalve et al., 2021). The inhibition is temporary and will cease with biodegradation of the NI (Lees, 1946).

Numerous studies have shown that NIs can reduce emissions of N_2O from nitrification by inhibiting ammonia monooxygenase activity (Byrne et al., 2020), and from denitrification and nitrifier denitrification by reducing the production of nitrate and nitrite (Ruser and Schulz, 2015). When used with synthetic fertilisers or manure, NIs often lead to 30–50% N_2O reductions (Qiao et al., 2015). It is therefore relevant to elucidate if NIs can also mediate against emissions of N_2O from crop residues. Chaves et al. (2006) found that treating vegetable crop residues with DCD or DMPP before incorporation reduced N_2O emissions. Ammonia oxidising bacteria are stimulated near interfaces between the soil and residues, and this activity can be inhibited by treating aboveground parts of grass-legume pastures with DMPP prior to incorporation (Duan et al., 2017). However, the effect on N_2O emissions is variable, and effects ranging from 0 to 33% reduction have been observed in studies simulating spraying of grassland with DMPP before cultivation (Duan et al., 2017; Kong et al., 2017; Nair et al., 2020). Treatment effects depend on residue distribution, and on soil O_2 and NO_3^- availability, and together these factors determine the balance between aerobic and anaerobic residue decomposition, and the proportion of N_2O being converted to N_2 (Senbayram et al., 2012).

Since NH_4^+ is much less mobile in soil environments compared to NO_3^- or NO_2^-, NIs can reduce nitrate leaching (Qiao et al., 2015) and thereby support higher N use efficiency in crop production (Abalos et al., 2014). As nitrification is also an O_2 consuming process, its inhibition may also substantially increase soil O_2 availability for residue decomposition around residue-soil interfaces (Nguyen et al., 2017). Some aspects need to be considered before NIs can be widely adopted. The use of nitrification inhibitors represents a cost to farmers, and incentives could be necessary if introduced for GHG mitigation. Cost estimates vary widely, from 10 to 90 € ha^{-1} yr^{-1} (MacLeod et al., 2015). The delay of ammonia oxidation can increase NH_3 volatilization (Qiao et al., 2015), although this will be small if residues are incorporated into the soil. No adverse effects or change in feeding behaviour of the earthworm *Lumbricus terrestris* were seen in a mesocosm study with ^{15}N labelled clover residues with or without DMPP treatment of above-ground parts (Kong et al., 2017), which indicates that non-target effects on e.g., the soil fauna may be limited, although this should be documented for individual NIs before being widely adopted.

3.7.2. N-immobilizing materials with high C:N ratio

Co-incorporation of N-immobilizing organic materials with immature crop residues can be a strategy to reduce N losses from crop residues (Congreves et al., 2013; Agneessens et al., 2014). It has been shown that materials such as immature compost with a high C:N ratio, straw, paper waste and sawdust can reduce nitrate leaching under controlled conditions, but the effect on N_2O emissions has not been widely investigated (Chaves et al., 2005). In a laboratory experiment, Chaves et al. (2005) found that co-incorporation of straw, immature compost and sawdust with residues from celery reduced cumulative N_2O emissions by more than 50%. However, homogeneous mixing of the organic materials is important to obtain N immobilization, and this can be difficult to achieve under field conditions (Chaves et al., 2005), and such efforts may also increase costs and management complexity for farmers. Depending on the characteristics of the organic materials and the specific conditions in the soil, the N immobilization phase could be followed more or less rapidly by remineralization (Chen et al., 2014). Thus, N_2O emissions could pick up in the medium to long term.

Co-incorporation of N-immobilizing materials can lead to decreased nitrate leaching, and co-addition of organic C may potentially increase SOC in the long term, with possible positive effects on crop yield in poor soils. Transient increases in CH_4 oxidation (sink) capacity in upland soils have been observed (Ho et al., 2015). As with mature residues having high C:N ratios, the potentially negative impacts of net N immobilization need to be managed carefully.

3.8. Crop mixtures versus single crops

Residues from crop mixtures may decrease (or increase) N_2O emissions compared to single crop residues. The reason is that mixtures of crop residues with contrasting biochemical characteristics can promote positive or negative non-additive effects on N release from the residues (Redin et al., 2014; Porre et al., 2020), with potential consequences for N_2O emissions. Non-additive effects are frequently explained by the nutrient transfer hypothesis: decomposers first use residues with a high N concentration, and then the released N becomes available and facilitates the decomposition of the more recalcitrant crop residue fractions (Hättenschwiler et al., 2005; Handa et al., 2014). Alternative explanations for positive non-additive effects include changes in C:N ratios (Zhou et al., 2019), improved water retention due to one of the residues in the mixture (Wardle et al., 2003), and enhanced fungal decomposer community due to wider variation in residue biochemical properties (Hättenschwiler et al., 2005; Otsing et al., 2018). Conversely, transfer of inhibitory compounds and/or phenolics between residues may cause negative non-additive effects (Freschet et al., 2012). These interactions have been mainly studied to understand decomposition rates and nutrient release from litter mixtures, but the consequences for N_2O emissions remain elusive. In the few available studies evaluating N_2O emissions from plant mixtures under field conditions, the contribution of residue-derived N_2O emissions was not determined (e.g., Davis et al., 2019; Abalos et al., 2021). If future research confirms the N_2O mitigation potential of residue mixtures, they can be implemented in many agroecosystems: multi-species swards in grasslands, cover crops, diversified crop rotations (effects such as changes in decomposer communities are expected to act over longer time-frames than a cropping season), and also in intercropping (Abalos et al., 2019). For cropping systems preventing simultaneous cultivation of more than one crop in a field, direct application of crop residue mixtures can be an alternative option.

Plant species mixtures can provide a range of ecosystem services, such as increased crop and forage yield, yield stability, pollinator diversity and production, and weed and pest suppression (Isbell et al., 2017). Plant mixtures can also reduce nitrate leaching and soil erosion (Gurr et al., 2003; Leimer et al., 2015; Tribouillois et al., 2016), and increase SOC (J. Chen et al., 2020; X. Chen et al., 2020). The challenges of implementing plant mixtures include, among others, development of new machinery, difficulties selecting species according to local climatic and soil variables, as well as adjusting N fertiliser management to multi-species mixtures (Abalos et al., 2019). These difficulties may reduce adoption by farmers.

3.9. Interactions with edaphoclimatic conditions

3.9.1. Crop residue incorporation in clay soils versus incorporation in sandy soils

Previous meta-analyses have found lower N_2O emissions after crop residue application to fields for soils with a high clay content (Chen et al., 2013; Xia et al., 2018). This may be because high clay content (i) decreases soil aeration and O_2 availability, thereby decreasing residue N release from decomposition (Skiba and Ball, 2002), and (ii) lowers gas diffusivity, promoting N_2O reduction to N_2 via complete denitrification (Gu et al., 2013). This implies that avoiding crop residue incorporation in coarse-textured soils whenever possible could be an N_2O mitigation strategy. From a climate change perspective, this may provide a dual benefit: fine-textured soils, which have the highest potential to sequester C via crop residue incorporation (Hütsch et al., 2002; Mathew et al., 2020), may be the ones with the lowest N_2O emissions after crop residue incorporation, particularly if the initial SOC content is low. This needs to be confirmed in future studies, since the positive relationship between soil clay content and the capacity of soil to store C is not always consistent (Liu et al., 2014), and because increases in SOC may eventually lead to higher N_2O emissions (Guenet et al., 2021). From an implementation perspective, farmers do not get to choose the soil texture of their fields, and therefore any action to address this mitigation measure must be mediated via regional, national and international land use policies. These policies must consider other important side-effects of incorporating crop residues into the soil according to soil type. Indeed, due to differences in water holding capacity, crop residue retention may increase nitrate leaching losses in sandy soils, while it may reduce them in loamy and clay-textured soils (Xia et al., 2018). In addition to higher soil C retention following crop residue return in fine-textured soils, NH_3 volatilization from crop residues is also lower in these soils due to higher CEC and ammonium adsorption by clay particles (Xia et al., 2018).

3.9.2. Aridity index <1 vs >1

Recently, the IPCC guidelines for emission inventories divided the emission factors of N sources, including crop residues, according to an aridity index (AI; mean annual precipitation to mean annual potential evapotranspiration). Higher emissions are assigned to crop residues in regions where AI is >1 (0.6%; uncertainty range 0.1–1.1%) compared to regions where AI is <1 (0.5%; uncertainty range 0.0–1.1%). A recent meta-analysis supports this decision (Abalos et al., 2022), although the differentiation for crop residues may be stronger than indicated by IPCC, since N_2O emissions from crop residues were 2 times higher for studies conducted under an AI >1. Consequently, limiting crop residue retention in regions where the AI >1 could be particular important for mitigation. However, as with soil clay content, this strategy to reduce N_2O emissions from crop residues requires thorough examination before it can be implemented by national or international land use policies, specifically as side effects on soil C storage are to be expected. That is, avoiding crop residue incorporation in regions with AI >1 may reduce soil C (Hu et al., 2018), and negatively impact soil health (Jansson et al., 2021). From a climate change perspective, AI is projected to decline in some regions (Lickley and Solomon, 2018), thus potentially reducing N_2O emissions. For a given soil texture, with decreasing AI, soil moisture is likely to be lower, and thus reduce the risk of nitrate leaching losses from the incorporated residues.

4. Future research priorities

In general, we argue that studies focused on crop residues should run for at least 10 years, since changes in SOC and associated side-effects are slow and likely undetectable over shorter time frames. Long-term monitoring of N_2O and N losses through hydrological pathways would also be required to understand the impact of e.g., high C:N residues (>30), and of adding N-immobilizing materials such as green waste compost or sawdust on N losses and to detect effects due to the possible re-mineralization of the immobilized N (Chaves et al., 2005). Such long-term studies should explore the maximum amount of residues that can be removed from the field under given management and climate regimes to avoid soil degradation (Merante et al., 2017), and the potential for using surplus residues as biofuel feedstock. We also stress that existing long-term trials need to be continued, but with a wider, multi-criteria focus, including GHG balances, nitrate leaching, yields, pathogens, and economic assessments, and expanded for different residue management options.

Up to now there is no targeted research available investigating the impact of residue incorporation timing in relation to soil moisture conditions, thereby considering effects on soil hydrological properties, decomposition, and risk for environmental N losses in the form of NH_3 volatilization, nitrate leaching, N_2O or N_2 emissions. Retention of residues in the autumn (instead of residue removal or incorporation by ploughing) may result in decreased N_2O emissions during winter and spring season freeze-thaw cycles (Wagner-Riddle et al., 2017). However, more studies are needed to confirm this mitigation opportunity.

For anaerobic digestion of crop residues, high pressure or temperature (or additives) can limit the cost-effectiveness of pre-treatments of fibre-rich biomass strongly, but combinations of treatments hold some promise for future developments and should be explored (Yu et al., 2019). Harvest time and composition of (low-quality and high-quality) crop biomass for anaerobic digestion can improve biogas yield as well as nutrient availability and soil biodiversity after field application (Drost et al., 2020; Fontaine et al., 2020), and this may also be true without digestion (Struijk et al., 2020). The consequences of these treatments for digestate biochemical composition and associated effects on N_2O emissions after field application, remain largely unknown.

Cost-effective use of nitrification inhibitors as a GHG mitigation strategy will require a better understanding of which conditions support nitrification-dependent N_2O emissions. This will likely depend on residue characteristics such as C:N ratio and O_2 demand, and on soil nitrate availability and O_2 supply. Some plant species can produce secondary metabolites that function as biological nitrification inhibitors, although mechanisms are not clear and results mixed; mechanisms may involve effects on N mineralization, as well as on nitrification (Pijlman et al., 2020). It is also not clear if such effects persist when plant residues of crops with ability to release biological nitrification inhibitors are incorporated ahead of a new growing season.

Research should also consider possible means of reducing direct N_2O emissions from immature residues. For example, immature residues can be used as feedstock for protein extraction through biorefining due to their high N content, and the remaining residue fraction with increased C:N ratio could then be returned to the field. However, the economic viability of this processes needs to be assessed. Another option would be to modify crop biochemical characteristics either by breeding or with chemicals (e.g., using desiccants) so that immature residues senesce shortly before termination (Sylvester-Bradley et al., 2015). For cover crops, the strategy for termination (i.e., mowing, herbicide) affects residue decomposition and N mineralization (Snapp and Borden, 2005), but the resulting effect on N_2O emissions deserves further research attention. We also need a better understanding of how farmers actually manage crop residues, as this would allow for living lab approaches.

Unfolding how to manipulate interactions between different residues in plant mixtures to mitigate N_2O emissions may open a new research avenue. First, we need to design experiments under controlled conditions to increase our mechanistic understanding of how these interactions between residues (i.e., nutrient transfer hypothesis, residue water retention, changes in microbial communities) may affect N_2O emissions, and to rank their relative importance. Then, we will be able to translate these findings into realistic field conditions to study the role of soil and environmental variables as regulators of residue interactions. Incorporating this information into crop, biogeochemical, process-based models (e.g., Daisy, APSIM, DNDC, DayCent, CoupModel, HERMES, ARMOSA, DSSAT, MONICA, WOFOST) is crucial to improve their capacity to predict the effect of crop residue management on GHG emissions, and therefore to design sustainable agroecosystems under current and future climatic conditions.

Soil texture is a broad proxy for several soil properties such as water retention, gas diffusivity or risk for nutrient leaching, and although at a global scale the relationships between N_2O and soil clay content are consistent, several soil properties must be considered at a finer scale (initial SOC content, gas diffusivity) before providing policy recommendations regarding residue incorporation or removal according to soil textural properties. If the relationships prove to be robust, future studies can use digital soil mapping (e.g., remote sensing, satellite imagery) to identify regional hotspots for N_2O emissions from crop residues, and to propose management practices to minimize them. Similarly, the aridity index is effectively a proxy for soil moisture content. However, the effect of AI and soil moisture on soil C and N cycling is complex. Some studies have shown increases in AI to be positively correlated with soil C and N (Delgado-Baquerizo et al., 2013), while other studies reported that increased soil moisture content decreased soil C (Mudge et al., 2021; Singh et al., 2021) and the soil C:N ratio (Mudge et al., 2021). The relevance of AI for land use recommendations to reduce N_2O emissions from crop residues may therefore depend on identifying more specific values across the AI spectrum, driving the magnitude of N_2O emissions released from soils.

More detailed, long-term field studies are also needed to increase the accuracy to predict N_2O emissions from crop residues through artificial intelligence, including machine learning approaches (e.g., random forest, stochastic gradient boosting modelling, artificial neural networks; Pan et al., 2021; Saha et al., 2021). Indeed, machine learning offers promise to improve field scale N_2O flux predictions, especially when used in combination with process-based models (Saha et al., 2021). As the number of available field studies increases, we will be able to use more advanced statistical tools to better understand the specific conditions determining the effectiveness of each mitigation practice for crop residue-derived N_2O emissions, and the mechanisms behind them. Currently, the contribution of crop residues to national N_2O emissions represents a challenging emission source to quantify accurately, and the methodology used in national inventories relies on fixed emissions factors that do not capture the emission reductions potentially achieved with the measures reported in our study (IPCC, 2019). Future increases in data availability will enable refinements in crop residue emission accounting, incorporating effects of mitigation measures.

5. Conclusions

Building upon a literature review and meta-analysis, we identified promising measures to reduce N_2O emissions from crop residues and assessed possible consequences of their implementation. Crop residue removal, shallow incorporation, incorporation of residues with C:N ratio >30, and avoiding incorporation of immature crops, are effective N_2O mitigation strategies at a general level. Practices related to crop residue incorporation timing and interactions with fertilisers did not consistently reduce N_2O emissions. This is due to the complex interactions between crop residue management, residue type, mineral N availability regardless of the source, and the soil and climatic factors regulating such emissions. Although the benefits of some mitigation measures clearly outweigh their potential drawbacks, some measures imply important trade-offs between N_2O mitigation and e.g., nitrate leaching or soil C storage. They are also in conflict with some important agroecological principles, such as increased use of immature crops (i.e., cover crops and grasslands) in arable cropping systems. We identified additional strategies with potential to address these challenges, but requiring further research: residue conversion into biochar or anaerobic digestate and field application, co-application with nitrification inhibitors or N-immobilizing materials, and use of crop mixtures. A better understanding of these mitigation measures may pave the way for a more sustainable management of crop residues in agroecosystems.

CRediT authorship contribution statement

Diego Abalos: conceptualization, data curation, formal analysis, writing - review & editing; **Sylvie Recous:** conceptualization, data curation; writing - review & editing; **Klaus Butterbach-Bahl:** conceptualization, review & editing; **Chiara De Notaris**: writing - review & editing; **Tatiana Rittl:** data curation, writing - review & editing; **Cairistiona F. E. Topp:** data curation, writing - review & editing; **Søren O. Petersen:** writing - review & editing; **Marina Bleken:** writing - review & editing; **Robert M. Rees:** writing - review & editing; **Sissel Hansen:** conceptualization, writing - review & editing; **Jørgen E. Olesen:** project administration, conceptualization, writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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