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OPINION

Challenges of accounting nitrous oxide emissions from agricultural crop residues

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Abstract

Crop residues are important inputs of carbon (C) and nitrogen (N) to soils and thus directly and indirectly affect nitrous oxide (N_2O) emissions. As the current inventory methodology considers N inputs by crop residues as the sole determining factor for N_2O emissions, it fails to consider other underlying factors and processes. There is compelling evidence that emissions vary greatly between residues with different biochemical and physical characteristics, with the concentrations of mineralizable N and decomposable C in the residue biomass both enhancing the soil N_2O production potential. High concentrations of these components are associated with immature residues (e.g., cover crops, grass, legumes, and vegetables) as opposed to mature residues (e.g., straw). A more accurate estimation of the short-term (months) effects of the crop residues on N_2O could involve distinguishing mature and immature crop residues with distinctly different emission factors. The medium-term (years) and long-term (decades) effects relate to the effects of residue management on soil N fertility and soil physical and chemical properties, considering that these are affected by local climatic and soil conditions as well as land use and management. More targeted mitigation efforts for N_2O emissions, after addition of crop residues to the soil, are urgently needed and require an improved methodology for emission accounting. This work needs to be underpinned by research to (1) develop and validate N_2O emission factors for mature and immature crop residues, (2) assess emissions from belowground residues of terminated crops, (3) improve activity data on management of different residue types, in particular immature residues, and (4) evaluate long-term effects of residue addition on N_2O emissions.

KEYWORDS
accounting, crop residues, immature, inventory, mature, nitrogen, nitrous oxide, soil

1 | INTRODUCTION

Crop residues contribute substantial inputs of carbon (C) and organic nitrogen (N) to the soil (Lal, 2005) and play an important role in the global flows of C and N through agroecosystems. Residues originate from both above- and belowground plant materials, which are added to soils when plants mature (e.g., annual crops such as cereals and oilseed crops) and when harvesting or mulching crops as part of soil fertility management (e.g., cover crops and green manures).

Crop residues are critical for sustaining cropland soil fertility and make a major contribution to sustain soil C stocks (Carvalho et al., 2017). However, they also contribute to nitrous oxide (N_2O) emissions directly through the addition of organic N and indirectly by affecting microbial source processes during the formation of N_2O. Depending on the amount and fate of C and N in the residues and their contributions to N_2O emissions or to the soil C and N balance, residues might increase or decrease the greenhouse gas (GHG) footprint of agricultural systems (Guenet et al., 2021). There are temporal aspects to such considerations, since the effect of crop residue management on soil C levels will saturate over time (Haas et al., 2022), whereas effects on N_2O emissions will generally persist under stable cropland management and environmental conditions.

The amount of N in crop residues is used in national GHG emission inventories to estimate N_2O emissions from agriculture. Residues are estimated to contribute to 9.3% of global agricultural N_2O emissions (0.72 Tg N_2O-N) in 2020, according to FAOStat (2023) with emissions having more than doubled since 1961. However, the proportion of global N_2O emissions from crop residues has been almost constant over time. This reflects the parallel increase in N fertilization rates and in crop yields that with fixed allometric functions and N concentrations results in an increasing amount of total N returned in crop residues.

In 2020, 22.2 Tg CO_2-eq were estimated to have been released as N_2O from agricultural crop residues in the EU (EEA, 2022), contributing to about 17% of direct N_2O emissions from agricultural soils. Nonetheless, the concerns on the accuracy of the quantification of this source have largely been neglected in inventory guidelines (Chen et al., 2013; Hergoualc'h et al., 2019), so current estimations of N_2O emissions from crop residues are associated with some of the largest uncertainties in national GHG inventories. These uncertainties relate to (1) the amount of residues (above- and belowground) and N concentration of the returned residue, (2) the magnitude of N_2O emissions associated with the application of crop residues of different biochemical quality to soils, and (3) how N_2O emissions and uncertainties differ with crop species, soils, climate, and management practices. Recent studies suggest that the concurrent C and N transformations are critical for N_2O emissions from crop residues (Charles et al., 2017; Chen et al., 2013; Xia et al., 2018).

There is wide consensus in the scientific community that the current inventory methodology that uses the N inputs in above- and belowground crop residues as the sole determining factor for estimating N_2O emissions fails to consider the underlying factors and processes affecting emissions (Abalos, Rittl, et al., 2022; Lashermes et al., 2022; Shan & Yan, 2013). While the methodology may well quantify the magnitude of the N_2O emissions from crop residue management, it likely fails to accurately consider and quantify the different sources of emissions, thus resulting in missed opportunities for potential mitigation. Here, we explore and discuss the shortcomings of the current approach for accounting N_2O emissions from crop residues and propose a way forward for developing an improved methodology.

2 | CURRENT ACCOUNTING OF RESIDUES IN INVENTORIES

The IPCC guidelines (Hergoualc'h et al., 2019) for reporting national inventories of GHGs provide guidance for calculating the amount of N in above- and belowground crop residues for estimating direct and indirect N_2O emissions. The IPCC has provided default values and relationships for a range of crop types. The methodology uses linear relationships (slopes and intercepts, differing between crop types) to enable estimation of crop residue biomass from yield activity data. It accounts for crop residues in annual grain and root crops, forage crops and the renewal of pastures. However, additional non-harvestable crops such as cover crops are not specifically included.

The IPCC 2006 guidelines (De Klein et al., 2006) stipulate a default emission factor of 0.01 kg N_2O-N kg^{-1} N returned in both above- and belowground residues. The 2019 refinement of the IPCC guidelines (Hergoualc'h et al., 2019) has updated the default emission factors for direct N_2O emissions from crop residues returned to soils calculated as 0.006 N_2O-N kg^{-1} N for wet climates and 0.005 N_2O-N kg^{-1} N for dry climates. However, direct experimental measurements of N_2O emissions from crop residues are challenging as in practice such emissions always happen on top of background soil emissions. Some of the crop residue emissions occur directly in the first days to weeks after residue incorporation, but crop residues also contribute to N bound in soil organic matter. There it effectively contributes to the background production of N_2O in soils, much of which originates from fertilizer N that is recovered by crops and then returned to the soil through crop residues (Kim et al., 2013). Background soil emissions are defined as those that occur in the absence of the direct input from any N fertilizer or manure, and crop residues therefore contribute significantly to this.

3 | BIOGEOCHEMISTRY OF RESIDUE NITROUS OXIDE EMISSIONS

Nitrous oxide emissions result primarily from the microbial processes of nitrification and denitrification (Butterbach-Bahl et al., 2013). Nitrification is an autotrophic oxidative aerobic process that transforms ammonium (NH_4^+) to nitrate (NO_3^-). Denitrification mainly occurs as a heterotrophic process under anaerobic conditions by stepwise reduction of NO_3^- to N_2 (Kraus et al., 2015). The major controls for both processes are the substrate availability (i.e., NH_4^+ and NO_3^-) and soil environmental conditions, such as soil water content, temperature, pH, labile C availability, and oxygen concentration (Butterbach-Bahl et al., 2013; Song et al., 2019).

Crop residues recycled to the soil influence N_2O emissions in several ways, that is, by providing a source of readily available C and N as substrates for microbial activity, and by modifying soil structure, oxygen balance, soil moisture, and temperature (Stavi et al., 2016). The different ways in which crop residues can influence N_2O emissions reflect the complexity and the antagonisms of their effects on soil processes involved in N_2O emissions, and they also influence the different pathways of N_2O formation. While some studies reported an increase in N_2O emissions with crop residues compared with nonamended soils (Shan & Yan, 2013), others showed a decrease in emissions (Basche et al., 2014), or even no difference between crop residues on the soil surface and bare soil (van Kessel et al., 2013). These results show that the effects of crop residues on N_2O emissions cannot be accurately predicted simply from the amount of N they contain, as implied in the IPCC emission factor approach.

One of the main factors controlling N_2O emissions is crop residue quality, that is, its biochemical and physical characteristics (Figure 1). These quality aspects determine the balance between N mineralization and N immobilization (due to microbial assimilation) during decomposition (Mary et al., 1996), as well as residue-C dynamics and partitioning between mineralization and stabilization (Lashermes et al., 2016). The concomitant C and N mineralization of crop residues will either consume or release mineral N and also stabilize N in soil organic matter derived from microbial residues and decomposed plant materials (Mitchell et al., 2018). This is important for GHG emissions because it determines the partitioning between short-term effects of residue recycling on microbial C and N transformations affecting N_2O emissions and medium- to long-term effects related to impacts on soil C and N stocks (Guenet et al., 2021) and on soil physical properties that may also influence N_2O emissions (Ball, 2013).

Mineralization of crop residues produces NH_4^+, which can subsequently be nitrified and denitrified (Figure 1). In conditions of low soil mineral N availability, the residue-derived N can be immediately assimilated by heterotrophic decomposing microorganisms, to fulfill their N requirements in parallel to C microbial assimilation, without any release of NH_4^+ or NO_3^- into the soil, at least in the short term. For a substrate with a high C:N ratio such as wheat straw, N will be removed from the soil's mineral N pool to sustain assimilation by decomposing microorganisms, and mineral N will have little or no availability for N_2O production, unless this mineral N is provided through fertilization. For a substrate with a low C:N ratio (e.g., the residue of N-rich crops such as vegetables [from lettuce, cauliflower, cabbage, carrot, etc.] or biomass left on soil from a plant harvested at immature stage [cover crops]), the amount of N available during substrate degradation will be sufficient or even exceed the microbial N requirements, and this excess N may accumulate in the soil and be subjected to N_2O production and emission.

It is, therefore, crucial to distinguish the "nitrogen effects" of crop residue recycling (through nitrification and denitrification, via residue N input and the mineralization–immobilization balance) from the various "carbon effects" on heterotrophic microbial communities and their impacts on the soil redox conditions due to oxygen consumption, and on the physical effects influencing soil water content and water and oxygen exchange influenced by changes in soil physical properties (Figure 1). All these effects interact with crop residue quality, placement, and spatial distribution and with the soil type. The lack of consistency reported in the literature, of the effects of crop residues on N_2O emission, could be a consequence of "carbon effects" or the soil environment, which make it difficult to predict emission from residue N inputs only (Lashermes et al., 2022). Other key points are that measurements on the contribution of root biomass, root turnover, root exudates, and their rate of decomposition, as well as contribution

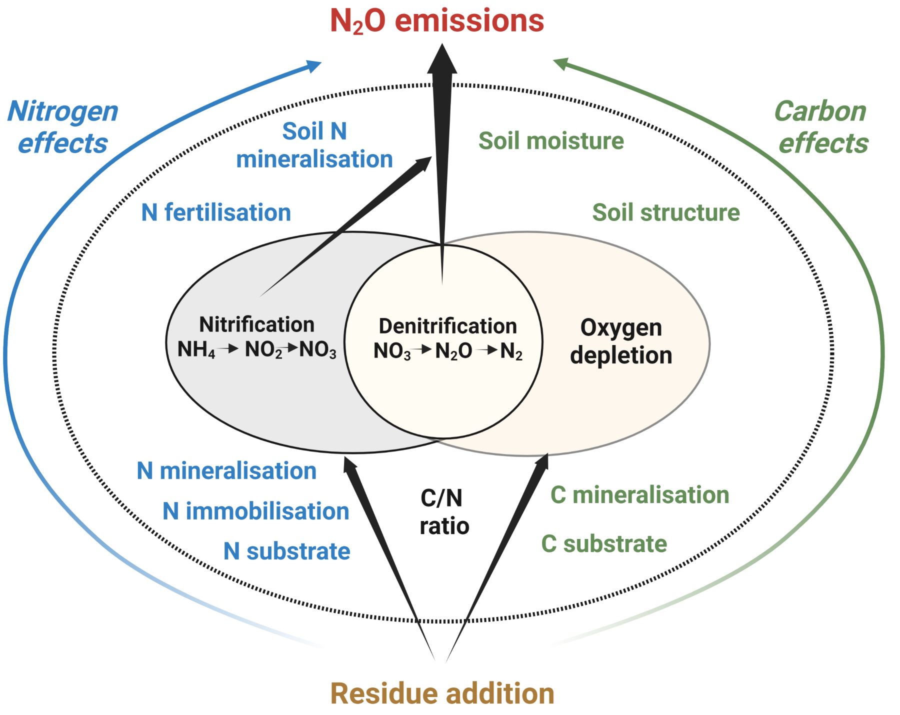

FIGURE 1 Nitrous oxide emissions from crop residue addition can be considered as N effects that are influenced by the amount added in residues (nitrogen effects), the role of added degradable C substrate for the microbial N transformations, and the effect of C mineralization on soil oxygen depletion (carbon effects). The C substrate also overall drives the microbial activity, including denitrification.

to medium- and long-term (background) emissions, are poorly understood and scarcely documented in both arable and particularly grassland systems (Anthony et al., 2023).

4 | CROP RESIDUE QUALITY AND MANAGEMENT

Cropping systems are characterized by a diversity of plant species that contribute to a range of residue inputs to soil, reflecting growing conditions, the stage of maturity and harvest time (Bertrand et al., 2009), and the type of plant organ (Freschet et al., 2012). The effect of the chemical composition of plant tissues, which includes soluble organic compounds such as nucleic acids, fatty acids and mineral N (NO_3^-, NH_4^+), and structural polymeric C compounds such as cellulose, hemicellulose, and lignin in the plant cell walls, on the biodegradability of crop residues is quite well established, but still difficult to predict accurately (Bertrand et al., 2006; Machinet et al., 2011; Talbot & Treseder, 2012). The chemical structure of crop roots makes them less rapidly degradable than stems and leaves (Bertrand et al., 2006; Rasse et al., 2005) with chemical structures differentially determining C and N mineralization processes (Jensen et al., 2005; Li et al., 2020). However, soil environmental conditions also influence crop residue decomposition, and this may differentially affect the mineralization of root and shoot residues (Tahir et al., 2016).

Harvesting operations and the type of soil tillage determine the location of crop residues in the soil profile and the degree of heterogeneity of their spatial distribution. In particular, while crop residues are incorporated into the soil to a depth depending on the type of plowing, in no-till or reduced tillage systems, crop residues are left on the soil surface to form a mulch. Soil-residue contact is then limited, making soil nutrients spatially "distant" from the residue-C left on the soil surface, reducing the accessibility of N to decomposers, and the opportunity for microbial immobilization (Coppens et al., 2006). Mulch of plant residues on the soil surface modifies the soil's water and thermal regimes, particularly by limiting evaporation under dry climatic conditions. These effects may stimulate microbial activity and increase the potential for anaerobic conditions (Pinheiro et al., 2019). At the interface with the soil, mulches represent "hot spots" for N_2O emissions, because this situation combines the microbial activity of oxygen-consuming decomposers, a source of N, and moisture conditions favorable to denitrification (Kravchenko et al., 2017). This effect depends on the mass and density of the mulch and its distribution at or near the soil surface. Mulches with N-rich residues, contained in some green manures, may also leach soluble highly degradable N and C compounds that in the soil can be substrates for N_2O production (Thiébeau et al., 2021). Therefore, in combination with reduced tillage or direct seeding, crop residues left as a mulch in conservation agriculture or in semiperennial cropping systems such as sugar cane (Sousa Junior et al., 2018) can not only increase soil C sequestration but also enhance N_2O emissions, and in some cases overriding the C sequestration benefits on the long-term net GHG balance (Lugato et al., 2018). Another long-term effect of enhancing soil C is the effect on soil bulk density and porosity (Williams et al., 2017), where the lower bulk density with residue addition generally provides better soil aeration that under some soil conditions lowers the denitrification rate and the N_2O emission potential (Mutegi et al., 2010).

Crop residues in soils or on their surface can lead to significant spatial variability in N_2O emissions due to the spatial heterogeneity in residue placement associated with crop harvesting operations, residue chopping, and incorporation by tillage (Staricka et al., 1991). This creates soil zones of intense microbial activity, which lowers oxygen concentration and enhances conditions for denitrification and N_2O emissions (Kravchenko et al., 2017; Kuntz et al., 2016; Li et al., 2016; Song et al., 2019). This is favored by crop residues with a high content of degradable C characterized by the neutral detergent soluble fraction (primarily soluble carbohydrates; Lashermes et al., 2022). The large spatial and temporal variation in N_2O emissions within microsites affected by crop residues and other factors has led to the concept of hotspots and hot moments as key drivers of N_2O emissions in agricultural systems (Kravchenko et al., 2017; Loecke & Robertson, 2009; Wagner-Riddle et al., 2020).

This knowledge can be used to inform the components of cropping systems that are particularly at risk of large N_2O emissions, representing critical moments for N_2O emissions that should be considered for inclusion in inventories and for mitigation (Sylvester-Bradley et al., 2015). These include:

- Autumn and winter periods where fresh crop residues remain on the soil surface (not incorporated). In cold areas, freeze–thaw can affect decomposition and N_2O fluxes (Bleken et al., 2022).
- Incorporation of N-rich and easily decomposable cover crops (Taghizadeh-Toosi et al., 2022). Emissions may further increase when the incorporation of cover crops is associated with the addition of N in mineral fertilizers or manure, as may happen when plowed in the spring (Abalos, Recous, et al., 2022).
- Cover crops that are frost-killed during winter (e.g., Brassica species) promoting decomposition of degradable C and N compounds and thus N_2O emissions (Li et al., 2015).
- Incorporation of green crop residues after harvesting in summer or autumn of vegetative crops, like vegetables, potatoes, and sugar beet (Nett et al., 2015).
- Plowing of grasslands (e.g., grass-clover swards) where degradable C and N in the incorporated plant materials can support nitrification and denitrification (Reinsch et al., 2018).

Given that there is inadequate activity data on crop residue management for different residue types available for these situations, these critical moments are not currently considered in the inventories, and it is also difficult to estimate their contribution to total annual emissions from agroecosystems, although these may be substantial (Anthony et al., 2023). The critical moments are crucial for affecting emissions in the short term; however, they also interact with long-term changes in soil properties and with the cropping system and fertilization regime.

5 | MODELLING NITROGEN AND CARBON EFFECTS

Many biogeochemical models have the capability of simulating C and N cycles in agroecosystems and associated soil N_2O emissions. They can identify effective strategies for crop residue management (quality of incorporated crop residues, amount of material, incorporation depth, etc.) that lower the GHG footprint of crop production. These models can be applied to various agricultural systems differing in soil properties, climate, or crop rotations. Models differ in complexity on how C and N cycles and soil N_2O emissions are simulated, thereby considering the multitude of processes involved from residue application until the emission of GHGs, especially N_2O (Brilli et al., 2017).

Most process-based models simulate N_2O emission from denitrification and nitrification as influenced by substrate availability (i.e., NO_3^- and NH_4^+) and, depending on the complexity of the model, factors that define the soil environmental conditions such as soil water content, temperature, pH, labile C availability, and oxygen concentration (Brilli et al., 2017; Butterbach-Bahl et al., 2013; Del Grosso et al., 2006). However, the impact of residue incorporation on soil physical properties, that is, soil pores, bulk density, and water holding capacity, is only considered by a few models (Brilli et al., 2017). This is often the case for the effect of tillage methods on the soil physical properties and the interaction with the incorporation of plant residues. Ehrhardt et al. (2018) evaluated the potential of using a process-based model ensemble to predict N_2O emissions at the field scale in arable and grassland systems and the associated uncertainties. The nonlinear dependencies of the factors influencing N turnover and N_2O hotspots with residue management make the handling of spatiotemporal effects particularly important for model performance. This is still a considerable challenge because of strong spatial variations in soil structure and distribution of substrates and microorganisms (Chakrawal et al., 2019) as well as of crop residues at a smaller scale than the resolution of current field scale biogeochemical models (Zhang et al., 2022).

6 | IMPORTANCE FOR BACKGROUND EMISSIONS

Understanding background N_2O emissions is important, not only because we need to accurately understand the human contribution to GHG emissions but also because background emissions are used in the calculation of emission factors for N_2O production following N input to agricultural systems (De Klein et al., 2006). Background emissions in most soils will be largely derived from the mineralization of soil organic matter and subsequent microbial N turnover processes, including nitrification and denitrification. Some emissions are also associated with the atmospheric deposition of reactive N. However, the primary source of the background emissions will eventually be the N inputs through plant litter and animal droppings, and regarding agricultural systems, by crop residues and manures.

From inventory and mitigation perspectives, there is a genuine interest in quantifying background emissions to ensure that we fully capture the anthropogenic emissions of N_2O associated with agricultural N management. Given that it is very difficult to make direct measurements of emissions from crop residues, inventories assume an emission factor approach to estimate the contribution that crop residues will make to emissions and therefore effectively acts as a proxy for the background emission itself. The methodology assumes that emissions from crop residues can be assessed within 1 year following incorporation. Nevertheless, from experimental evidence, it is known that crop residue decomposition while occurring rapidly at first, will decline and could continue beyond 1 year (Follett et al., 2007). It is equally possible that decomposition may result in most emissions being restricted to a period of a few weeks or months following incorporation (Badagliacca et al., 2017).

Estimates of background emissions have been derived from experiments where N_2O emissions have been measured in the absence of N additions. A review showed that the magnitude of these emissions from agricultural soils was around 1.1 kg N_2O-N ha^{-1} $year^{-1}$ (Bouwman, 1996). Both global and regional analyses of background emissions have indicated a link between land use and emissions that could be associated with differences in site and soil properties such as pH, bulk density, and air temperature (Aliyu et al., 2018; Kim et al., 2013). This suggests that long-term effects of residue addition on N_2O emissions may be mitigated by good soil management related to soil pH (Zhu et al., 2019), drainage (Dobbie & Smith, 2006), and soil structure (Pulido-Moncada et al., 2022). However, it also highlights a potential tradeoff in residue management since effects of increasing soil organic carbon can be associated with increased N_2O emissions.

7 | PERSPECTIVES FOR IMPROVED ACCOUNTING AND RESEARCH GAPS

The conceptual graph in Figure 2 presents a summary of the main drivers of N_2O emissions from residues with short-, medium-, and long-term timeframes related to influential factors and processes as outlined in Figure 1. The N_2O emissions from crop residues in the short term are mainly associated with the quality of the residues, where immature residues are associated with substantially larger emissions than mature residues (Abalos, Rittl, et al., 2022). This distinction is made based on the physiological stage of the crop when the residues are generated. However, the current accounting system does not make this differentiation (Hergoualc'h et al., 2019). The current inventory methodology mostly considers the residue sources from the mature category. In contrast, several of the immature crop residues are ignored or overlooked. This calls for revisiting the IPCC methodology for estimating N_2O emissions from crop residues, and a potential avenue would be to distinguish mature and immature crop residues with separate emissions factors from the two categories (Sylvester-Bradley et al., 2015). Such a differentiation would greatly impact the targeting of potential mitigation measures, since mature and immature crop residues are managed and prioritized very differently by farmers (De Notaris et al., 2022).

Drivers	Short term (months)	Medium term (years)	Long term (decades)
Residue-related variables	Residue quantity	Soil N fertility	Soil organic N stock
	Residue quality • Mineralizable N • Degradable C		Soil structure (porosity)
Environmental modifiers	Soil pH	Soil pH	Soil pH
	Soil moisture	Soil moisture	Soil moisture
	Temperature	Temperature	Temperature
	Freeze-thaw		
Cropping system management	Residue management	Crop sequences	Tillage
	Ploughing of leys		
	N fertilization	N fertilization	Soil cover
	Hotspots / moments		

FIGURE 2 Drivers of nitrous oxide emissions from crop residues in the short (months), medium (years), and long term (decades) and how this may be influenced by management.

Crop residue amendment has implications for soil fertility in the medium term, including potential effects on soil N fertility that affects the need for application of N fertilizer, particularly the use of immature N-rich residues and grass leys (Pullens et al., 2021). This will affect the use of N fertilizer, but these effects on N_2O emissions are already well described in the IPCC emission inventory methodology. Long-term effects of residue management potentially affect background emissions by influencing the mineralization from the soil organic N stock. However, this is modified by the effects of returning organic matter on soil structure and porosity with lower soil bulk density following residue application, which tends to reduce emissions.

The effects of crop residue quality on N_2O emissions are known to be linked to soil type and soil properties, as well as the method and timing of residue incorporation in soil (Abalos, Recous, et al., 2022). Crop residue management is only to a very limited extent included as part of policy measures to reduce agricultural GHG emissions. Emission reductions can only be effectively incentivized and implemented as mitigation measures, if there are documented and verified effects reflected in national inventories and if uncertainties can be significantly reduced. Such efforts require focus on the critical moments for N_2O emission identified above.

We suggest that differentiating between mature and immature crop residues may greatly improve the accuracy of the emissions accounting and that this may lower the barriers for adoption of effective mitigation technologies. However, there are still many research gaps to overcome for achieving improved accuracy and applicability of the accounting for mitigating N_2O emissions from crop residues, including (1) validated emission factors for mature and immature crop residues, (2) improved knowledge on emissions from belowground residues and the importance of belowground residue quality for N_2O emissions, (3) improved activity data on residue management, including methodologies to quantifying amounts of different residue types, (4) improved information on the influence of environmental conditions, (5) improved data on long-term effects of residue addition on N_2O emissions, and (6) improved representation of the micro-scale spatial heterogeneity in simulation models for simulating N_2O emissions associated with residue management.

8 | CONCLUSIONS

There is considerable evidence that N_2O emissions from crop residues applied to soil are affected by the biochemical characteristics of the residues and that both N and C contents and their management greatly affect emissions. This is not currently accounted for in the IPCC emission inventory methodology. A distinction between mature and immature aboveground crop residues may be a relatively straightforward approach that would greatly improve the accuracy of the accounting as well as allow better targeting of suitable mitigation strategies. However, the revision of emission factors for specific crop residues and the timing and placement of residues are likely to require further research. Other more fundamental research gaps in our understanding of emissions from crop residues include (1) separating N_2O emissions from residues and soil, (2) understanding and modelling micro-scale spatial effects of C and N turnover from residues, including those from root residues, and (3) the importance of short-term versus long-term effects of residue management, that is, the importance of direct residue effects versus soil quality effects of N_2O emissions.

AUTHOR CONTRIBUTIONS

Jørgen E. Olesen: Conceptualization; funding acquisition; investigation; methodology; project administration; visualization; writing – original draft; writing – review and editing. **Robert M. Rees:** Conceptualization; writing – original draft; writing – review and editing. **Sylvie Recous:** Conceptualization; writing – original draft; writing – review and editing. **Marina A. Bleken:** Conceptualization; writing – original draft; writing – review and editing. **Diego Abalos:** Conceptualization; visualization; writing – review and editing. **Ishita Ahuja:** Conceptualization; writing – review and editing. **Klaus Butterbach-Bahl:** Conceptualization; writing – original draft; writing – review and editing. **Marco Carozzi:** Conceptualization; writing – review and editing. **Chiara De Notaris:** Conceptualization; writing – review and editing. **Maria Ernfors:** Conceptualization; writing – review and editing. **Edwin Haas:** Conceptualization; writing – review and editing. **Sissel Hansen:** Conceptualization; writing – review and editing. **Baldur Janz:** Conceptualization; writing – review and editing. **Gwenaëlle Lashermes:** Conceptualization; writing – review and editing. **Raia S. Massad:** Conceptualization; writing – review and editing. **Søren O. Petersen:** Conceptualization; writing – review and editing. **Tatiana F. Rittl:** Conceptualization; writing – review and editing. **Clemens Sheer:** Conceptualization; writing – review and editing. **Kate E. Smith:** Conceptualization; writing – review and editing. **Pascal Thiébeau:** Conceptualization; writing – review and editing. **Arezoo Taghizadeh-Toosi:** Conceptualization; writing – review and editing. **Rachel E. Thorman:** Conceptualization; writing – review and editing. **Cairistiona F. E. Topp:** Conceptualization; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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REFERENCES

Abalos, D., Recous, S., Butterbach-Bahl, K., De Notaris, C., Rittl, T. F., Topp, C. F. E., Petersen, S. O., Hansen, S., Bleken, M. A., Rees, R. M., & Olesen, J. E. (2022). A review and meta-analysis of mitigation measures for nitrous oxide emissions from crop residues. *Science of the Total Environment*, *828*, 154388. https://doi.org/10.1016/j.scitotenv.2022.154388

Abalos, D., Rittl, T. F., Recous, S., Thiébeau, P., Topp, C. F. E., van Groeningen, 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

Aliyu, G., Sanz-Cobena, A., Müller, C., Zaman, M., Luo, J., Liu, D., Yuan, J., Chen, Z., Niu, Y., Arowolo, A., & Ding, W. (2018). A meta-analysis of soil background N_2O emissions from croplands in China shows variation among climatic zones. *Agriculture, Ecosystems & Environment*, *267*, 63–73. https://doi.org/10.1016/j.agee.2018.08.003

Anthony, T. L., Szutu, D. J., Verfaillie, J. G., Baldocchi, D. D., & Silver, W. L. (2023). Carbon-sink potential of continuous alfalfa agriculture lowered by short-term nitrous oxide emission events. *Nature Communications*, *14*, 1926. https://doi.org/10.1038/s41467-023-37391-2

Badagliacca, G., Ruisi, P., Rees, R. M., & Saia, S. (2017). An assessment of factors controlling N_2O and CO_2 emissions from crop residues using different measurement approaches. *Biology and Fertility of Soils*, *53*, 547–561. https://doi.org/10.1007/s00374-017-1195-z

Ball, B. (2013). Soil structure and greenhouse gas emissions: A synthesis of 20 years of experimentation. *European Journal of Soil Science*, *64*, 357–373. https://doi.org/10.1111/ejss.12013

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

Bertrand, I., Chabbert, B., Kurek, B., & Recous, S. (2006). Can the biochemical features and histology of wheat residues explain their decomposition in soil? *Plant and Soil*, *281*, 291–307. https://doi.org/10.1007/s11104-005-4628-7

Bertrand, I., Prevot, M., & Chabbert, B. (2009). Soil decomposition of wheat internodes of different maturity stages: Relative impact of the soluble and structural fractions. *Bioresource Technology*, *100*, 155–163. https://doi.org/10.1016/j.biortech.2008.06.019

Bleken, M. A., Rittl, T. F., Nadeema, S., & Hansen, S. (2022). Roots and other residues from leys with or without red clover: Quality and effects on N_2O emission factors in a partly frozen soil following autumn ploughing. *Science of the Total Environment*, *831*, 154582. https://doi.org/10.1016/j.scitotenv.2022.154582

Bouwman, A. F. (1996). Direct emission of nitrous oxide from agricultural soils. *Nutrient Cycling in Agroecosystems*, *46*, 53–70. https://doi.org/10.1007/BF00210224

Brilli, L., Bechini, L., Bindi, M., Carozzi, M., Cavalli, D., Conant, R., Dorich, C. D., Doro, L., Ehrhardt, F., Farina, R., Ferrise, R., Fitton, N., Francaviglia, R., Grace, P., Iocola, I., Klumpp, K., Leonardi, J., Martin, R., Massad, R. S., … Bellochi, G. (2017). Review and analysis of strengths and weaknesses of agro-ecosystem models for simulating C and N fluxes. *Science of Total Environment*, *598*, 445–470. https://doi.org/10.1016/j.scitotenv.2017.03.208

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*, 1621. https://doi.org/10.1098/rstb.2013.0122

Carvalho, J. L. N., Hudiburg, T. W., Franco, H. C. J., & DeLucia, E. H. (2017). Contribution of above- and belowground bioenergy crop residues to soil carbon. *Global Change Biology Bioenergy*, *9*, 1333–1343. https://doi.org/10.1111/gcbb.12411

Chakrawal, A., Herrmann, A. M., Koestel, J., Jarsjö, J., Nunan, N., Kätterer, T., & Manzoni, S. (2019). Dynamic upscaling of decomposition kinetics for carbon cycling models. *Geoscientific Model Development Discussions*, *13*, 1399–1429. https://doi.org/10.5194/gmd-13-1399-2020

Charles, A., Rochette, P., Whalen, J. K., Angers, D. A., Chantigny, M. H., & Bertrand, N. (2017). Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. *Agriculture Ecosystems and Environment*, *236*, 88–98. https://doi.org/10.1016/j.agee.2016.11.021

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

Coppens, F., Garnier, P., De Gryze, S., Merckx, R., & Recous, S. (2006). Soil moisture, carbon and nitrogen dynamics following incorporation versus surface application of labelled residues in soil columns. *European Journal of Soil Science*, *67*, 894–905. https://doi.org/10.1111/j.1365-2389.2006.00783.x

De Klein, C., Novoa, R. S. A., Ogle, S., Smith, K. A., Rochette, P., Wirth, T. C., McConkey, B. G., Mosier, A., Rypdal, K., Walsh, M., & Williams, S. A. (2006). N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In *2006 IPCC Guidelines for National*

Greenhouse gas Inventories. Intergovernmental Panel on Climate Change (IPCC).

De Notaris, C., Abalos, D., Mikkelsen, M. H., & Olesen, J. E. (2022). Potential for the adoption of measures to reduce N_2O emissions from crop residues in Denmark. *Science of the Total Environment*, *835*, 155510. https://doi.org/10.1016/j.scitotenv.2022.155510

Del Grosso, S. J., Parton, W. J., Mosier, A. R., Walsh, M. K., Ojima, D. S., & Thornton, P. E. (2006). DAYCENT national-scale simulations of nitrous oxide emissions from cropped soils in the United States. *Journal of Environmental Quality*, *35*, 1451–1460. https://doi.org/10.2134/jeq2005.0160

Dobbie, K. E., & Smith, K. A. (2006). The effect of water table depth on emissions of N_2O from a grassland soil. *Soil Use and Management*, *22*, 22–28. https://doi.org/10.1111/j.1475-2743.2006.00002.x

EEA. (2022). Annual European Union Greenhouse Gas Inventory 1990–2020 and Inventory Report 2022. Submission to the UNFCCC Secretariat. European Environmental Agency.

Ehrhardt, F., Soussana, J.-F., Bellochi, G., Grace, P., McAuliffe, R., Recous, S., Sandor, R., Smith, P., Snow, V., de Antoni Migliorati, M., Basso, B., Bhatia, A., Brilli, L., Doltra, J., Dorich, C. D., Doro, L., Fitton, N., Giacomini, S. J., Grant, B., … Zhang, Q. (2018). Assessing uncertainties in crop and pasture ensemble model simulations of productivity and N_2O emissions. *Global Change Biology*, *24*, e603–e616. https://doi.org/10.1111/gcb.13965

FAOStat. (2023). *FAO climate change: Agrifood systems emissions*. https://www.fao.org/faostat/en/#data

Follett, R. F., Paul, E. A., & Pruessner, E. G. (2007). Soil carbon dynamics during a long-term incubation study involving C-13 and C-14 measurements. *Soil Science*, *172*, 189–208. https://doi.org/10.1097/ss.0b013e31803403de

Freschet, G. T., Aerts, R., & Cornelissen, J. H. C. (2012). A plant economics spectrum of litter decomposability. *Functional Ecology*, *26*, 56–65. https://doi.org/10.1111/j.1365-2435.2011.01913.x

Guenet, B., Gabrielle, B., Chenu, C., Arrouays, D., Balesdent, J., Bernoux, M., Bruni, E., Caliman, J.-P., Cardinael, R., Chen, S., Ciais, P., Desbois, D., Fouche, J., Frank, S., Henault, C., Lugato, E., Naipal, V., Nesme, T., Obersteiner, M., … Zhou, F. (2021). Can N_2O emissions offset the benefits from soil organic carbon storage? *Global Change Biology*, *27*, 237–256. https://doi.org/10.1111/gcb.15342

Haas, E., Carozzi, M., Massad, R. S., Butterbach-Bahl, K., & Scheer, C. (2022). Long term impact of residue management on soil organic carbon stocks and nitrous oxide emissions from European croplands. *Science of the Total Environment*, *836*, 154932. https://doi.org/10.1016/j.scitotenv.2022.154932

Hergoualc'h, K., Akiyama, H., Bernoux, M., Chirinda, N., Del Prado, A., Kasimir, A., MacDonald, D., Ogle, S. M., Regina, K., & van der Weerden, T. (2019). N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Chapter 11, Volume 4 (AFOLU).

Jensen, L. S., Salo, T., Palmason, F., Breland, T. A., Henriksen, T. M., Stenberg, B., Pedersen, A., Lundstrom, C., & Esala, M. (2005). Influence of biochemical quality on C and N mineralization from a broad variety of plant materials in soil. *Plant and Soil*, *273*, 307–326. https://doi.org/10.1007/s11104-004-8128-y

Kim, D.-G., Giltrap, D., & Hernandez-Ramirez, G. (2013). Background nitrous oxide emissions in agricultural and natural lands: A meta-analysis. *Plant and Soil*, *373*, 17–30. https://doi.org/10.1007/s11104-013-1762-5

Kraus, D., Weller, S., Klatt, S., Haas, E., Wassmann, R., Kiese, R., & Butterbach-Bahl, K. (2015). A new LandscapeDNDC biogeochemical module to predict CH_4 and N_2O emissions from lowland rice and upland cropping systems. *Plant and Soil*, *386*, 125–149. https://doi.org/10.1007/s11104-014-2255-x

Kravchenko, A. N., Toosi, E. R., Guber, A. K., Ostrom, N. E., Yu, J., Azeem, K., Rivers, M. L., & Robertson, G. P. (2017). Hotspots of soil N_2O emission enhanced through water absorption by plant residue. *Nature Geoscience*, *10*, 496–500. https://doi.org/10.1038/ngeo2963

Kuntz, M., Morley, N. J., Hallett, P. D., Watson, C., & Baggs, E. M. (2016). Residue-C effects on denitrification vary with soil depth. *Soil Biology and Biochemistry*, *103*, 365–375. https://doi.org/10.1016/j.soilbio.2016.09.012

Lal, R. (2005). World crop residues production and implications of its use as a biofuel. *Environment International*, *31*, 575–584. https://doi.org/10.1016/j.soilbio.2016.09.012

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

Lashermes, G., Recous, S., Alavoine, G., Janz, B., Butterbach-Bahl, K., Ernfors, M., & Laville, P. (2022). N_2O emissions from decomposing crop residues are strongly linked to their initial soluble fraction and early C mineralization. *Science of the Total Environment*, *806*, 150883. https://doi.org/10.1016/j.scitotenv.2021.150883

Li, F., Sørensen, P., Li, X., & Olesen, J. E. (2020). Carbon and nitrogen mineralization differ between incorporated shoots and roots of legume versus non-legume based crops. *Plant and Soil*, *446*, 243–257. https://doi.org/10.1007/s11104-019-04358-6

Li, X., Petersen, S. O., Sørensen, P., & Olesen, J. E. (2015). Effects of contrasting catch crops on nitrogen availability and nitrous oxide emissions in an organic cropping system. *Agriculture, Ecosystems and Environment*, *199*, 382–393. https://doi.org/10.1016/j.agee.2014.10.016

Li, X., Sørensen, P., Olesen, J. E., & Petersen, S. O. (2016). Evidence for denitrification as main source of N_2O emission from residue-amended soil. *Soil Biology and Biochemistry*, *92*, 153–160. https://doi.org/10.1016/j.soilbio.2015.10.008

Loecke, T. D., & Robertson, G. P. (2009). Soil resource heterogeneity in terms of litter aggregation promotes nitrous oxide fluxes and slows decomposition. *Soil Biology and Biochemistry*, *41*, 228–235. https://doi.org/10.1016/j.soilbio.2008.10.017

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

Machinet, G. E., Bertrand, I., Barriere, Y., Chabbert, B., & Recous, S. (2011). Impact of plant cell wall network on biodegradation in soil: Role of lignin composition and phenolic acids in roots from 16 maize genotypes. *Soil Biology and Biochemistry*, *43*, 1544–1552. https://doi.org/10.1016/j.soilbio.2011.04.002

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

Mitchell, E., Scheer, C., Rowlings, D., Conant, R. T., Cotrufo, M. F., & Grace, P. (2018). Amount and incorporation of plant residue inputs modify residue stabilization dynamics in soil organic matter fractions. *Agriculture, Ecosystems and Environment*, *256*, 82–91. https://doi.org/10.1016/j.agee.2017.12.006

Mutegi, J. K., Munkholm, L. J., Petersen, B. M., & Hansen, E. M. (2010). Nitrous oxide emissions and controls as influenced by tillage and crop residue management strategy. *Soil Biology and Biochemistry*, *10*, 1701–1711. https://doi.org/10.1016/j.soilbio.2010.06.004

Nett, L., Fuss, R., Flessa, H., & Fink, M. (2015). Emissions of nitrous oxide and ammonia from a sandy soil following surface application and incorporation of cauliflower leaf residues. *Journal of Agricultural Science*, *153*, 1341–1352. https://doi.org/10.1017/S0021859615000027

Pinheiro, P. L., Recous, S., Dietrich, G., Weiler, D. A., Schu, A. L., Bazzo, H. L. S., & Giacomini, S. J. (2019). N_2O emission increases with mulch mass in a fertilized sugarcane cropping system. *Biology and Fertility* *of Soils*, *55*, 511–523. https://doi.org/10.1007/s00374-019-01366-7

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.

Pullens, J. W. M., Sørensen, P., Melander, B., & Olesen, J. E. (2021). Legacy effects of soil fertility management on cereal dry matter and nitrogen grain yield of organic arable cropping systems. *European Journal of Agronomy*, *122*, 126169. https://doi.org/10.1007/s13593-022-00773-9

Rasse, D. P., Rumpel, C., & Dignac, M. F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilization. *Plant and Soil*, *269*, 341–356. https://doi.org/10.1007/s11104-004-0907-y

Reinsch, T., Loges, R., Kluss, C., & Taube, F. (2018). Renovation and conversion of permanent grass-clover swards to pasture or crops: Effects on annual N_2O emissions in the year after ploughing. *Soil & Tillage Research*, *175*, 119–129. https://doi.org/10.1016/j.still.2017.08.009

Shan, J., & Yan, X. (2013). Effects of crop residue returning on nitrous oxide emissions in agricultural soils. *Atmospheric Environment*, *71*, 170–175. https://doi.org/10.1016/j.atmosenv.2013.02.009

Song, X., Ju, X., Topp, C. F. E., & Rees, R. M. (2019). Oxygen regulates nitrous oxide production directly in agricultural soils. *Environmental Science & Technology*, *53*, 12539–12547. https://doi.org/10.1021/acs.est.9b03089

Sousa Junior, J. G. D. A., Cherubin, M. R., Oliveira, B. G., Cerri, C. E. P., Cerri, C. C., & Feigl, B. J. (2018). Three-year soil carbon and nitrogen responses to sugarcane straw management. *Bioenergy Research*, *11*, 249–264. https://doi.org/10.1007/s12155-017-9892-x

Staricka, J. A., Allmaras, R. R., & Nelson, W. W. (1991). Spatial variation of crop residue incorporated by tillage. *Soil Science Society of America Journal*, *55*, 1668–1674. https://doi.org/10.2136/sssaj1991.03615995005500060028x

Stavi, I., Bel, G., & Zaady, E. (2016). Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems. A review. *Agronomy for Sustainable Development*, *36*, 32. https://doi.org/10.1007/s13593-016-0368-8

Sylvester-Bradley, R., Thorman, R. E., Kindred, D. R., Wynn, S. C., Smith, K. E., Rees, R. M., Topp, C. F. E., Pappa, V. A., Mortimer, N. D., Misselbrook, T. H., Gilhespy, S., Cardenas, L. M., Crauhan, M., Bennett, G., Malkin, S., & Munro, D. G. (2015). *Minimising nitrous oxide intensities of arable crop products (MIN-NO). Project report no. 548*. AHDB Cereals and Oilseeds.

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

Tahir, M. M., Recous, S., Aita, C., Schmatz, R., Pilecco, G. A., & Giacomini, S. J. (2016). In situ roots decompose faster than shoots left on the soil surface under subtropical no-till conditions. *Biology and Fertility of Soils*, *52*, 853–865. https://doi.org/10.1007/s00374-016-1125-5

Talbot, J. M., & Treseder, K. K. (2012). Interactions among lignin, cellulose, and nitrogen drive litter chemistry–decay relationships. *Ecology*, *93*, 345–354. https://doi.org/10.1890/11-0843.1

Thiébeau, P., Girardin, C., & Recous, S. (2021). Water interception and release of soluble carbon by mulches of plant residues under contrasting rain intensities. *Soil & Tillage Research*, *208*, 104882. https://doi.org/10.1016/j.still.2020.104882

van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M. A., Linquist, B., & van Groenigen, K. J. (2013). Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: A meta-analysis. *Global Change Biology*, *19*, 33–44. https://doi.org/10.1111/j.1365-2486.2012.02779.x

Wagner-Riddle, C., Baggs, E. M., Clough, T. J., Fuchs, K., & Petersen, S. O. (2020). Mitigation of nitrous oxide emissions in the context of nitrogen loss reduction from agroecosystems: Managing hot spots and hot moments. *Current Opinion in Environmental Sustainability*, *2020*(47), 46–53. https://doi.org/10.1016/j.cosust.2020.08.002

Williams, D. M., Blanco-Canqui, H., Francis, C. A., & Galusha, T. D. (2017). Organic farming and soil physical properties: An assessment after 40 years. *Agronomy Journal*, *109*, 600–609. https://doi.org/10.2134/agronj2016.06.0372

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, J., Zhang, W., Jansson, P.-E., & Petersen, S. O. (2022). Modeling nitrous oxide emissions from agricultural soil incubation experiments using CoupModel. *Biogeosciences*, *19*, 4811–4832. https://doi.org/10.5194/bg-19-4811-2022

Zhu, G., Song, X., Ju, X., Zhang, J., Möller, C., Sylvester-Bradley, R., Thorman, R. E., Bingham, I., & Rees, R. M. (2019). Gross N transformation rates and related N_2O emissions in Chinese and UK agricultural soils. *Science of the Total Environment*, *666*, 176–186. https://doi.org/10.1016/j.scitotenv.2019.02.241

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