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Review of factors controlling N_2O emission from crop residues

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1. Summary

We made a meta-analysis on field emissions of N_2O associated with crop residues. The IPCC methodology has used N remaining in the crop residues as a proxy to estimate N_2O emissions from residues. Previous meta-analyses showed that both C and N availability in residues influence N_2O emissions. However, management, soil attributes, and climate are also influential. By using a more detailed dataset of residue biochemical quality combined with random-effects meta-analysis, we showed that: (i) N added with crop residues and residue biochemical quality are the most important predictors of crop residue effects on N_2O emissions, while soil properties and weather conditions had only minor effects; (ii) the concentration of easily degradable fractions (water-soluble C and neutral detergent soluble fraction) and the structural fractions (hemicelluloses, cellulose and lignin) in the residues explained the variability of N_2O emissions among different residue types; (iii) N_2O predictors that comprise different biochemical qualities, such as maturity criteria and residue type explained more of N_2O emissions than amount of N applied in crop residues and content of individual biochemical compounds in the residues; (iv) immature crop residues showed a larger impact on soil N_2O emissions than mature crop residues. The use of residue maturity as a co-predictor for N_2O emissions from crop residues may predict better than solely the amount of residue N returned to soil.

2. Introduction

Soil N_2O fluxes associated with the return of crop residues are influenced by different factors with contradictory effects, making it hard to conclude based on results of single studies. Therefore, a quantitative synthesis of results across multiple studies is desirable. Previous meta-analyses have shown that there is a large variation in observed N_2O emissions associated with the application of crop residues. For example, in warm temperate and tropical climate zones, residue returning treatments had significant stimulatory effect on N_2O emissions (Hu et al., 2019), while within European environmental zones returning of crop residues often has been found to have no significant effect on the magnitude of soil N_2O emissions (Lehtinen et al., 2014). Also, residue C:N ratio has been found to be an important predictor of residue N_2O emissions (Hu et al., 2019). Although geographical characteristics and biochemical quality of the residue are constantly mentioned as paramount factors that influence the decomposability of residues, and thus the release of mineral N and finally soil N_2O production in soils, these factors are not considered by the current IPCC approach when calculating N_2O emissions associated with crop residues.

The objective of the review was to synthesise the results of short-term (< 2 years) field studies on the effect of crop residue returning on soil N_2O emissions. We were able to identify a significant number of relevant papers on factors affecting N_2O emission from crop residues to make a meta-analysis of the data. By synthesizing these data, we aimed to identify the main drivers of short-term soil N_2O emissions associated with application of crop residues and to rank their importance, thereby searching for invariants in drivers across a large range of environmental conditions. We have chosen to explore the short-term impact of crop residues as there is not enough data from long-term experiments. Our study differs in main aspects from previous meta-analyses (Chen et al., 2013; Lehtinen et al., 2014; Charles et al., 2016; Hu et al., 2019). First, we used only field studies. The choice of using only field studies was because the effect size of crop residue returning on N_2O emissions derived from laboratory measurements are normally greater as compared to field experiments (Chen et al., 2013). Second, we included renewal grassland studies, because temporary grasslands make up a substantial share of arable land in Europe especially in the Scandinavian countries and in some regions with high livestock densities, e.g. the Netherlands, Belgium and Bretagne (Lesschen et al., 2014). Third, most important, we used a biochemical characterization of the crop residue, which allow us to explore in more details the role of the biochemical quality of residues on N_2O emissions.

3. Materials and methods

The meta-analysis was based on the database created in WP2.1 and was done in cooperation with WP6. We used the log response ratio (LnRR) as effect size, which is a common metric in meta-analyses. We performed a weighted mixed-effects meta-analysis, using the rma.mv function in the metafor package (Viechtbauer, 2010), including Study/Observation as a random effect because several studies contributed more than one effect size. Effect sizes from individual studies were weighted by the inverse of the variance. Missing variances were estimated using the average coefficient of variation across the dataset (van Groenigen et al., 2017). We used a Wald test to evaluate statistical differences between subgroups within categories. We used a random-meta-forest approach to identify the most important predictors of crop residue effects on N_2O emissions.

4. Results and discussions

Crop residues can lead to both increases and reductions in N_2O emissions. Crop residue incorporation increased N_2O emissions for cover crops (50%), grasslands (216%) and vegetables (183%), but not for cereals, grain legumes, rice, or sugar cane. Increasing amounts of N returned (kg N ha^{-1} yr^{-1}) with the crop residues but the variation was large (Fig.1).

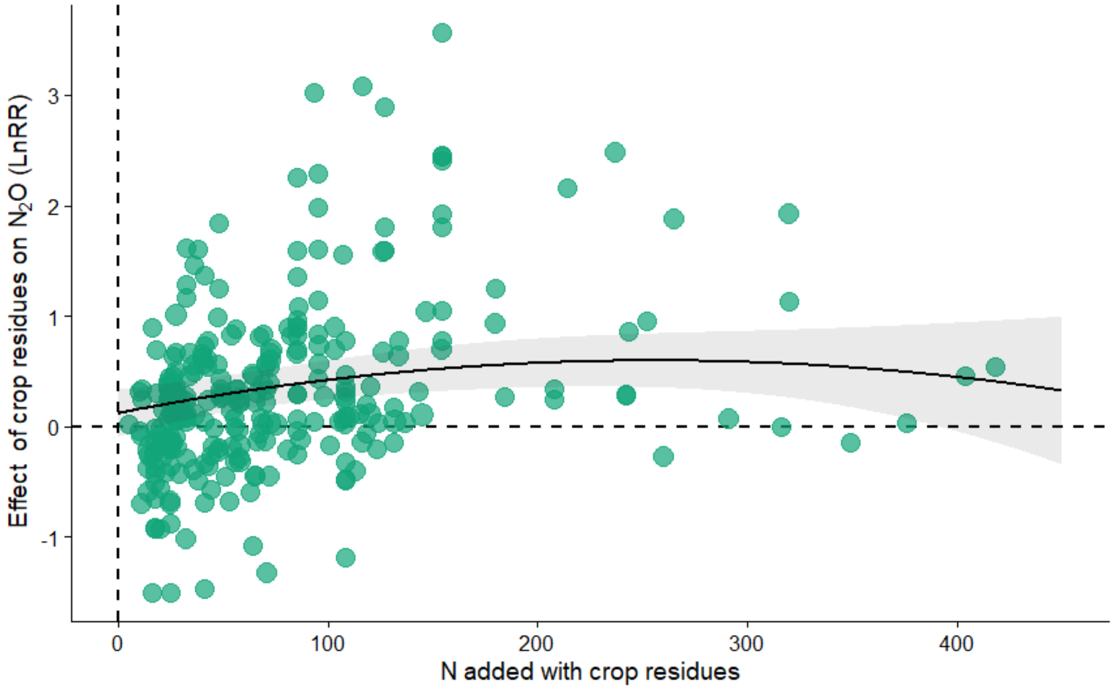

Figure 1. Meta-analytic scatterplot of the effect of N added with crop residues (kg N ha^{-1} yr^{-1}) on N_2O emissions.

Increasing share of easily degradable fraction in the residues raised N_2O emissions. This can be illustrated by the different impact of mature and immature residues (Fig. 2). Immature residues differed from mature residues by their low C:N: N ratio, low cellulose (%) concentration and high soluble NDS VS relative (%) concentrations. However, there was no significant difference in the relative concentration of lignin or hemicellulose contents between mature and immature residues. In our dataset, immature residues were composed by cover crops, vegetable residues and grassland renewal, which had already been shown by previous meta-analyses to increase the response ratio of N_2O emissions when incorporated into the soil (Basche et al., 2014; Muhammad et al., 2019; Shan and Yan, 2013). Mature residues were mostly cereal straw.

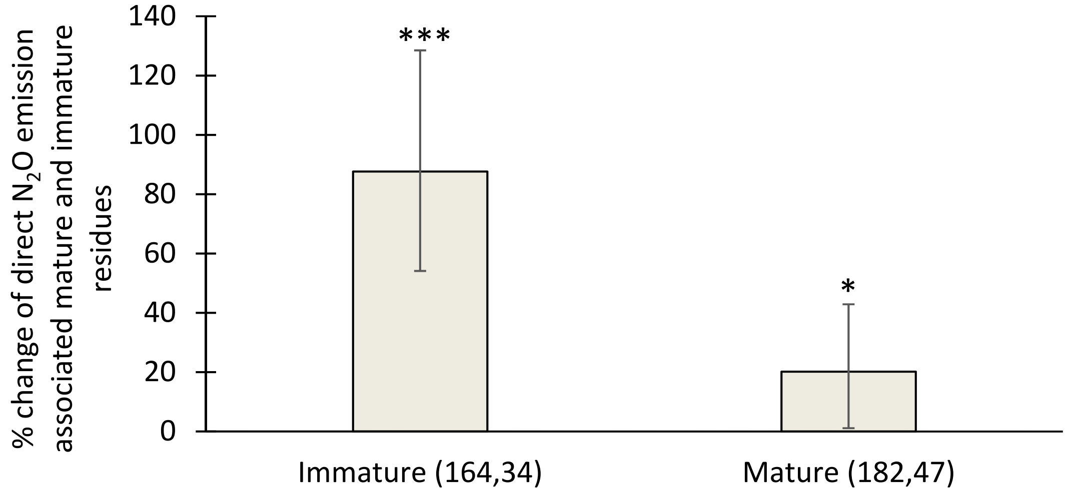

Figure 2. Relative increase in field N_2O emission (mean ± 95% CIs) associated to mature and immature crop residues application compared to corresponding non-amended field situations. The number of observations and studies are shown in parentheses. The effect was considered significant if the 95% CIs of the mean did not overlap with zero. The maturity criteria are explained in 2.1.3.

Our dataset clearly shows the strong positive correlation between residue N concentration and soluble VS concentration. Crop residue rich in easily degradable fractions (water-soluble C, soluble VS fraction) increase the C availability for biological N transformation processes in soils and speed up microbial growth. However, the C:N ratio does not determine the intensity of C mineralisation, but needs to be interpreted as a proxy of the chemical quality of these residues, resulting from the high correlation between residue N concentration and soluble (or soluble C) concentration. Here, we showed clearly that the proportion of easily degradable fractions (soluble fraction and the proportion of water-soluble C) vs. the structural fraction (hemicelluloses, cellulose and lignin) in the residues explained the variability of N_2O emissions among different residue types, the two being correlated.

Addition of crop residue rich in easily degradable fractions have also indirect effects on N_2O emission via promoting denitrification by creating an anaerobic environment and by providing energy sources for denitrifying bacteria (Surey et al., 2020). During short-term anoxic conditions due to high O_2 demand, denitrifying organisms rely on soluble compounds from fresh residues as major C sources (Surey et al., 2020). In their meta- analysis, Chen et al. (2013) and Hu et al. (2019) found a positive correlation between soil N_2O and CO_2 emissions following residue returning, indicating that increased microbial activity after residue addition favoured N_2O production. The relationship between biochemical quality of crop residues and denitrification related to N_2O emission is illustrated by Fig. 3.

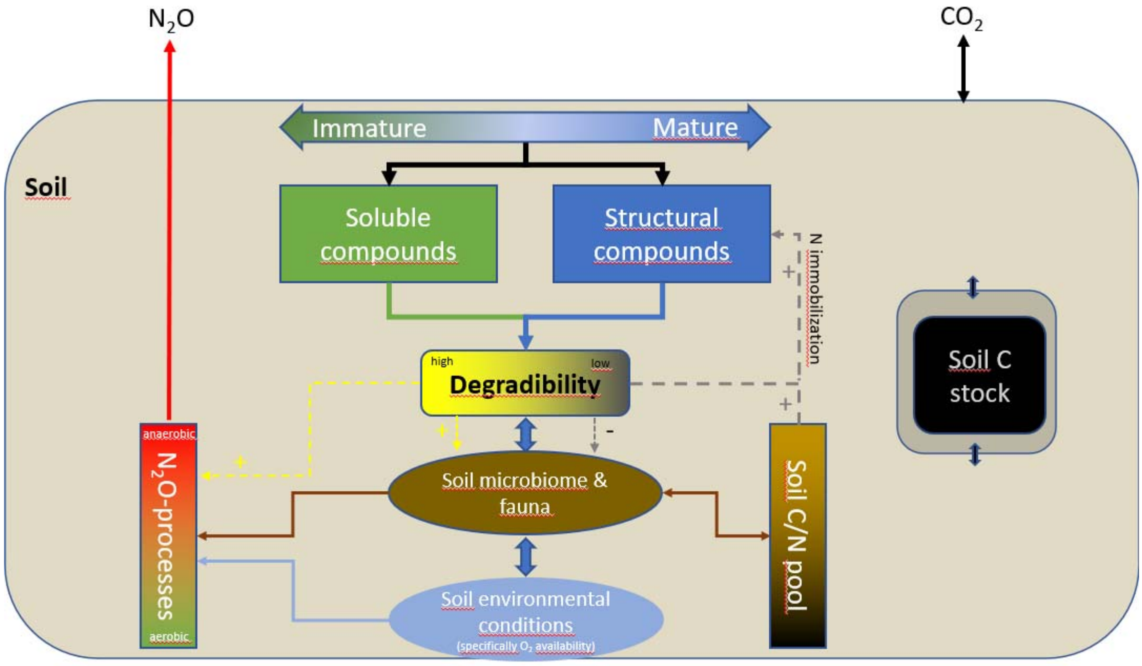

Figure 3. Impact of biochemical quality and degradability of crop residues on denitrification related to N_2O emission.

Linear meta-regressions indicated that residue C:N ratio (Qm = 15.9, $p < 0.001$), soil pH (Qm = 8.5, $p = 0.014$), SOC (Qm = 6.44, $p = 0.011$), soil N (Qm = 9.17, $p = 0.002$) and Aridity index (Qm = 5.26, $p = 0.021$) exerted a lower, but significant, influence on crop reside N_2O emissions. High C:N ratios (above c. 30), neutral soil pH, low SOC and low soil N content led to lower N_2O emissions. The effect size of applying crop residues in sites with humid climate (aridity index >1) was 2 times larger than on sites with a drier climate (aridity index <1).

We found that soil pH, SOC, soil N and Aridity Index had minor importance on the crop residue induced N_2O emissions as observed in in previous meta- analyses (Chen et al., 2013; Hu et al., 2019; Muhammad et al., 2019; Shan & Yan, 2013). The Aridity Index, to best of our knowledge, was not included in a meta-study yet. Our findings suggested that Aridity Index reflect better the influence of local conditions on N_2O emission than total annual precipitation and annual temperature alone.

5. Conclusions

This study provides evidence that crop residue returning to soils influences N_2O emissions, and that amount of residue N applied, and biochemical quality are better predictors than soil properties and climatic conditions. However, neither returned residue N nor other residue biochemical qualities solely adequately explain soil N_2O emissions. Rather the overall biochemical composition of the residue better explained the derived soil N_2O emissions after residue returning. Maturity criteria and residue type, which comprise different biochemical qualities, seem promising approaches to improve prediction of N_2O emissions from crop residues. However, data availability from field studies on GHG is scarce and dominated by specific types of crop residue, and even more rare are field studies that provide a detailed residue biochemical quality characterization. By using a residue quality dataset combined with meta-analysis, this study provided new insights on the drivers of N_2O emissions as summarized; however, the statistical fit of our models still could be improved by data on biochemical quality of crop residues from trials on N_2O-emissions associated with these residues.

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