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# Effects of the quality, amount and spatial distribution of arable and ley crop residues on field $N_2O$ emissions

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# 1. Summary

We present results from a 2-year field study in southern Sweden, on annually cropped fields, and two 1-year field studies in southern Norway, on temporary grassland. Gas fluxes were measured over the winter season, from early or mid-autumn to late spring. Residues of different qualities (ley with clover, ley without clover, winter wheat and sugar beet) were studied in combinations with management options (aboveground residues removed, retained or doubled). In selected treatments, the effects of an increase in pH were investigated.

The outcomes of the studies imply that sugar beet residues, ley herbage containing red clover, and possibly other "immature" residues, produce higher $N_2O$ emissions at higher residue application rates - their removal could therefore be considered as a mitigation option, although the effect may not always be large. For wheat residues, and likely also other "mature" residues, the results indicate that removing residues may increase $N_2O$ emissions, although inconsistencies and effects well beyond the initial few months call for further study. It is clear from our results that residue quality strongly affects $N_2O$ emission patterns and should not be neglected.

Our results add to previous evidence that moderately cold winter conditions with frozen soil at ~0°C can elicit strong $N_2O$ production, if there is sufficient substrate for heterotrophic respiration, as in the case of temporary grassland renewal. The slightly warmer conditions, with very little snow cover, in the Swedish study, provided a contrast with relatively low winter emissions.

Based on the low emission factors for ley roots observed, and the difficulties in distinguishing background from root emissions and estimating amounts of root N, one may consider an alternative approach to the current IPCC methodology, not assigning any specific emission to roots, but instead include them in an estimate of background emissions.

We could demonstrate that liming a low-pH soil can be an effective $N_2O$ emission mitigation tool, even when the nitrogen source is primarily organic and nitrification is an essential step prior to denitrification.

# 2. Introduction

Emissions of $N_2O$ associated with crop residues depend on a number of interacting factors and although laboratory based studies are helpful in elucidating the mechanisms behind emissions, field studies are needed to obtain realistic estimates of how the emissions vary and integrate over space and time. There is currently little empirical knowledge from field studies on the specific $N_2O$ emissions from crop residues, which impairs attempts to assess emissions and elect mitigation strategies. The IPCC default methodology for GHG accounting uses a single emission factor for all plant residues and for both belowground and aboveground parts. It is reasonable to expect, however, that differences in residue quality, both between crops and between belowground and aboveground parts, affect emissions due to differences in both mineral N release and provision of C to microorganisms. Aboveground residues, except stubble, can be removed from the field and used for feed, bedding, biofuel or biogas substrate, or they can be left in the field for nutrient transfer to the next crop (green manure), or for building soil C. The effects of managing the aboveground residues, by removal or retention, depend on the quality and quantity of the non-removable residues (belowground residues and stubbles) that are left in the field. In order to be able to identify high risk situations and mitigation options for $N_2O$ emissions, as well as improving GHG accounting, it is important to improve estimates of the quality and quantity of non-removable residues and to understand the effects on $N_2O$ emissions associated with residue quality, quantity and interactions between quality and quantity.

We performed a 2-year field study in southern Sweden, on annually cropped fields, and two 1-year field studies in southern Norway, on temporary grassland. Gas measurements were carried out from early or mid-autumn to late spring in all experiments, since in cold climates a high proportion of $N_2O$ emissions occurs during winter, when the soil is wet and there are periods of freezing and thawing. The removal of aboveground residues was studied for both annual and grassland crops and for crops with contrasting residue qualities. Effects of addition of extra residues were studied, since an uneven distribution of residues can result in patches with high residue concentrations and high application rates can be relevant in cut-and-carry systems. Interactions between residue quantity, residue quality and pH were studied. Raising soil pH by liming has been suggested as a strategy for $N_2O$ mitigation, since low pH impairs the last denitrification step, promoting $N_2O$ production, but liming of residue rich grassland may instead increase $N_2O$ production due to increased mineralization and nitrification.

# 3. Materials and methods

The study in Southern Sweden (Ernfors and Jensen, in prep.) was carried out at the SITES Lönnstorp research station (55.666252, 13.115851), at the Swedish University for Agricultural Sciences (SLU). The soil was a sandy loam (2.3% organic matter; pH 6.5). The conventionally managed reference plots of an established cropping system experiment were used (the SAFE_REF plots). The two factor experiment consisted of (1) a “residue quality” treatment with two contrasting crops: winter wheat (WW; ”mature” residues) and sugar beet (SB; “immature” residues), and (2) a management treatment with aboveground residues removed, left or doubled. All plots were ploughed, at the end of October. Emissions of $N_2O$ were measured for two winter seasons, from late October to late April/early May, using non-steady-state manual chambers. Plant residue quality was analysed and soil moisture and temperature were measured in all plots.

In order to calculate $N_2O$ emission factors for crop residue additions according to the IPCC 2019 guidelines, background emissions need to be subtracted from the total measured emissions, to obtain values representing the emissions induced by the residues themselves. This is not straightforward, and the values chosen to represent background emissions have a considerable influence on the resulting emission factors, particularly for emissions from roots. Finding a suitable control to represent background emissions is not straightforward. Using a fallow was not considered an option, since the growing season conditions would have been very different compared to the cropped plots. Instead, for the sugar beet plots, where the residue amount-to-emission patterns were relatively consistent, linear regressions were fitted to the data for each of the two years and the intercept values, at zero crop biomass, were used as background emission values. This allowed for comparisons with the default IPCC emission factor. Emission factors were calculated for the period up to spring farming operations. Belowground biomass N was calculated based on IPCC default values for winter wheat and “potatoes and tubers”.

The two studies in Southern Norway were carried out in the same field experiment, in Ås (59º39’47”N, 10º46’42”E), at the Norwegian University of Life Sciences (NMBU). The soil was a clay loam (31% clay, 46% silt, 2.81 % total C). Fully randomized combinations of (1) sward type (grass; clover-grass with white clover; clover-grass with red clover; red clover in pure stand), (2) soil pH ($pH_{CaCl_2}$ ~4.8 and ~5.8) and (3) nitrogen application rates (low; normal) were available. The swards were at the end of their 3rd production year. Swards were ploughed in mid-September. In both studies, soil mineral N, soil pH and plant residue quality were analysed, and soil moisture and soil temperature were monitored.

In one study (NMBU 1; Bleken et al., in prep.) the amount and biochemical quality of roots to 30 cm was determined for the grass mixture, red clover-grass mixture and red clover pure stand. In the same experiment, manual non steady-state chambers were used to measure $N_2O$ emissions after ploughing on the low pH grass and red clover-grass treatments, with or without removal of the herbage of the last harvest. Subplots with living grass and subplots which had been decorticated early in the spring and kept fallow were used as controls. For the emission factor calculations, the unploughed ley value was chosen to represent background emissions. The amount of $N_2O$ in soil air and water was quantified to 45 cm depth in two treatments by sampling soil air through porous caps probes.

The other study (NMBU 2; Bleken and Rittl, in prep.) addressed the effect of soil pH, and $N_2O$ fluxes were measured before and after ploughing, on high and low pH plots, by means of a self-moving automated field chamber. Plots with grass, red clover and red or white clover-grass mixture were used. The clover-grass plots included low and normal N fertilizer treatments.

# 4. Results and discussion

The mean daily $N_2O$ emissions, from the time of ploughing (September or October) to late spring (April or May; before any spring farming operations) were 7.9, 3.8, 1.8-2.4 and 0.1-0.7 g $N_2O$-N $ha^{-1}$ $d^{-1}$ for grass-clover ley, grass ley, sugar beet and winter wheat, respectively, when removable residues or herbage were retained. When residues or herbage were removed, the corresponding emissions were 4.6, 3.8, 1.1-1.7 and 0.6-0.7 g $N_2O$-N $ha^{-1}$ $d^{-1}$. Removing aboveground herbage or residues thus decreased $N_2O$ emissions for grass-clover ley and sugar beet, but did not affect emissions from the grass ley, whereas for winter wheat the results were inconsistent. Doubling the amounts of removable residues increased $N_2O$ emissions to 2.1-4.3 g $N_2O$-N $ha^{-1}$ $d^{-1}$ for sugar beet, while for winter wheat there was an increase to 1.5 g $N_2O$-N $ha^{-1}$ $d^{-1}$ in the first year and a decrease to 0.3 g $N_2O$-N $ha^{-1}$ $d^{-1}$ in the second year. The higher emissions from the leys compared to the sugar beet and winter wheat, was not necessarily an effect of crop residue quality or quantity, but could very well have been an effect of the cold Norwegian winter, with deep soil frost, snow and snow melt, in accordance with previous studies that have indicated a frost-prone climate as a risk factor for $N_2O$ emissions.

The emission dynamics over time were similar for the two ley types in Norway, with highest emissions during episodic diurnal snow melt on frozen soil, and lowest during a period when the soil was frozen under a snow cover and air temperatures were below 0°C. In the sugar beet and winter wheat experiments in Sweden, $N_2O$ emission dynamics differed between the two crops, with the highest emissions during the first 4-6 weeks in the sugar beet treatments, with some additional smaller winter peaks, while the emissions in the WW treatments remained low during the whole period. In the Swedish experiment, measurements continued for a few weeks after spring farming operations (harrowing, fertilization and sowing), with the aim of investigating if there were interactions between spring fertilization (and disturbance) and the residues added in the autumn. Especially in the second year, a large part of the total emissions occurred after spring farming operations and did indeed vary with the quality and quantity of previously added residues. In the second year, $N_2O$ emissions after spring farming operations correlated positively with the amount of sugar beet residues, but negatively with the amount of wheat residues, with the highest emissions coming from the winter wheat treatment where residues were removed. These contradictory effects were most likely connected to decomposition patterns and immobilisation/mineralisation of N.

In the Norwegian study, the emission factor for non-removable residues was the same for grass-clover as for grass only. When extrapolated to one year, assuming the same average $N_2O$ flux as observed during the 252 day experiment period, the calculated emission factor for the non-removable ley residues, with or without red clover, was 0.37% (CV 46%), which is lower than the 0.6% default value for organic residues in wet climate, as presented in the IPCC 2019 revised guidelines, though within the expected coefficient of variation. The specific emission factor for retaining the last herbage yield of the clover-grass was 1.2%, while retaining the herbage of the grass had no additional effect on the emission. Quality alone could not explain the low emission factors observed for non-removable residues. A separate laboratory study using the same field material, with separate incubation of roots, stubble and herbage, supported this conclusion. Our results suggest that the IPCC default algorithms overestimate the amount of belowground residues after red clover, and underestimate the nitrogen concentration belowground. In spite of this, the discrepancy between our results and the IPCC estimates was not so much in the estimations of residue amounts as in the emission factors. The average emission factors for the sugar beet treatments, when extrapolated to one year as was done for the ley emission factors, were 0.29% (CV 24%) and 0.15% (CV 19%), in the first and second year, respectively, when the background emission corrections were applied. For winter wheat the corresponding values were -1.1% (CV 86%) and -0.26 (CV 20%), respectively. The negative emission factors for winter wheat suggest that removal could potentially be counterproductive. The emission factors for sugar beet were much lower than the default annual IPCC emission factor of 0.6 %, despite the extrapolation. Interactions with spring fertilization underlines the importance of measurements over full years, or preferably whole rotations.

In the second NMBU study, liming reduced the cumulative emissions after ploughing from all swards, on average to ~50% of those on non-limed controls, in spite of higher mineral N content in limed soils. Emissions correlated with herbage yields in the preceding growing seasons, which were largest for the grass-clover mixtures and smallest for red clover in pure stand. The yield-scaled $N_2O$ emissions were highest on low pH soils at all yield levels; this was a true result of soil pH on $N_2O$, as herbage yields were not increased by liming. Cumulative emissions were not linked to the share of clover in the leys. The results indicate that if primary production enhanced microbial activity, including that of nitrifiers and denitrifiers, the effect of pH on promoting a complete denitrification to $N_2$ overruled this effect and mitigated the whole $N_2O$ emission.

# 5. Conclusions

In summary, the results showed that sugar beet residues, ley herbage containing red clover, and possibly other “immature” residues, produce higher $N_2O$ emissions at higher residue application rates; their removal could therefore be considered as a mitigation option, although the effect may not always be large. For wheat residues, and likely also other “mature” residues, the results indicated that removing residues may increase $N_2O$ emissions, although inconsistencies and effects well beyond the initial few months call for further study. It is clear from our results that residue quality strongly affects $N_2O$ emission patterns and should not be neglected.

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Based on the low emission factors for ley roots observed, and the difficulties in distinguishing background from root emissions and estimating amounts of root N, one may consider an alternative approach to the current IPCC methodology, not assigning any specific emission to roots but instead include them in an estimate of background emissions.

We demonstrated that liming a low-pH soil can be an efficient $N_2O$ emission mitigation tool, even when the nitrogen source is primarily organic and nitrification is an essential step prior to denitrification.

# 6. References

Bleken MA, Rittl T (2021) Soil pH-increase strongly mitigated $N_2O$ emissions from ploughing of grass and clover swards in autumn: a winter field study. *Submitted to Science of the Total Environment.*

Bleken MA, Rittl T, Nadeem S, Hansen S (2021) Roots and other residues from leys with or without red clover: quality and effects on $N_2O$ emission factor after ploughing. *Submitted to Science of the Total Environment.*

Ernfors M, Jensen ES (2021) Effects of residue quality and quantity on cold season $N_2O$ emissions. *In prep., for Science of the Total Environment.*