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Effects of crop residue vertical distribution, temperature, moisture and freeze-thaw on N_2O/CO_2 emissions

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1. Summary

Three main incubation studies were conducted to identify how management, residue properties and soil properties, alone or in interaction, affect N_2O emissions. The aim was to contribute to improving both inventories and mitigation strategies. Treatments used in various combinations were: residue type, vertical residue distribution, fertilization, soil moisture, soil type and freezing/thawing. The results showed clearly that several factors interact to determine the magnitude of N_2O emissions after addition of residues to soil. We conclude that inventories should ideally integrate other factors than the total amount of N added with the residues and also take into account the effects of combinations of factors. Although the mechanisms behind N_2O emissions are complex, the results pointed to combinations of residue type, management, soil type and season that create particularly high risks of N_2O emissions, and field situations representing such combinations could be targeted for mitigation.

2. Introduction

When crop residues are added to soil, there is a potential for both sequestration of carbon and emissions of nitrous oxide (N_2O). Several factors affect the magnitudes of these processes: residue type, climate, soil type and agricultural management. This work package focuses on effects of interactions between residue quality (defined here as its chemical composition) and management, on mainly N_2O emissions, under set climatic conditions resembling a northern European climate and with a selection of soil types. The management types chosen for study were incorporation strategy and mineral nitrogen fertilization.

Crop residue incorporation in agricultural soils is a major element in crop management. Incorporation of crop residues can, compared to decomposition at the soil surface, reduce NH_3 losses, but the placement within the soil will prevent residue water loss, increase soil water holding capacity and create hotspots of microbial C and N turnover. The intense microbial activity increases oxygen (O_2) demand locally and the placement of the residues in more confined spaces decreases O_2 supply, which fuels the development of anaerobic microsites, promoting denitrification. For N_2O emissions from denitrification, the ratio of incomplete denitrification (producing N_2O) to complete denitrification (producing N_2), is also affected by oxygen availability, which further complicates the prediction of N_2O emissions. The type of residue incorporation, for example an even mixing by a cultivator tool in contrast to the burying of larger lumps of residues by ploughing, determines the distribution of residues within the soil, and affects anaerobic microsite development. Residue-induced hotspots of microbial C and N turnover in soil, in interaction with the quality of the residues, also affect the rates and location of N mineralisation and immobilisation, determining where and in which amounts mineral nitrogen will be available for nitrification and denitrification.

Soil texture, structure and water-filled pore space (WFPS) will determine gas and solute diffusivity and hence interact with the residue distribution in determining the availability and distribution of oxygen and nitrate in different parts of the soil. Mineral nitrogen fertilization provides substrates for nitrification and denitrification and promotes N_2O emissions. We used an addition of nitrate to evaluate how interactions with residue quality and residue distribution affects N_2O emissions from, primarily, denitrification. In Northern climates, freezing and thawing of the soil sometimes induce large N_2O emissions. Several mechanisms can contribute to this effect, including release of soluble compounds from dead microorganisms and plant residues. We induced two short freezing and thawing episodes, in one of the laboratory studies, to see how these interacted with residue quality and distribution. In this study, the incubation temperature was lowered from 15 to 4 °C for ten days before freezing, to create a more realistic scenario.

Despite the complexity of how site factors, management and residue quality interact with the total N supply to create N_2O emissions, a recent refinement of the IPCC methodology only proposes two default N_2O emission factors for crop residues: 0.6 and 0.5% of residue-N for wet and dry climates, respectively, and only considers the amount and N content of crop residues. The objective of this task was to identify how management, residue properties and soil properties, alone or in interaction, affect N_2O emissions, in order to both improve inventories and guide mitigation strategies. Especially important was to identify combinations of factors that create particularly high N_2O emissions – the so-called “hot spots” and “hot moments”.

3. Materials and methods

Three main incubation studies were conducted, by individual partners or in collaborations. An incubation protocol was agreed upon within WP3, which was largely followed in the individual experiments investigating different effects and interactions, as outlined below. The three experiments, which are presented in three manuscripts aimed for peer-reviewed journals, are referred to in this text according to the acronym for the partner where the main work was done (AU, SLU and INRAE).

The following aspects were defined from the beginning, in the common protocol: Application rate (4 t DM ha^{-1}), distribution (on the surface, mixed at 0-4 cm depth, or in a layer at 4 cm depth), bulk density (1.25 g cm^{-3}), WFPS (40 or 60%) and nitrate addition (no addition or NO_3-N adjusted to 100 mg kg^{-1}). Gas measurements were either manual or automated (see the respective manuscripts). In addition to N_2O, CO_2 was measured in all studies and NO, NH_3 and CH_4 in some. Complementary measurements of NO_3^- and NH_4^+ were made in all three studies.

The three incubation studies contributed to the objectives of the task by investigating the effects of the following treatments and treatment combinations:

	Factors varied and combined	Factors kept constant
AU (Taghizadeh-Toosi et al., 2021)	Residue quality (red clover, winter wheat) x residue distribution (mixed, layered) x fertilization (no addition, NO_3-N adjusted to 100 mg kg^{-1}) x WFPS (40% and 60 %)	Soil type (sandy loam), temperature/freeze-thaw (15°C)
SLU (Ernfors and Jensen, in prep)	Residue quality (sugar beet, wheat straw) x residue distribution (surface, mixed, layered) x temperature/freeze-thaw (two freezings or no freezing)	Soil type (sandy loam), fertilization (no addition), WFPS (60 %)
INRAE (Chandra et al., in prep)	Residue distribution (surface, mixed, layered) x soil type (low, medium, high clay)	Residue quality (red clover), fertilization (NO_3-N adjusted to 100 mg kg^{-1}), WFPS (60 %), temperature/freeze-thaw (15°C)

4. Results and discussion

Selected results and conclusions are summarised below, with acronyms referring to the experiments mentioned in section 3.

N_2O emissions were typically, and independent of soil type and distribution, short-lived and declined to background levels within 10 days for N_2O, and within 30 days for CO_2 (INRAE, AU). The exception was the SLU study, where both N_2O and CO_2 emissions continued to differ between treatments until the end of the 60 day experiment, likely due to a lower incubation temperature. The emission patterns illustrated the importance of measuring with short intervals during the first few days in order to capture the highest emission peaks.

Interactions between WFPS, soil type and nitrate concentrations:
Very different levels of N_2O emission were observed when incubating the same residue in three different soils at 60% WFPS (INRAE). At a high WFPS, oxygen consumed by residue decomposition is not replaced to the same extent by diffusive supply, thereby creating anaerobic hotspots that favour denitrification and N_2O emissions. However, the relationship between WFPS and soil gas diffusivity depends on soil texture and structure, which may have caused the differences between the soils. More detailed studies are needed to clarify why some soils are more prone to N_2O emissions. When anaerobic hotspots are created, the effect on N_2O emissions will also depend on the availability of nitrate. In the treatment where nitrate was added, N_2O emissions were much higher at 60% WFPS compared to 40% WFPS, while without the nitrate addition they were not significantly different (AU). The practical implication may be that there are interactions between residue decomposition and fertilisation in spring, which need to be studied further.

Residue distribution:
The magnitude of N_2O emissions was affected by residue distribution under high-moisture conditions (WFPS 60%) only, but it was affected in different ways depending on residue quality and nitrate addition (AU, INRAE, SLU). With nitrate addition and an "immature" residue (red clover), a mixed distribution gave much higher emissions than a layered distribution in the AU study and there was a similar tendency, but without statistical significance, in the INRAE study with the same treatments and the same soil (a sandy loam). In contrast, when nitrate was not added, N_2O emissions were higher with a layered than with a mixed residue distribution, for both "mature" and "immature" residues (winter wheat and sugar beet, respectively) in the SLU study, while in the AU study there were no differences. These results can be interpreted in the context of what limits denitrification (which would be the main process producing N_2O emissions at a high water content). With an abundance of nitrate, denitrification is likely to be carbon limited, and immature residues, which contain easily available carbon, could induce more denitrification if distributed to many microsites. Without nitrate addition, denitrification is likely to be nitrate limited and a concentration of residues could more easily provide the surplus of nitrate needed for higher rates.

Applying the residues on the soil surface yielded lower N_2O emissions than a layered distribution for one of the soils in the INRAE study, and there were also NH_3 emissions from this treatment. In the SLU study, emissions were similar in the surface application and layered treatments, but both were higher than for the mixed distribution. The SLU laboratory setup was not as conducive to NH_3 losses, since there was no turbulence in the headspace, which may have caused the difference.

The INRAE laboratory conditions were more representative of field conditions and the emission patterns may therefore be, as well.

Freeze-thaw:

The freezing of the soil in the SLU experiment was done after 17 days at 15°C followed by 9 days at 4°C, mimicking a transition from autumn to winter. We found no increases in emission in connection to the freezing-thawing events, in any treatment. The freezing was short (2 days), and we did not expect emissions at thawing by a release of accumulated gas. We had hypothesized, however, that the freezing and subsequent thawing would induce N_2O emissions through release of labile C and N from the residues. At the first freezing, the sugar beet residues, which may have been the most likely emitter of N_2O due to their high content of nitrogen and soluble compounds, already had a collapsed structure, which could be the reason why freezing had no effect.

5. Conclusions

Our results show clearly that several factors interact to determine the magnitude of N_2O emissions after addition of residues to soil. One implication is that inventories should not focus only on the total amount of N added with the residues, but also integrate other factors and combinations of factors. Another implication is that it seems possible to mitigate emissions by avoiding particularly risky combinations of residue type, management, soil type and season. Identifying such combinations may not be entirely straightforward - our results indicate, for example, that a management choice such as method of residue incorporation can have opposite effects on N_2O emission rates depending on other factors, such as nitrate availability. The combination of high soil water content, fertilisation and addition of immature residues seemed to conjure up a perfect storm of nitrous oxide emissions, which is well in agreement with both theory and previous studies. Field situations where this and similar combinations can occur, for example when residues are present at the time of spring fertilisation, need to be studied further. From a methodological perspective, our findings suggest that standardized short-term laboratory incubations are suitable for clarifying mechanisms underlying soil N trace gas emissions due to residue incorporation, especially since emissions usually peaked in the first few days and leveled out relatively quickly.

6. References

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