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6.1 Report on mitigation measures for selected cropping systems in Northern Europe targeting N_2O hotspots

and

6.2 Report on effectiveness of measures for mitigating GHG from crop residues

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1. Summary

We combined a literature review, meta-analysis and expert knowledge to identify and assess measures for mitigating N_2O emissions from crop residues. Crop residue removal, shallow incorporation, incorporation of residues with C:N ratio > 30, and avoiding incorporation of immature crops were the measures leading to significantly lower N_2O emissions. Other practices such as incorporation timing and interactions with fertilizers were less conclusive. Our analysis also show that N_2O emissions from crop residues are lower in regions where the mean annual precipitation to mean annual potential evapotranspiration ratio is < 1, and from soils with high clay content. We identified additional strategies with potential to reduce crop residue N_2O emissions requiring further research: conversion into biochar or anaerobic digestate and field application, co-application with nitrification inhibitors or N-immobilizing materials, and use of crop mixtures. Potential positive and negative side-effects of the analyzed measures in relation to yield, soil organic carbon sequestration, nitrate leaching and ammonia volatilization are presented in this report. Our results reveal the N_2O mitigation potential of several practices associated to crop residue management, and important knowledge gaps within this field of research.

2. Introduction

Regulating atmospheric greenhouse gas (GHG) concentrations and ensuring sufficient food for the growing world population are two of the greatest challenges facing our planet today. Crop residue incorporation into agricultural soils has been posited as a tool to simultaneously tackle both challenges. This is because crop residue incorporation may increase net soil C storage thereby removing atmospheric CO_2, and it may improve soil fertility thus enhancing sustainable food production (Watson et al., 2002). However, the potential benefits of crop residue retention for climate change mitigation can be largely offset by increased emissions of the powerful greenhouse gas nitrous oxide (N_2O) after incorporation. Agricultural soils are the largest source of N_2O emissions, and crop residues account for a substantial fraction of such emissions (EEA, 2020). Global N_2O emissions from crop residues have been increasing steadily over the last decades, reaching approximately 0.224 Gt CO_2-eq in 2017 (FAOSTAT 2020). To harness the benefits of crop residue retention, we must identify the conditions and residue management strategies that reduce N_2O emissions after incorporation without negative consequences for soil C sequestration and soil fertility. This can only be achieved with a better understanding of the interactions between crop residue management, type and edaphoclimatic factors. In WP6, we combined a literature review, meta-analysis and expert knowledge to identify and assess measures for mitigating N_2O emissions from crop residues.

3. Materials and methods

A (non-systematic) literature review was used to screen the literature and synthesize the state-of-the-art in terms of mitigating N_2O emissions associated to crop residues. Based on the literature and on discussions among the authors of this deliverable, we categorized the measures according to commonalities among them, evaluated the degree of certainty associated to their mitigation potential, the specific conditions under which every measure is expected to be effective, and the positive and negative side-effects in relation to yield, soil organic carbon sequestration, nitrate leaching and ammonia volatilization.

For the meta-analysis, the database built in WP2 to test the effect of crop residue quality parameters on N_2O emissions was extended by incorporating the crop residue management operations of every observation. We used the log response ratio (LnRR) as effect size, which is a common metric in meta-analyses (Hedges et al., 1999; Osenberg et al., 1999). 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 mitigation measures. An overview of the mitigation measures is presented in Table 1.

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

Categorization	Mitigation measure	Reference
Residue physical management	Crop residue removal versus residue in the field	This study; Figure 1
	Residues left on the field surface (e.g., mulching) versus residue incorporation	This study; Figure 2
	Shallow incorporation versus deep incorporation	This study; Figure 3
Residue incorporation timing	Fall incorporation versus spring incorporation	This study; Figure 4
	Crop residue incorporation when the soil is dry versus when the soil is wet, or when rainfall is forecasted	Rochette et al. (2008)
Interactions with fertilization	Residue incorporation followed by fertilizers application versus residue incorporation without fertilizer application	This study; Figure 5
	Residue incorporation followed by synthetic versus organic fertilizer	This study; Figure 6
Additives and crop residue modifications	Biochar	Cayuela et al. (2014)
	Anaerobic digestate	Petersen, (1999); Baral et al. (2017)
	Nitrification inhibitors	Kong et al. (2017)
	Addition of N-Immobilizing materials with high C:N ratio (e.g., green waste compost, cereal straw, sawdust) to crop residues	Agneessens et al. (2014)
Crop type	Choice of crops I: residues with C:N ratio < 30 versus residues with C:N ratio >30	This study; Figure 7
	Choice of crops II: Avoid incorporation of immature crops with high WSC	Meta-analysis of WP2
	Choice of crops III: plant mixtures versus monocultures	Abalos et al. (2020)
Edaphoclimatic conditions	Crop residue incorporation in sandy soils versus incorporation in clay soils	Xia et al. (2019)
	Aridity index < 1 vs > 1	This study; Figure 8

4. Results and discussion

4.1 Residue physical management

4.1.1 Crop residue removal versus residue in the field

We found that crop residue incorporation increases N2O emissions by 44% (Fig. 1). The main reason for the lower emissions with residue removal is that the nutrients present in the crop residues, particularly N and C, are not released to the soil. Positive side-effects: Use of crop residues for e.g., biofuel production and biorefinery, which increase farmers´ revenue and decrease GHG emissions out of the farm. Negative side-effects: Due to nutrient exports out of the field, crop yields may decrease after several years, as well as SOC, and nitrate leaching may increase due to lower soil organic matter content (Xia et al., 2018). Crop residue incorporation into the soil may also soil improve water use efficiency, soil structural stability, soil capacity expansion, as well as reduce soil bulk density.

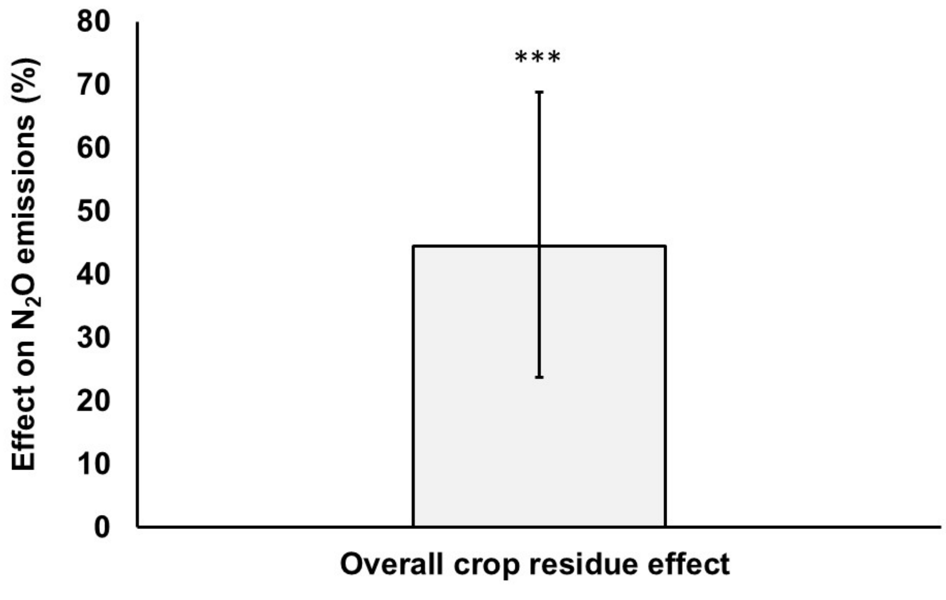

Figure 1: Effect of crop residue incorporation on N_2O emissions.

4.1.2 Residues left on the field surface (e.g., mulching) versus residue incorporation

The decay rate of crop residues placed on the soil surface is slower than when the residues are incorporated into the soil (Chen et al., 2014), which could lead to lower N_2O emissions. However, our results did not confirm this hypothesis, as leaving crop residues in the soil surface did not reduce N_2O emissions compared to incorporation into the soil (Fig. 2). *Negative side-effects*: Due to the slow decomposition of surface-applied plant residues, the net release of N is delayed which may reduce crop yields. Leaving plant residues on the soil surface also creates a cooler and wetter environment than incorporation of plant residues into the soil, which may affect plant growth. *Positive side-effects*: A higher reduction in N leaching and runoff can be achieved by surface crop residue application compared to soil incorporation (Xia et al., 2018). Straw surface application can protect the soil surface against the erosive impacts of rainfall and reduces the formation of surface cracks and crusts (Blanco-Canqui et al., 2006). It may also reduce soil evaporation, of importance in dry climates.

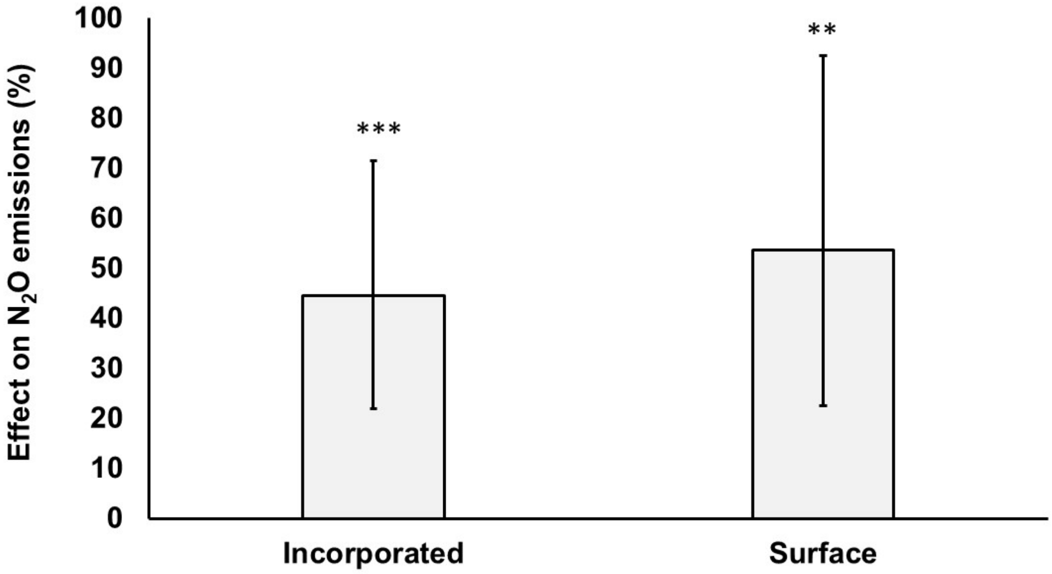

Figure 2: Effect of incorporating or leaving the residues on the soil surface on crop residue incorporation on N_2O emissions.

4.1.3 Shallow incorporation versus deep incorporation

We found a trend for higher N_2O emissions when crops residues are incorporated at depth (> 15 cm) as compared to a more shallow incorporation. This is probably an interactive effect of crop residue placement and the tillage system required for such placement. Six et al. (2004) argued that following long-term adoption of NT/RT (i.e., shallow incorporation), increased soil organic matter content can improve soil structure and therefore decrease the tendency for the formation of anaerobic microsites conducive to N_2O production (Malhi et al., 2006; Ussiri et al., 2009). Additionally, the rate of replenishment of O_2 consumed by soil microorganisms decreases with depth, and therefore crop residue decomposition is more likely to cause O_2 limitation and increase N_2O emissions if crop residues are incorporated by moldboard ploughing as opposed to a more shallow distribution (Petersen et al., 2011). These results were later supported by the meta-analysis of Van Kessel et al. (2013), and seem to be confirmed by our results. *Negative side-effects*: Reduced tillage systems may reduce crop yields and yield stability, require larger use of herbicides, promote stratification of phosphorus and potassium in the soil profile, and may have larger ammonia losses (Spiess et al., 2020). *Positive side-effects*: Reduced tillage may increase SOC concentrations in the upper soils layers, fuel and labour saving, lower costs, preservation of earthworms and other soil fauna, improve water infiltration and soil moisture conservation, prevent soil erosion and improve trafficability (Spiess et al., 2020).

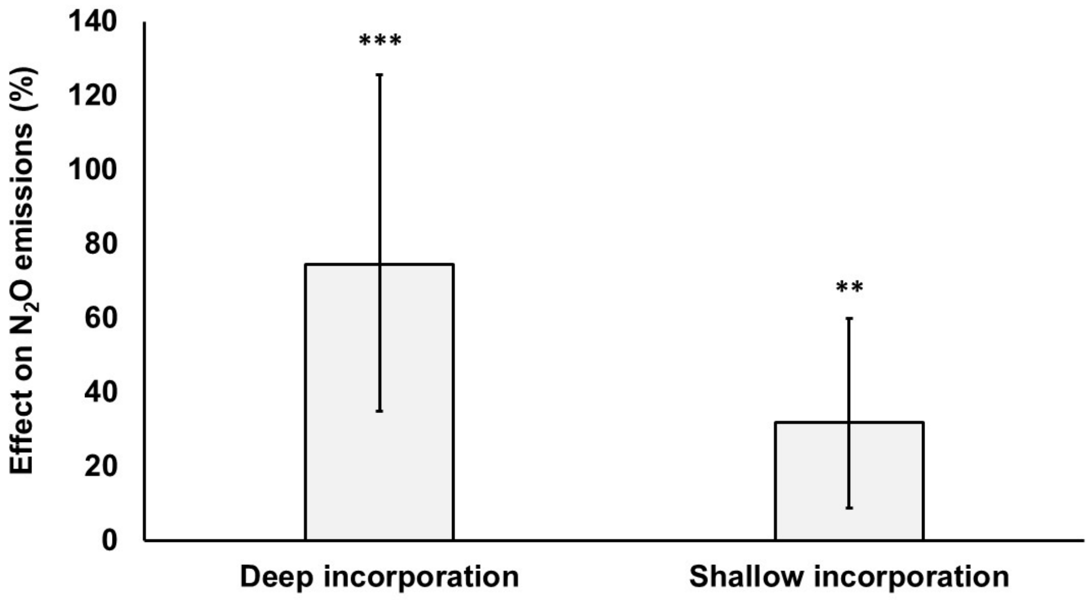

Figure 3: Effect of shallow (0-15 cm) and deep (>15 cm) crop residue incorporation on N_2O emissions.

4.2 Incorporation timing

4.2.1 Fall incorporation versus spring incorporation

The season in which crop residues are incorporated into the soil, does not seem to have a strong effect on the magnitude of N_2O released. It is likely that the specific crop residue quality parameters of the crops that are incorporated in either the fall or spring, which depends on their physiological characteristics and requirements, are more important drivers of the magnitude of N_2O release. *Negative side-effects*: Fall incorporation has been shown to increase N leaching (Hansen and Djurhuus, 1997; Stenberg et al., 1999). *Positive side-effects*: Ploughing in the fall can avoid nitrogen immobilization during the plant growth period, and therefore increase yield.

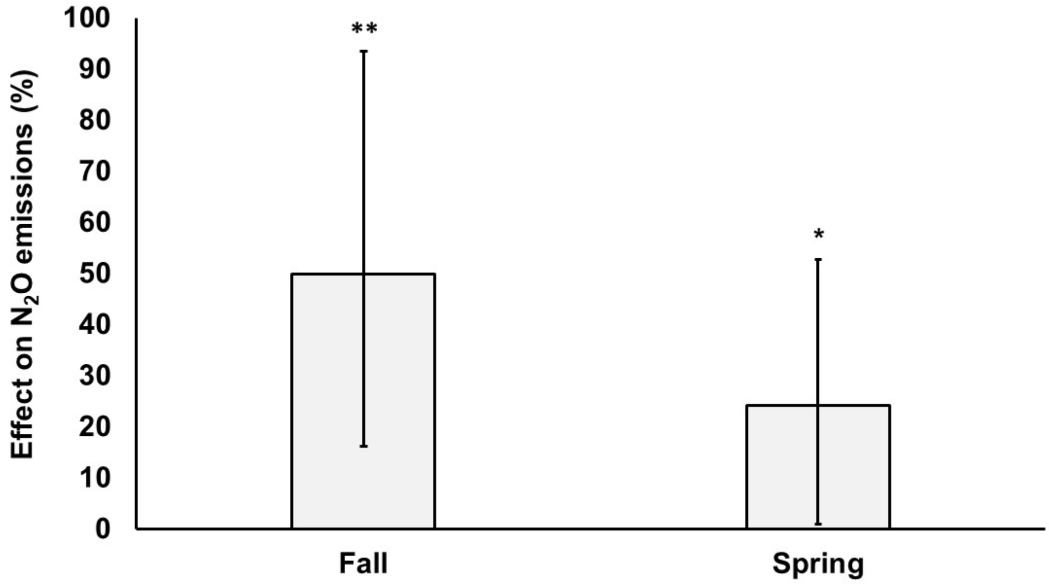

Figure 4: Effect of incorporating crop residues in the fall or spring on N_2O emissions.

4.2.2 Crop residue incorporation when the soil is dry versus when the soil is wet, or when rainfall is forecasted

In principle, incorporating crop residues when the soil is wet due to rainfall or irrigation may increase N_2O emissions. This is because anaerobic conditions in the soil combined with increased C availability from crop residue decomposition may provide suitable conditions for N_2O production by denitrification. However, clear generalizations regarding this effect are not possible, since the outcome in terms of N_2O emissions is likely to depend on interactions between soil moisture and residue incorporation depth. Reviewing pairwise comparisons of N_2O emissions from no-till vs. ploughed systems, Rochette et al. (2008) found that higher soil water content in no-till soils usually results in lower aeration and greater N2O emissions than in tilled soils. In contrast, increases in soil moisture when crop residues are incorporated at depth may reduce O_2 concentration to levels promoting complete denitrification, in turn decreasing N_2O emissions.

Negative side-effects: Crop residue incorporation when the soil is dry may increase NH_3 volatilization from crop residues, although the magnitude of this N loss from crop residues is likely to be of minor importance. Decreased crop residue mineralization due to dry soil conditions may generate a mismatch between residue N release and crop N demand. *Positive side-effects*: Wet soil conditions when crop residues are incorporated may impose difficulties for trafficability and soil operations. It may also affect germination and subsequently, yield.

4.3 Interactions with fertilization

4.3.1 Residue incorporation followed by fertilizer application versus residue incorporation without fertilizer application

We found that N_2O emissions from soil tend to be lower when crop residues are incorporated together with fertilizer (either synthetic, organic, or in combination) (Fig. 5), but this is because N_2O emissions from fertilizer application are reduced, not because direct N_2O emissions from crop residues decrease. The results for "with fertilizer" express the relative emissions of plots with fertilizer and crop residue incorporation relative to plots with fertilizer (but without crop residues), meaning that in this case the increase in N_2O emissions induced by crop residues is lower than that compared to the effect of crop residues relative to plots without crop residues and without fertilizer ("without fertilizer" results). Nitrogen fertilizers are the main source of soil N_2O emissions, and when applied with crop residues (particularly those with a high C:N ratio), part of the available N is immobilized due to the supply of organic C from the residues. Accordingly, the availability of soil mineral N for nitrifiers and denitrifiers is reduced, and in turn the release of N_2O from the soil. *Negative side-effects*: In conventional systems, reduced crop yields and fertilizer N use efficiency due to immobilization of mineral N, when crop residues and fertilizer are applied at the same time. This is particularly important in the short-term. To enhance fertilizer N use efficiency and crop yields by avoiding large amounts of fertilizer N immobilization, N-fertilizer should be applied some time after plant residues are returned (i.e., several weeks or months). Temporary immobilization of fertilizer-N may increase losses via nitrate leaching if N becomes available later in the growing season, when the risk for leaching is higher due to higher rainfall and lower plant N demand. *Positive side-effects*: Adding a complementary source of N (mineral or organic) when crop residues are incorporated into the soil could stimulate straw mineralization increasing N-use efficiency and producing higher yields (Garcia-Ruiz and Baggs, 2007). This is particularly relevant in organic systems and in situations where organic sources of N are the major N inputs.

Figure 5: Effect of incorporating the residues with and without fertilizer application on N_2O emissions.

4.3.2 Residue incorporation followed by synthetic versus organic fertilizer

The increase in N_2O emissions induced by crop residues seems to be higher when incorporated with organic fertilizers than with synthetic N sources (Fig. 6). It is possible that the anaerobic environment created by organic fertilizers due to the addition of organic C and water, leading to further increases in O_2 consumption, may favor denitrification and associated N_2O emissions. *Negative side-effects*: Organic fertilizers provide other nutrients (e.g., P, K) in addition to N, and may increase SOC and yield in poor soils. Use of energy and emissions of GHG during the industrial Haber-Bosch process of N-fixation for synthetic fertilizer production. *Positive side-effects*: The use of synthetic fertilizers with crop residues may lead to higher yield because the exact N amount and availability is easier to estimate, and therefore plant N demand can be more easily satisfied.

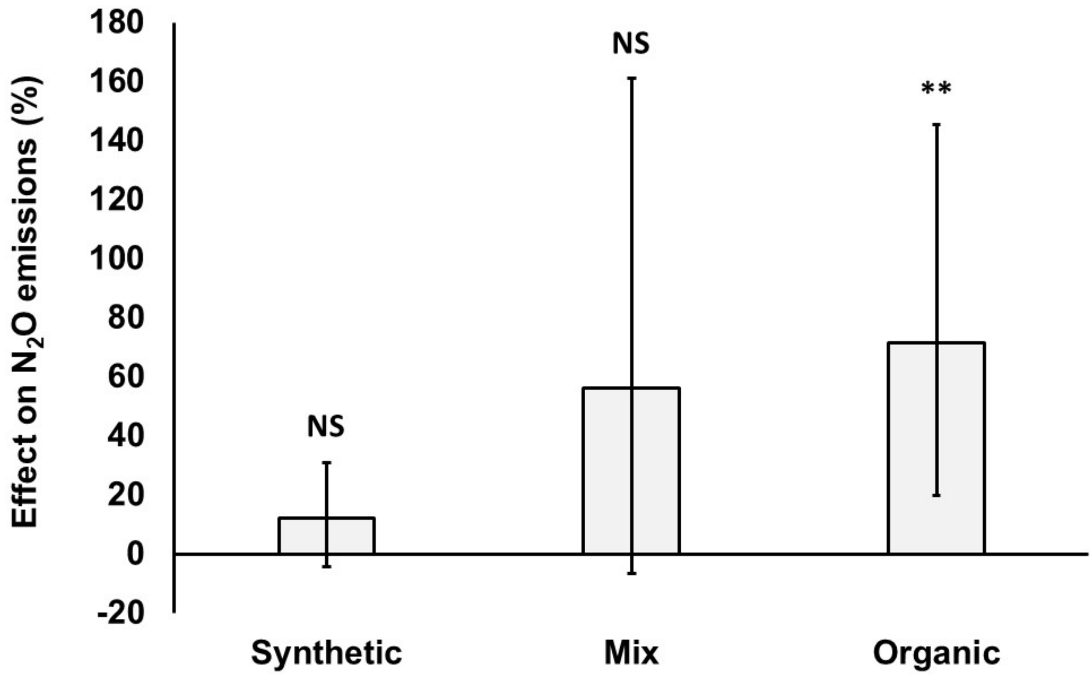

Figure 6: Effect of incorporating crop residues on N_2O emissions as affected by fertilizer type.

4.4 Additives and crop residue modifications

4.4.1 Biochar

A potential strategy to mitigate N_2O emissions from crop residues, is to turn them into biochar, and then apply this material to the field. Biochar is the C-rich product derived from biomass pyrolysis of feedstock such as crop residues. A recent meta-analysis of field studies showed that biochar decreased N_2O emissions across several cropping systems including maize, wheat, rice, vegetables and pasture (Verhoeven et al., 2017). *Negative side-effects*: Increased costs, reduced supply of nutrients and resources for soil macro- and micro-fauna (considering that crop residues are completely removed from the field to be used as feedstock for biochar production). *Positive-side effects*: Increased yield, higher SOC, lower nitrate leaching, improvement in the soil's physical properties, water and nutrient retention, increased cation exchange capacity, changes in nutrient conditions and/or liming in acidic soils (Biederman and Harpole, 2013).

4.4.2 Anaerobic digestates

Crop residues can be digested under anaerobic conditions to produce biogas and digestates as a by-product. Anaerobic digestion lowers labile organic C content, increases ammonium content, and increases the pH value of digested crop residues. This has implications for C and N turnover after field application; by reducing O_2 demand and C availability, the potential for N_2O emissions compared to untreated organic residue may decline, although this effect depends on the type of residue (Petersen, 1999; Baral et al., 2017). The liming effect of a higher pH value can decrease N_2O emissions when applied to acidic soils (Wang et al., 2021).

Negative side effects: Digestate application increases soil C storage and produces benefits over soil quality in the long term, but the potential for C sequestration (per unit of initial residue amount) remains to be clarified, and could be lower when compared with undigested crop residues. *Positive side-effects*: Heat and power generation from anaerobic digestion may partially substitute fossil fuels and thereby reduce radiative forcing from anthropogenic emissions of carbon dioxide (Don et al., 2012). Digestates normally contain a higher proportion of N in mineral form available for plant uptake (De Vries et al., 2012), leading to higher yields.

4.4.3 Nitrification inhibitors

Nitrification inhibitors (NIs) deactivate temporarily the enzyme responsible for the first step of nitrification, the oxidation of NH_4^+ to NO_2^-. This may limit direct N_2O emissions from nitrification, as well as the production of substrates for nitrifier denitrification and denitrification (Ruser and Schulz, 2015). Also, reducing nitrate availability for denitrification could increase the proportion of N_2O being converted to N_2 (Senbayram et al., 2012), and inhibiting O_2 consumption from nitrification activity may improve soil O_2 status. Accordingly, fertilizers applied with nitrification inhibitors often lead to 30-50% N_2O reductions during the initial months following fertilizer application. Spraying crop residues shortly before incorporation also has potential to lead to N_2O reductions, as shown by recent studies (Kong et al., 2017), but further research is needed to confirm these results.

Negative side-effects: Increased costs, potentially higher NH_3 volatilization. *Positive side-effects*: Reductions in N leaching, increases in yield.

4.4.4 Addition of N-Immobilizing materials with high C:N ratio (e.g., green waste compost, cereal straw, sawdust) to crop residues

Co-incorporation of crop residues with other organic material may influence N_2O emissions either through N immobilization in microbial biomass of mineralized residue N or by reducing the residue N mineralization rate (Agneessens et al., 2014). Biochemical characteristics that promote N immobilization or decrease N mineralization include a high C:N ratio, a high lignin content and high polyphenol content. Materials rich in C and low in N stimulate immobilization of soil mineral N through microbial uptake, whereas addition of materials high in lignin or polyphenol content slows down microbial decomposition of crop residues. Polyphenols have a twofold influence on the N mineralization and immobilization process: (1) they possess a strong affinity for amide groups and hence have a strong protein binding capacity (Palm et al., 1991), and (2) they exert a direct toxic effect on soil microbial biomass hence suppressing N mineralization (Capasso et al., 1995). Materials, such as immature compost, straw, paper waste and saw dust, belong to these categories and have been shown to reduce N leaching under controlled conditions (Congreves et al., 2013).

Negative side-effects: Lower crop yield due to N-immobilization; N_2O emissions may increase due to e.g., high soil moisture content. *Positive side-effects*: Decreased leaching due to N-immobilization. Co-addition of organic C, potentially increasing yield and SOC in the long-term in poor soils. Transient increase in CH_4 oxidation (sink) capacity in upland soils (Ho et al., 2015).

4.5 Crop type

4.5.1 Choice of crops I: residues with C:N ratio < 30 versus residues with C:N ratio >30

Crop residues with C:N ratio less than 30 are expected to result in net N mineralization, while those with C:N ratios higher than 30, as is generally the case in cereal straw, cause immobilization (Alexander 1977). Our meta-analysis confirms this threshold, and indicates that these mechanisms explain the differences in N_2O emissions between crop types according to their C:N ratios. Immobilization of soil N may decrease N_2O emissions due to decreased availability of ammonium and nitrate for the processes of nitrification and denitrification (Baggs et al. 2000).

Negative side-effects: All the ones previously discussed regarding increased N immobilization. *Positive side-effects*: Nitrate leaching reduction. Increases in SOC content are greater with crop residues with a C:N ratio larger than 30 compared to a smaller ratio (Xia et al., 2018), although this effect is expected to appear primarily in the short term.

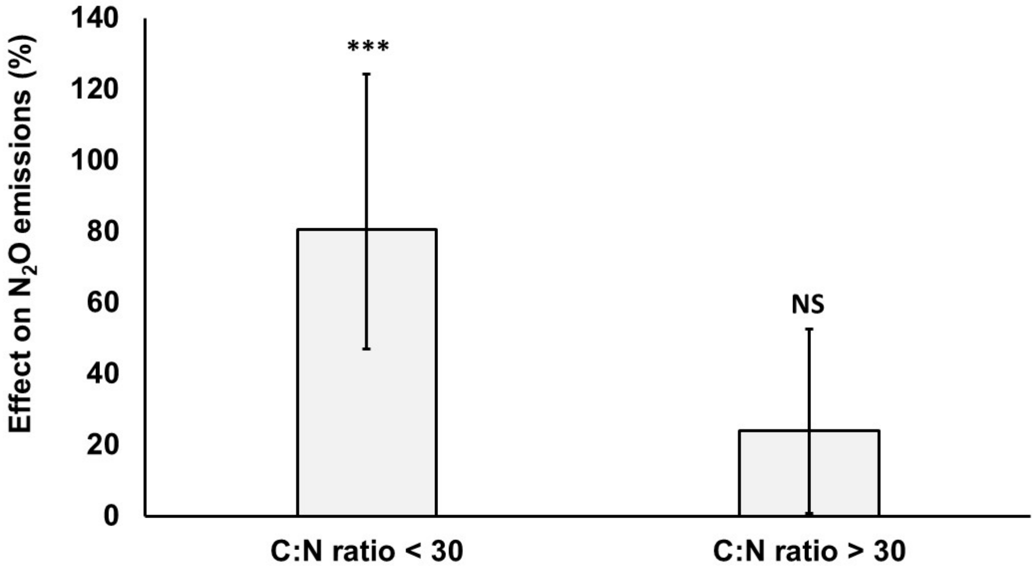

Figure 7: Effect of crop residue C:N ratio on N_2O emissions.

4.5.2 Choice of crops II: Avoid incorporation of immature residues

As revealed in the meta-analysis of WP2, incorporation into the soil of immature crops increases N_2O emissions compared to incorporation of mature crops. Immature residues show a specific overall composition of low C:N ratio (effects explained above), low cellulose content, high water soluble carbon content (providing easily degradable C for denitrifiers), and high N concentration. Immature residues are mainly represented by green plant biomass (cover crops, vegetable residues and grasslands) whereas mature residues are mainly straw. Incorporation of immature crops should be done considering other environmental and management conditions that minimize crop residue-derived N_2O fluxes.

Negative side-effects: To avoid retention of immature residues in the field, the above-ground biomass should be removed. The N taken up by cover crops, which could be subsequently available through mineralization after incorporation, could reduce N fertilizer requirements of the subsequent crop. This is of crucial importance in low input and organic systems.

4.5.3 Choice of crops III: plant mixtures versus monocultures

When crop residues with divergent qualities are mixed there could be interactions during the decomposition processes, resulting in non-additive effects of species mixtures on nutrient release from the residues and therefore on N_2O emissions (Porre et al., 2020). To explain non-additive effects, the nutrient transfer hypothesis is most frequently mentioned. This hypothesis states that decomposers preferentially feed on high N litters. The subsequent release of N could then be transferred to the low N litter and thus facilitate the decomposition of the more recalcitrant fraction of crop residues (Hättenschwiler et al., 2005), causing non-additive mass loss in mixtures by accelerating the decomposition rate of the more recalcitrant residue (Handa et al., 2014). Other mechanisms that could cause non-additive effects are improved water retention due to one of the component residues in a mixture (Wardle et al., 2003), transfer of toxic compounds and/or phenolics between litter components causing non-additive negative effects (Freschet et al., 2012), and enhanced chemical diversity fostering a richer microbial and fungal decomposer community and thus promoting residue decay rates (Hättenschwiler et al., 2005; Otsing et al., 2018). The potential outcomes of these interactions in terms of N_2O emissions require further research.

Negative side-effects: Development of new machinery may be needed; difficulties selecting species according to local climatic and soil variables; adjusting N fertilizer management to multi-species mixtures; negative farmers' perception. *Positive side-effects*: Increased yield. Reduced nitrate leaching and higher SOC are also likely, but require further research.

4.6 Edaphoclimatic conditions

4.6.1 Crop residue incorporation in clay soils versus incorporation in sandy soils

Previous meta-analyses have found a negative relationship between N_2O emissions following crop residue return and soil clay content (Xia et al., 2018; WP2). This may be because increasing clay content decreases soil aeration and oxygen availability, thereby decreasing straw decomposition and associated N release (Skiba and Ball, 2002). Moreover, soils with higher clay content (>40%) are generally characterized by low gas diffusivity, which may enhance N_2O reduction to N_2 through complete denitrification (Weitz et al., 2001). This implies that soils with the lowest potential to sequester C via crop residue incorporation may be the ones with the largest N_2O emissions after crop residue incorporation. Contradicting this, the meta-analysis of Liu et al. (2014) found a negative relationship between SOC increases from crop residue incorporation and soil clay content.
Negative side-effects: Straw return to sandy soils may increase N leaching; conversely, straw return decreases leaching in loamy and clay soils (Xia et al., 2018). *Positive side-effects*: Crop residue incorporation may have stronger positive effects on yield in sandy soils than in loamy and clay-textured soils (Xia et al., 2018).

4.6.2 Aridity index < 1 vs > 1

Recently, IPCC has divided the emission factors of N sources including crop residues according to an aridity index (AI; mean annual precipitation to mean annual potential evapotranspiration; IPCC, 2019). Higher emissions are assigned to crop residues in regions where AI is > 1 (0.6%; Uncertainty range 0.1–1.1%) compared to regions where AI is < 1 (0.5%; Uncertainty range 0.0–1.1%). Our meta-analysis supports this decision, although the differentiation for crop residues may be stronger than that indicated by IPCC, since N_2O emissions from crop residues were 2 times higher for studies conducted under an AI > 1 (Fig. 8).

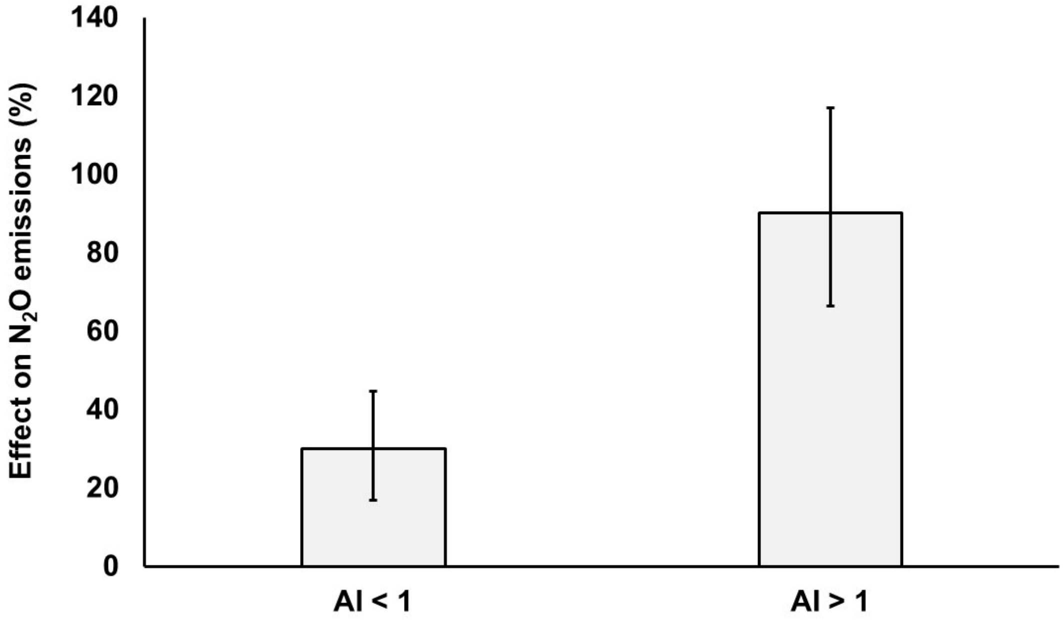

Figure 8: Effect of crop residue incorporation on N_2O emissions as affected by the aridity index (AI; mean annual precipitation to mean annual potential evapotranspiration) defined by IPCC.

5. Conclusions

Building upon a meta-analysis using an extended database from WP2 and expert knowledge, plus information extracted from previous meta-analyses, we assessed the N_2O mitigation potential of several crop residue management strategies. The results show that crop residue removal, shallow incorporation, incorporation of residues with C:N ratio > 30, and avoiding incorporation of immature crops are effective at a general level. However, practices related to crop residue incorporation timing and interactions with fertilizers did not consistently reduce N_2O emissions. This is due to the complex interactions between crop residue management, residue type, and the soil and climatic factors regulating such emissions. Accordingly, an assessment of mitigation measures must specify the conditions under which specific practices may be effective. We propose additional strategies that warrant further research: conversion into biochar or anaerobic digestate and field application, co-application with nitrification inhibitors or N-immobilizing materials, and use of crop mixtures. Potential positive and negative side-effects of the analyzed measures in relation to yield, soil organic carbon sequestration, nitrate leaching and ammonia volatilization are presented in this report. Although the benefits of some mitigation measures clearly outweigh their potential drawbacks, others imply important trade-offs and must be recommended according to specific policy priorities.

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