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1. Summary

Crop residue incorporation is a common practice to increase or restore organic matter in agricultural soils. However, this may increase soil emissions of nitrous oxide (N_2O). ResidueGas addressed the estimation of N_2O emissions from residue amendments, and to what extent these emissions can be offset by increasing in soil organic carbon (SOC) stocks with soil residue incorporation.

The results of ResidueGas illustrate the importance of the large variation in the quality of crop residues and their management on N_2O emissions. The project developed a large database of residue quality representing important aspects for addressing impacts on greenhouse gas (GHG) emissions and soil fertility from application as soil amendments. A meta-analysis of field experiments showed that crop residue effects on N_2O emissions were best predicted by easily degradable fractions and N returned with crop residues. However, due to functional coordination among residue attributes, a simplified index based on the stage of residue maturity provided the most robust approach to classify crop residues according to their potential to regulate N_2O emissions. Thus, immature residues strongly stimulated N_2O emissions, whereas mature residues had marginal effects on N_2O.

These findings were corroborated by new experimental data from laboratory and field experiments. Results showed that N_2O emissions from N in roots were less than half that of N in aboveground residues, which were associated with biochemical characteristics of above- versus belowground residues. The experimental results also showed an interaction of crop residue management with soil mineral N with greater emissions from incorporation of immature residues when soil mineral N was high, in particular when residues were mixed into the soil. The experiments showed that residue removal would be an effective mitigation option for immature crop residues, whereas for mature crop residues effects of management were smaller and inconsistent.

Modelling of crop residue management for cropping systems across Europe under both current and projected future climate shows that long-term effects of residue management on GHG balances is determined by effects on N_2O emissions. Changing rates of addition in residues leads to temporary changes in SOC over 10-15 years; however, effects of changes in residue management on N_2O emissions persist and outweigh possibly effects on SOC stocks. Furthermore, simulations show that residue removal has greater effects on N_2O emissions than the method of its application, i.e. surface application or topsoil incorporation.

An analysis of published studies on crop residue management showed the importance of distinguishing between residue characteristics. A questionnaire survey of farmers in Denmark and Norway showed that retention of crop residues was the most widely used option was to employ management strategies to maintain or improve SOC. Consequently, removal of plant residues was considered negatively for ecosystem services as well as crop production.

ResidueGas has proposed a new concept for quantifying N_2O emissions, where the emission factor is determined by crop residue characteristics, distinguishing mature and immature residue types. The main crop types belonging to immature residue– cover crops, grasslands

and vegetables – are important for the delivery of multiple ecosystem services. Thus, these residues should be managed judiciously to avoid their potentially high N_2O emissions.

2. Introduction

The nitrogen (N) content of crop residues is used in national inventories to estimate nitrous oxide (N_2O) emissions from agriculture. Crop residues also make a major contribution to sustaining or enhancing soil carbon (C) stocks and thus soil fertility. Depending on the amount of C and N in crop 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 production systems.

The current estimations of N_2O emissions from crop residues are associated with some of the highest uncertainties in national GHG inventories, as also illustrated by very large differences in national methods for estimating crop residue N inputs (EEA, 2014). These uncertainties are related to: 1) the amount and N content of the returned residue; 2) the magnitude of N_2O emissions associated with the application of residues to soils; and 3) how this differs with crop species, soils, climate and management. Studies have shown that N_2O emissions following additions of N from incorporated crop residues vary considerably and to a large extent that may depend upon degradability of the residue C source. N_2O emissions following incorporation and the amount of C sequestered from crop residues will also depend greatly on soil and climatic conditions and the method of incorporation. The large uncertainties in methods for estimating N input in crop residues and the N_2O emissions associated with crop residue management not only leads to uncertain and variable national emission estimates, it is also a considerable barrier for identifying, incentivizing and implementing effective mitigation options. ResidueGas therefore aimed to develop a new improved method for inventorying N_2O emissions from crop residues that allow hotspots for such emissions to be identified and suitable mitigation options to be developed, targeted and implemented.

The research objectives were to:

- Propose a new and improved methodology to estimate N_2O emissions from crop residues for the most important cropping systems in Europe, for use in national emissions inventories.
- Assess the relative importance of crop residue management for total N_2O emissions and the soil C and N balance of agricultural systems across different cropping and residue management systems for various soils and for different climates, as a basis for the identification and implementation of mitigation strategies.

The expected results were:

- Documentation of an improved methodology to quantify N_2O emissions from agricultural crop residues management, thus providing a basis to identify targeted measures for reducing these emissions. This includes a standard methodology for estimating the amount of N in residues, improved emission factors for different crop rotation systems in different soils and climates, and identification of the effects of residue quality and management on emissions.
- Quantitative information about crop residue management strategies with respect to their net greenhouse gas effect in terms of N_2O emissions, radiative forcing and soil C storage, which will be used to identify best practices for residue management.

The hypotheses were that:

- Predictions of N_2O emissions from crop residues can be improved by considering the availability of N and the degradability of organic carbon in residues, and how these effects are modified by soil and climatic conditions.
- Suitable mitigation measures for crop residue management need to consider effects on both N_2O emissions and soil C and N storage and that significant emission reduction can be achieved by changes in current residue management at crop and rotation scales.

2.1 Project organisation

The project was organised in seven workpackages with project coordination in WP7, including data management, project dissemination, exploitation and communication. WP7 also oversaw the involvement of stakeholders in project meetings and activities in WP5 (inventories) and WP6 (mitigation). WP1 and WP2 reviewed current knowledge on N and C in crop residues and their contributions to N_2O emissions and SOC stock changes. WP1 developed datasets on crop residue quality and methods for estimating C and N input to soils as basis for improved standards on crop residue quality and quantity for estimating emissions. WP2 used existing datasets to explore which factors (residue, soils, climate, cropping system, residue management) that affect N_2O emissions from crop residues. WP3 and WP4 expanded current knowledge on the effect of residue quality on GHG emissions through experimental studies and modelling. WP3 did this through an experimental program applying both laboratory incubation experiments and field studies. The information from WP1, WP2 and WP3 was feeding into the improvement of simulation models in WP4, and these models were used to develop a simplified residue Decision Support Tool (DST) used for recommending improved inventory methodology in WP5 and identifying and quantifying potential and opportunities for GHG mitigation in WP6. A strong stakeholder interaction throughout the project guided the development on inventory methodology in WP5 (inventory stakeholders) and the identification of mitigation options in WP6 (farming and policy stakeholders).

3. Improved quantification of N and C inputs in crop residues (WP1)

To estimate the amount of crop residues left in the field, the IPCC 2006 guidelines provide data based on international literature reviews. They provide equations for integrating the influence of yield on the amount of residues left in the field, and for calculating the contribution of root biomass of these crops, via a root biomass: aboveground biomass ratio. Most of the references to parameterise these equations come from studies based on references from North America, where yields can be quite different from those observed in Europe. In this context the objective of WP1 was to review these quantitative approaches and in particular to provide updated references for crop residue quality across different European countries and different cropping systems.

3.1 Objectives

The objectives of WP1 were twofold:

- Task 1.1 aimed at updating and synthetizing methods to quantify the residue N inputs. During the course of the project, it was decided to focus on two improvements in the determination of plant residue returns (i) the spatial heterogeneity of the mass and/or amount of N of plant residues, either resulting from the spatial variability of production and yields or crop operations at harvest. (ii) The estimate of belowground plant biomasses (root systems) and their relationships with aboveground production for a large range of crops. While the first question relied on experimental data from partners, the second question relied mostly on available literature.
- Task 1.2 aimed at collecting data and providing a dataset of chemical features of crop residues, firstly N content but also carbon characteristics allowing to improve the assessment of short-term (direct emissions) and medium- to long-term effects (contribution to background emissions) of crop residues recycling.

3.2 Progress and results

3.2.1 Update and synthesis of methods to N and C inputs to soils from crop residues (Task 1.1)

The relevance of the equations to inform the mass and quality of crop residues was discussed throughout the project. The comparison of the proposed default references between the IPCC method and the data of each country was carried out in WP5. It appears that the data differ significantly in terms of yield levels, N fertilization rates and harvesting methods between countries, which modify the ratio residue: yield, the amount of mass exported vs. returned, the average N content values of the residue.

The literature investigation on the allometric relationships between aboveground and belowground biomasses focused on synthesis studies with sufficient data to derive general laws. These recent comprehensive studies do not, however, allow us to free ourselves from the particular situations in which they were conducted in order to propose a modification of the IPCC method. The most notable results are the work of Hu et al. (2018) showing that for example for cereals (wheat and barley) that, across a large range of farming systems and years in Denmark, the fixed root biomass based on the most influential factors (farming system and species) provided the lowest error of prediction for estimation of root biomass, compared with the use of fixed allometric relationships such as root/shoot ratio. This conclusion applied also to catch crops and weed roots. The conclusion that yield-independent values provide closer estimates for belowground carbon inputs to soil of cereals in different farming systems than yield-based functions was also reached by Hirte et al. (2018) in two Swiss long-term field trials comparing different farming systems (bio-organic, conventional) and fertilization treatments (zero, manure, mineral). These results are some of the few in the literature, due to experimental difficulties (and more oriented towards the contribution of root C to soil, than to the plant allometric relationships), and, at present, do not allow to propose an alternative formulation of the equation to estimate the root biomass. However, the recent results argue for a research effort on this issue, and it will also be useful to better characterize root litters from a chemical point of view (nitrogen content and decomposability) in order to potentially adapt the emission factors for this type of litter, if necessary.

The second aspect was the spatial variability of crop residues in/on the soils, associated to harvesting operations and to grain and straw yields, as well as their qualities, which vary across farmer's field. This variability may potentially influence the C-N cycling during the decomposition of crop residues and the emitted N_2O per unit of biomass returned.

A first part of the work was carried out in Denmark and Sweden, with the aim of determining 1) the within-field variability in straw dry matter production of pea (*Pisum sativum* L.), oat (*Avena sativa* L.) and winter wheat (*Triticum aestivum* L.) in farmers' fields, and 2) the relationship between straw and grain DM yields for eventual management of residues to minimize GHG emissions. We used farmer's field in Denmark and Sweden and established grids of 50 plots within fields of 1-10 ha. We found significant variability in straw yields, even within 1 ha fields and a linear relationship between grain and straw yields. This shows that there is a potential for determining parts of the field with high and low straw production based on combiners with yield meters and GPS equipment. This opens the possibility for crop residue management to minimize emissions of CO_2 and N_2O. The variability of straw yields may potentially be considered in models to make more precise estimates of the effects of crop residues on the emission of CO_2 and N_2O.

The second contribution to this question was run in Eastern France, to characterize spatial variability in farmer's field in conservation agriculture, with the measurement of mulch masses of pea, and oilseed rape and mulch thickness for maize crop. It was done by collecting the biomass left using a micro plot approach across several transects perpendicular to the advancement line of the harvester combiner. The estimates showed for example that the mean mass of pea residues at 200 g m^{-2} varied from about 50 to 350 g m^{-2} according to position in the field, and for oilseed rape, the mean 1130 g m^{-2} varied in the range 500 to 1600 g m^{-2}, with a pattern of heterogeneity designed by the axis of advancement of the harvester combiner.

3.2.2 Open dataset of biomass and chemical quality of crop residues from European area (Task 1.2)

The dataset is made up of data collected in 177 documents, including 158 scientific articles, 3 books, 4 PhD theses, 2 Master theses, 7 reports and 3 conference presentations. This literature was published between January 1985 and January 2021. The 158 scientific articles used were published in 44 journals. These works were carried out in 17 European countries. The dataset includes about 2300 individual data records. It is structured in five categories according to the crop type: main crops (24% of occurrences), pasture and forage crops (21% of occurrences), green manure and cover crops (30% of occurrences), vegetable crops (5% of occurrences), and energy crops (21% of occurrences). While field crops are well represented, this is not the case for vegetable crops, for which data are still rare. This work made it possible to generate, for each category of crop type, a raw data file and a mean data file. The raw data provide a diversity of values for each plant species for a given variable. The dataset includes a file, which describes the list of terms and abbreviations used, and a file with references: authors name and year published, journal name and access link.

The literature survey was carried out for the experimental works carried out in the European area, using the following keywords: “crop residue” OR “biomass” OR “areal dry matter” OR “straw” OR “root” OR “root dry matter” OR “main crops” OR “forage crops” OR “meadow” OR “cover crop” OR “catch crop” OR “green manure” OR “legume”, AND “N content” OR/AND “C content” OR/AND “biochemical composition”. Several directions of data retrieval have been pursued, in English and without limit of publication year: query of several search engines: Web of Science, Researchgate, Google Scholar. In addition, we systematically explored the reference list of the relevant articles, which made it possible to find more articles/reviews to which the initial keywords had not been associated. We also contacted the authors to obtain the raw data of their published works. During this collection phase, we collected all elementary data (e.g., biomass, %N, %C, lignin content, etc.) available, even partial, and we calculated values where possible, based on information given in the articles. However, many articles were not retained, because they presented aggregated data and/or modelled plant growth adjustments, without presenting sufficient information on the initial data. The data set is located on the data INRAE repository. https://data.inrae.fr/

3.3 Outcomes and perspectives

We found a significant within-field variability of the pea, oat, winter wheat, maize and oilseed rape straw yields (several tons DM/ha) even in fields of only 1 ha. In the Danish experiment, there was a linear relationship between grain and straw yields of the three crops, indicating a potential for determining part of the field with high and low straw production based on a combiner yield meter and GPS. This opens the possibility for crop residue management to minimize emissions of N_2O. The French experiment also showed a pattern of distribution directly associated to harvesting operations, heterogeneity of distribution, which could be minimized in the future, by adapted post-harvest management. The variability of straw yields and distribution may potentially be considered in models for improving the estimates of crop residues effect on emissions of CO_2 and N_2O.

By collecting information in the literature, we built a data set available regarding crop residue biomass and quality as open source:

- These data are primarily intended for researchers working on the agricultural and environmental impacts of agricultural activities (soil carbon storage, fertilization management, GHG emissions), because the composition of residues left on the soil is one of the factors, along with climate, soil geophysical environment and management (e.g. tillage) that determines the consequences of crop residue management;

- This collection of data made it possible to generate average values by plant species and type of use which should correspond to some stakeholders needs, such as national GHG inventories agencies in the European area, and IPCC experts;
- These data are rarely available to users because they are expensive to acquire, and mostly distributed across a wide range of scientific publications as well as unpublished data sources; this dataset is freely available to all users, through its deposit on the Data INRAE repository (https://doi.org/10.15454/LBI3U7);

This dataset is intended to be updated each year, based on new data published in the literature.

4. Review of factors controlling N_2O emissions (WP2)

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 to calculate N_2O emissions associated with crop residues.

4.1 Objectives

During the project period new results were published redirecting some of the below objectives. Also, due to the intensive cooperation among the WPs, some objectives were addressed in cooperation with other WPs. The main objective was to quantify the magnitude and variability of N_2O emissions associated with the application of crop residues to soils and identify strategies to reduce emissions. Specific objectives were to:

- Quantify the magnitude and variability of direct and indirect N_2O emissions over time associated with the application of different types of crop residues
- Explore and quantify the impact by soil and climatic conditions on N_2O emissions from crop residues
- Explore and quantify the impact by management factors on N_2O emission peaks
- Through statistical analyses identify high-risk and low-risk conditions for N_2O emissions from crop residues

4.2 Progress and results

4.2.1 Database on N_2O emissions from crop residues (Task 2.1)

The database contained 75 studies which originated 346 pairwise comparisons between treatments with return of crop residues and control without addition of crop residues, from 62 sites in 19 countries. All other factors were constant for both treatment and control group, except for the grassland where grassland renewal (treatment) was compared to permanent grassland (control), which is the analogous practice to crop residue incorporation in these systems.

Europe contributed to 43% of the comparisons (n=148). In Europe, 32% of the data were from residues classified as cover crop and 80% as green plant biomass; 60% of the N_2O comparisons were from situations where fertilizer was applied. Regarding climate, 60% of our comparisons comprised dry climate (Aridity Index (AI) < 1) and 40% wet climate (AI >1). The database was first built in the database program Access, and later converted to Excel, to facilitate the dissemination.

4.2.2 Review on N_2O emissions from crop residues (Task 2.2)

We decided to make the review as a meta-analysis. We studied potential drivers of short-term (c. 2 years) direct N_2O emissions from returned crop residues and decided to leave out indirect emissions as data availability was very low. We used the log response ratio (LnRR) as effect size and performed a weighted mixed-effects meta-analysis, using the rma.mv function in the metafor package (Viechtbauer, 2010). Additionally, we used a random-meta-forest approach to identify the most important predictors of crop residue effects on N_2O emissions. We selected and defined factors that encompassed different crop types, residue properties, residue types, soil properties, weather conditions, crop management and methodological approach. Most papers did not have sufficient data on residue properties, so we estimated values with the help of the crop residue quality database in WP1. We observed that the residue properties, which are influenced by crop maturity, had a large impact on the N_2O emissions associated with the crop residues. Based on the stage of physiological maturity of the crop at harvest we classified the crop residues as mature or immature and observed that the impact of immature residues on N_2O emissions were larger than for mature residues. Residue C:N ratio, soil pH, SOC, soil N and Aridity index exerted a lower impact on N_2O emissions associated with crop residues than residue properties, but still significant.

The meta-analysis was done in cooperation with WP6. The objective to explore and quantify the impact by management factors was transferred to the review provided by WP6, but in an initial stage of the meta-analyses we observed that the impact of whether the residue was incorporated or mulched, applied in spring or fall or fertilizer was applied was lower than the impact of residue properties. The results of the meta-analysis have been used in WP5 and WP6 although the database and the meta-analysis is not yet published as the database and the results have been continuously available for them.

4.3 Outcomes and perspectives

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 with the crop residues and increasing share of easily degradable fraction in the residues raised N_2O emissions. Residue N-application and residue properties overcame soil and climatic properties as N_2O predictors. Residue maturity rather than solely amount of residue N returned to soil may be used as a predictor for N_2O emissions from crop residues.

This study provides evidence that returning crop residue 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 individual residue biochemical qualities may 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 N_2O emissions is scarce and dominated by specific types of crop residue, and even more rare are field studies that provide a detailed characterization of residue biochemical quality. By using a residue quality dataset combined with meta-analysis, this study provided new insights on the drivers of N_2O emissions; however, the statistical fit of our models would still likely be improved if measured quality residue data were provided.

5. Experiments on residue quality, management and soil parameters (WP3)

When crop residues are added to soil, there is potential for sequestration of carbon but also for emissions of nitrous oxide (N_2O). The degree to which N_2O emissions offset C sequestration after residue addition to soil is not well known and several factors affect the emissions: residue type, climate, soil type and agricultural management. The IPCC default methodology for GHG accounting uses a single emission factor for all plant residues and for both aboveground and belowground parts, assuming a direct proportionality between N_2O emissions and residue N input. Emissions have, however, shown to be very variable and it is reasonable to expect that differences in residue chemical composition (sometimes referred to as ”quality”) between crops, between different stages of maturity and between belowground and aboveground parts will affect emissions due to differences in mineral N release and provision of C to microorganisms. Management practices such as tillage, N fertilization and removal/redistribution of residues can also influence N_2O emissions by altering the amounts, relative amounts and availabilities of N and C in different parts of the soil. Tillage and removal/redistribution also affect soil oxygen concentrations - directly through their impact on soil structure and distance between residues and soil surface, and indirectly through the consumption of oxygen when residues are decomposed. We performed several laboratory studies and two field studies to build a better understanding of how management, residue properties and soil properties, alone or in interaction, affect N_2O emissions, with the aim of improving inventory methodology and guiding mitigation strategies for Northern European climatic conditions.

5.1 Objectives

The overall objectives of WP3 were to determine the separate and interacting effects of (1) crop residue quality, (2) residue management, (3) soil type, (4) soil moisture and (5) soil temperature/freezing, on N_2O and CO_2 emissions.

5.2 Progress and results

5.2.1 Contributions to the improvement of inventory methodology:

We incubated a wide range of residues, including cover crop, ley, intercrop and root residues, using four different soils under controlled laboratory conditions, to assess the effects of residue chemical composition on N_2O emissions and soil respiration. It was clear from the results that the chemical composition of the residues strongly affects N_2O emission patterns and should not be neglected in inventories. Aboveground residues with C:N ratios above 25, that usually belong to the category of ”mature” residues (straw etc.) could be assumed to induce low N_2O emissions, at least during the first two months. For residues with C:N ratios below 25, often fresh green residues and cover crops, the soluble C content was an important driver for N_2O emissions, which means a high concentration of easily degradable C should be regarded as a risk factor for N_2O emissions. Degradable C is not a commonly measured variable, but crop species and its physiological maturity at the time of incorporation or addition to the soil could be used as a proxy for short-term N_2O emissions, under Northern European climatic conditions - at least at times when fertilizer is not added, as is generally the case in autumn. This could be used for improving accuracy of inventories.

The emissions induced by belowground residues were only studied for grassland species and should be studied further, but the results indicated a very low impact on the total N_2O emission, regardless of the chemical composition of the residues. This suggests that the current inventory methodology may be overestimating the contribution of belowground residues to total N_2O emissions, for grasslands. Based on these low emission factors for ley roots, and the difficulties in estimating the amount of root N and distinguishing background emissions from root emissions, 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.

The laboratory studies showed that N_2O emissions were low at a lower soil water content (40% water filled pore space), while at a high soil water content (60% water filled pore space), emissions were sometimes high or very high. Emission peaks in the field also often coincided with a high soil water content, for example around snowmelt. This agrees with previous studies and may be useful for adapting inventory methodology to local or regional climates or to dry *versus* wet years.

Our field studies added to previous evidence that moderately cold winter conditions with frozen soil at temperatures ~0°C can elicit strong N_2O production, while the laboratory results and the field results from a site with a milder climate showed that short-term freezing events, at times when residues were already partly decomposed, had only negligible effects on N_2O emissions. More work is needed to clearly identify the situations when cold temperatures affect emissions, so that these can be taken into account in inventories.

In the incubation studies, there were marked differences in emissions between soils. The causes of this could not clarified with the experimental setup used, but may be used in future research synthesis.

5.2.2 Contributions to identifying mitigation options

The results of the field studies implied that aboveground sugar beet residues, ley herbage containing red clover, and possibly other "immature" residues, produce higher N_2O emissions at higher residue application rates, which means that removing them from the field, for use as feed, bedding, biofuel or biogas substrate, could 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.

The combination of high soil water content, fertilisation and addition of immature residues strongly enhanced nitrous oxide emissions in the laboratory, which agrees with both theory and previous studies. This suggests that avoiding combinations of residue type, management, soil type and season that produce these conditions is a mitigation option. The incubation experiments provided some evidence that the effect of tillage on N_2O emissions depends on the chemical composition of the residues and the presence of nitrate from fertilization. With nitrate addition and an "immature" residue, a mixed residue distribution (mimicking the effect of a cultivator), produced higher N_2O emissions than a layered distribution (mimicking the effect of ploughing). In contrast, when nitrate was not added, a layered distribution produced higher emissions than a mixed residue distribution, for both a “mature” and an “immature” residue, in one study, while no difference was detected in another study.

With regard to the comparison between leaving residues on the soil surface *versus* incorporating them into the soil, N_2O emission results from the incubation studies were not conclusive. The situation with residues on the soil surface may be more suitable to investigate in the field, since the variations in moisture and temperature at the soil surface, due to constantly changing weather conditions, are virtually impossible to mimic in the laboratory.

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

5.3 Outcomes and perspectives

The results from this experimental work package have brought us several steps closer to being able to give solid advice to farmers on how to adjust residue management to decrease N_2O emissions. The experimental results have also strengthened the conclusion from WP2 that residue type and residue maturity could be used to improve inventories of N_2O emissions associated with crop residues. The improved knowledge regarding possibilities of controlling N_2O emissions through management can be used for inventory purposes further down the line, providing that management choices can be easily documented and their effects in a field situation are further confirmed.

6. Decision support for crop residue management based on biogeochemical models (WP4)

The source strength of agricultural soils for N_2O is significantly dependent on field management. Fertilizer as well as crop residue management are important factors affecting soil processes and associated N_2O emissions. Thus, reducing the input of N to soil can effectively mitigate direct emissions of N_2O from agroecosystems. Crop residues, which represent a substantial input source of C and N to soils, can potentially increase C sequestration and fostering N_2O emissions. Consequently, knowing the effect of crop residue on N_2O emission represents a fundamental aspect to derive residue management strategies. Soil incorporation of crop residues with low C:N ratios have been found to promote both N_2O emissions and heterotrophic respiration, while some studies report no effect when the residues are left on the soil surface, which can, most likely, be attributed to slower decomposition rates of the residues. Generally, decomposition and mineralisation of residues increase with increasing contact area between residues and soil, and therefore faster decomposition of residues may be expected if residues are incorporated (ploughed) into the soil, compared to scenarios with residues left on the soil surface (i.e. minimum tillage). However, conflicting results have been reported, most likely due to differences in climate and properties of soils (e.g. pH, texture, SOC) and residues between studies, i.e. factors which do significantly affect soil environmental conditions (moisture, O_2 availability, temperature) and, thus, key microbial processes, specifically nitrification and denitrification, involved in N_2O formation, consumption and emission.

The use of simulation models able to simulate the effects of the agricultural practices on the biogeochemical cycles represents a valuable method to investigate the processes associated with N_2O emissions. The simulation of the soil-plant-atmosphere continuum assures a comprehensive assessment of this phenomenon. In fact, modelling allows to perceive the complex relations between soil physical, chemical and biological processes behind gaseous exchanges. Moreover, process modelling represents the arguably most reliable way how to scale site results to the EU scale and to explore by scenarios studies the interaction between climatic, edaphic and crop factors and field management on soil N_2O emissions and soil C stock changes. Given that the use of such models is rather complicated and, thus, not accessible for end users such as farmers and advisors, more simple decision support tools need to be developed, which may be based on results obtained by complex models.

6.1 Objectives

WP4 aimed at improving two well-established biogeochemical models, LandscapeDNDC (KIT) and CERES-EGC (INRA), to assess residue management effects on the GHG balance of agricultural systems from site to EU scale and for different scenarios of residue management. Furthermore, results of the modeling exercise should be summarized in a cost effective tool to support end-users to obtain simple approximate estimates of soil N_2O emissions and SOC changes as affected by residue management.

Specific objectives were to:

- Assess and improve the capability of LandscapeDNDC and CERES-EGC for simulating residue quality and management effects on net GHG emissions, thereby also using data as generated within ResidueGas;
- Simulate effects of different residues management strategies under typical North European cropping systems, soil types and climatic conditions for current and future conditions;
- Use simulation data for developing a fully functional Decision Support System (DST), which allows end users to assess residue management on the field scale GHG balance, here represented by effects on soil N_2O emissions and soil C stock changes.

6.2 Progress and results

All objectives of WP4 have been met. For site scale model application we found that simulated crop yields, as well as the N content of the residues were in a good agreement with the measurements. Modelled cumulative N_2O emissions over the measurement period were mostly within the confidence intervals of the measurements, and showed a good agreement for most sites over the measurement period. Effects of crop residue management on soil C stocks could be not assessed as relevant field observations are missing. However, the reliability of ecosystem C flux simulations by the models used within ResidueGas has been shown in earlier studies.

Simulation of residue effects at EU scale showed that the incorporation of crop residues into the soil has the potential to increase soil carbon content within the first 20 to 30 years after the alteration of the management from the baseline, even up to 1% of baseline SOC per year. These results support international initiatives such as the ‘4 per 1000’ that are promoting enhanced carbon sequestration in agricultural soils as a way to mitigate agricultural greenhouse gas emissions. However, our modelling results also show that increasing soil residue incorporation to a maximum rate will enhance soil N_2O emissions, counterbalancing the positive effect of soil carbon sequestration. Furthermore, it should be noted that the ’4 per 1000’ strategy will only be applicable if soil tillage is reduced and N fertilization amounts adapted to crop demand, i.e. if farmers are considering increased N availability due to SOM mineralisation.

To allow end users to assess the impact of residues management on soil carbon dynamics and nitrous oxide (N_2O) emissions from arable soils a web-based decision support tool was developed. For this, we used outputs of the complex models to identify on basis of a random forest machine learning approach the main drivers of changes in soil organic carbon dynamics and soil N_2O emissions in response to residue management.

6.3 Outcomes and perspectives

The process models used within ResidueGas have been further revised, improved and tested for their capability to simulate residue effects on soil C stocks and soil N_2O emissions. We developed a harmonized EU wide database on crop and field management. Both, the improved models as well as the harmonized database are extremely helpful for future studies targeting e.g. best management practices to reduce the climate footprint of crop production in Europe. The developed decision support system will be further updated and possibly extended in its functionality to allow end users, e.g. farmers and advisors, to retrieve tangible information on best management practice advice for residue management.

7. Recommendations for improved inventories (WP5)

The IPCC methodology provides a very crude estimate of N_2O emissions from crop residues in conventional arable based systems. Field experiments have shown that crops residues with a high N concentration (> 2% N) pose the greatest risk. Field and laboratory experiments in WP2 and WP3 have shown that N_2O emissions from crop residues are driven by residue quality characteristics such as total N and available C, and therefore correct estimation of this contribution in inventory reporting is essential. This calls for a new method to account for N_2O emissions from residues that better reflect residue amounts and qualities, and possibly how they are managed and on which soils. Crop residues also add N to the soil which depending on biochemical quality and C:N ratio adds to the long-term soil organic matter and N, and which is mineralized over longer time spans thus contributing to background N_2O emissions. IPCC (2006) states that 'background' emissions "are not 'natural' emissions but are mostly due to contributions of N from crop residue". Therefore, any changes to residue accounting methodology should consider implications for the accounting of 'background' emissions and consider the impact that they may have in affecting emission factors (EFs) measured for other N sources (synthetic N fertilisers and manures). Also, the possible double-counting of N_2O emissions from both background emissions and from crop residues should be considered.

Estimates of the magnitude of background emissions have been derived from experiments in which N_2O emissions have been measured in the absence of N additions. Extensive reviews of relevant literature have demonstrated the magnitude of these emissions is around 1.1 kg N_2O-N ha^{-1} y^{-1}. However, few studies have characterised the factors determining variation in these emissions and how they vary with annual changes in weather conditions, soils and land-use.

7.1 Objectives

The overarching objectives were to provide a new analysis and synthesis of data collected within the project to improve estimates of GHG emissions from crop residues reported in national inventories. Specific objectives were:

- To improve our understanding of the factors controlling background emissions of N_2O
- To develop using activity data and modelling from WPs 1-4 an improved methodology for calculating emissions of N_2O from crop residues
- To share with stakeholders improved methodologies for the estimation of emissions and the application of this methodology in different parts of Europe.

7.2 Progress and results

The core results from ResidueGas reflected in studies undertaken in WPs 1-4 were used to develop new recommendations for reporting N_2O emissions from crop residues. A workshop with inventory compilers from the European countries represented in ResidueGas was hosted in the spring of 2021. This formed the bases for a research paper on possible changes in inventory methodology for crop residues.

Background emissions of nitrous oxide from UK soils contributed to a mean flux of 0.75 kg N ha^{-1} yr^{-1}. To place this in context, if a soil received a fertiliser application of 150 N ha^{-1} yr^{-1} the nitrous oxide emission associated with application would be 1.5 kg N ha^{-1} yr^{-1} using default IPCC emission factors. In some circumstances measured background emissions from UK soils exceeded 2.5 kg N ha^{-1} yr^{-1} and therefore understanding the factors that contribute to this variability in emissions are important not only from the perspective of GHG accounting, but also in terms of mitigation. Our analysis has shown that no single factor could explain the variability in background emissions, but that these were influenced by climate and soil properties. The range of background emissions observed in UK studies is broadly in range with that reported in the international literature, and reflects the impacts of multiple variables in controlling N_2O emission sources.

7.3 Outcomes and perspectives

Following completion of the published outputs from this WP it is anticipated that the work will in future years contribute to improved reporting of GHG emissions from crop residues in national inventories. We have already been in contact with the Global Research Alliance on agricultural greenhouse gas emissions regarding publicity around the work that we have been doing on inventory improvement. They have agreed that after the completion of this work they will support promotion of our activities to the wider research community.

8. Implications for GHG mitigation (WP6)

Crop residue incorporation into agricultural soils has been posited as a tool to simultaneously tackle both reductions in GHG emissions and supporting soil fertility. 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 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.

8.1 Objectives

The objective is to identify and quantify mitigation measures that can reduce nitrous oxide emissions crop residues in North European cropping systems while also contributing to storing soil carbon. Specific objectives were:

- To identify components of cropping systems where there is a considerable potential for reducing nitrous oxide emissions
- To identify mitigation measures and quantify their effectiveness for net GHG emissions reductions (nitrous oxide and SOC storage) at field scale
- With stakeholders to assess the feasibility and scalability if selected mitigation measures and thus the potential for reducing net GHG emissions from cropping systems

8.2 Progress and results

8.2.1 Effectiveness of mitigation measures

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.

8.2.2 Feasibility and scalability of mitigation measures

The feasibility of alternative strategies for the management of crop residues, as assessed through a structured questionnaire that was addressed to farmers in Northern European countries. In Denmark, the survey was distributed via email to 5154 representative farmers, of which 592 completed it. In Norway, the survey was mainly distributed via social media and 45 completed responses were collected. The questions included background information on farming system and values (e.g., perceptions about sustainability), current management of crop residues and acceptability of alternative management options (including obstacles and incentives).

The importance of sustainable farming was acknowledged by the large majority of respondents. Aspects related to soil fertility had a high level of agreement, while emissions of greenhouse gases was one of the aspects with the lowest priority, especially in connection with management decisions. Overall, the majority of respondents in both countries employ management strategies to maintain or improve soil orgaic matter; retention of plant residues was the most widely used option (74%). Consequently, removal of plant residues was considered negatively in connection with ecosystem services as well as crop production. On the other hand, retention of residues on the field surface or incorporation (shallow and deep) were perceived as management options with positive effects. The main barrier to the adoption of alternative methods of residue management for the mitigation of nitrous oxide emission was "Lack of knowledge about which option is most effective", including the use of nitrification inhibitors. The main solutions were "Indicators and tools for farmers to measure progress in reducing farm emissions" and the strengthening of farm advisory services (knowledge and advice) and financial support.

8.3 Outcomes and perspectives

The results show that crop residue removal, 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. In addition, we propose strategies that warrant further research: conversion into biochar or use of anaerobic digestion before field application, co-application with nitrification inhibitors or N-immobilizing materials, and use of crop mixtures. 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. A questionnaire survey of farmers in Denmark and Norway showed that retention of crop residues was the most widely used option was to employ management strategies to maintain or improve SOC. Consequently, removal of plant residues was considered negatively for ecosystem services as well as crop production. There are therefore potential large barriers among farmers for adopting effective measures to reduce GHG emissions.

9. Project coordination, data management and communication (WP7)

This research in ResidueGas aimed to provide a step change in our ability to report and subsequently control GHG emissions from crop residues. Despite their importance as an emissions source crop residues have some of the highest levels of uncertainty of any term in National Emissions inventory. The coordinated programme in ResidueGas of experimentation, data mining and modelling will provide new understanding of the processes generating emissions and allow better reporting and mitigation.

9.1 Objectives

The objective was to ensure efficient coordination of the project activities, including the organisation and sharing of data and communication of project results as well as involvement of stakeholders.

9.2 Progress and results

Several meetings within the project group were organized in order to facilitate cooperation:

- Kick-off meeting, Foulum (DK), 27-28 November 2017
- Mid-term meeting, Edinburgh (UK), 12-14 March 2019
- End-term meeting, Reims (FR), 2-4 March 2020
- Finalizing meeting, webinar, 10+12 November 2020
- End-of-project meeting, webinar, 11 March 2021

ResidueGas considered four primary impacts that the workplan is designed to deliver through research outputs and action in close communication with stakeholders (Fig. 1): 1) Reduced uncertainty of inventories of N_2O from residues, 2) Incorporation of mitigation of N_2O from residues in inventories, 3) Quantified mitigation potential for crop residue management, and 4) Barriers identified for mitigation through crop residue management. These impacts were achieved through five major actions as outlined below.

9.2.1 Present results for policy and inventory advisory groups

Results have been presented to policy makers through communication via the Global Research Alliance on Agricultural Greenhouse Gases (GRA) and through a stakeholder webinar with participation of policy makers and regulatory authorities (see 9.2.4). In addition, a policy brief has been drafted, which will be communicated via the project website, project partners and GRA.

Inventory compilers were invited to the ResidueGas kickoff meeting outlining the challenges for inventory compilers. A special GHG inventory workshop organized in UK in March 2018, and finally GHG inventory stakeholder webinar on improved accounting of N_2O from crop residues, 4 May 2021.

9.2.2 Present results for the research community

The ResidueGas project and results from the project have been presented at several conferences, seminars and workshops.

9.2.3 Prepare papers for peer-reviewed publication

A large number of scientific papers have been submitted to and published in scientific journals with peer review. In addition, ResidueGas has agreed with Elsevier to a special issue on crop residues of Science of the Total Environment. This issue will be published early 2022.

9.2.4 Organise final conference for science, inventory and policy

A final conference of the project was organised as a webinar on 3 May 2021 with participation of 207 stakeholders. The webinar showed that farmers primarily see residues from a soil fertility perspective, which does not necessarily align with low GHG emissions. The presentations from the webinar are available at the project website.

9.2.5 Prepare articles and fact sheets for the agricultural community

Fact sheets on GHG emissions from crop residues and how these may be managed have been drafted, and these will be translated to the languages of the participating countries and used for communication through the partner outlet channels.

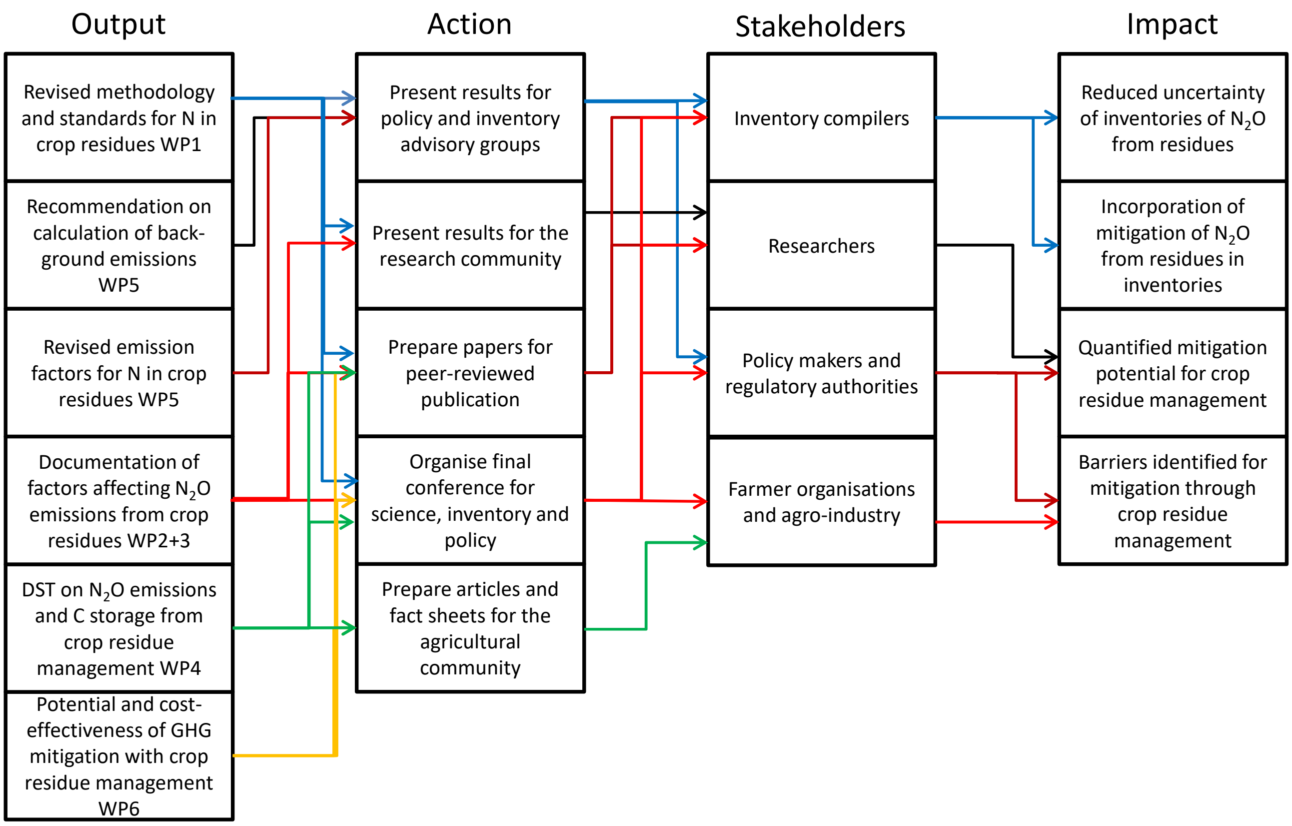

Figure 1: Overview of project outputs and actions on communication and stakeholder interactions leads to the anticipated impacts.

9.3 Outcomes and perspectives

There has been considerable interest by inventory compilers in producing more accurate accounting, and the methods suggested by ResidueGas may well fulfil this, but it will require considerable effort within the inventory community to have this implemented. A new method for accounting for nitrous oxide emissions from crop residues will be necessary for implementing effective measures for mitigating nitrous oxide emissions from crop residues.

10. Conclusions

ResidueGas has successfully reached the key objectives. This included the following aspects that would have not been possible without the intense collaboration among project partners: 1) We achieved to develop the scientific basis for a new method for quantifying N_2O emissions from crop residues and assessed its value for mitigation efforts, and 2) we were able to compare parameterization and simulation results of two process oriented models on site and EU scale.

The following key practical finding were made:

- Long-term GHG emissions associated with crop residues is determined by N_2O emissions, not soil carbon storage.
- Immature crop residues are more important for N_2O emissions than mature residues, and soil incorporation of immature residues in situation with high soil mineral N should be avoided.
- Roots contribute less to N_2O emissions than aboveground immature residues.
- Farmers are currently reluctant to effectively manage N_2O emissions from immature residues, in particular through residue removal.
- A simple decision support tool which allows to estimate the effects of residue management for changes in soil C stocks and N_2O emissions

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13.3 Popular science articles

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Recous, S. Quels rôles ont les paillis végétaux de surface sur les cycles du carbone et de l'azote dans les sols. Association française d'étude des sols (AFES) Webinar https://vimeo.com/385417679) 16 January 2020
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13.4 Datasets

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