ResidueGas DELIVERABLE NO. 4.1

Testing the performance of CERES-EGC and LandscapeDNDC to simulate effects of residue management on soil N_2O emissions

March 2021

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This report is a publicly accessible deliverable of the ResidueGas project. The present work has been carried out within the project ‘Improved estimation and mitigation of nitrous oxide emissions and soil carbon storage from crop residues’, which is funded in the frame of the ERA-NET FACCE ERA-GAS. FACCE ERA-GAS has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 696356.

Haas, E., Carozzi, M., Massad, R.S,, Scheer, C., Butterbach-Bahl, K., 2021. Testing the performance of CERES-EGC and LandscapeDNDC to simulate effects of residue management on soil N_2O emissions. ResidueGas deliverable report 4.1, April 2021

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1. Summary

Ecosystem modelling represents a suitable approach to reproduce effects of agricultural practices on carbon (C) and nitrogen (N) biogeochemical cycles in the soil, plant and atmosphere continuum. This kind of process models allow to perceive the complex relations which regulates the processes associated with GHG emissions, e.g. the greenhouse gas nitrous oxide (N_2O). This activity aims to evaluate and improve process-based models to reproduce effects of residue incorporation in agricultural soils onm soil N_2O emissions. For testing the models (CERES-EGC and LandscapeDNDC) we used data obtained in 52 field experiments lasting 6 up to 12 months each. Data were provided from five experimental sites in northern Europe: Gleadthorpe (UK), Terrington (UK), Ås (NW), Lönnstrop (SW), Foulum (DK). Most of the experiments assessed incorporation *vs* removal of residues from croplands, exploring different managements and pedoclimatic conditions. Two process-based biogeochemical models, CERES-EGC and Landscape-DNDC were parameterised and calibrated to reproduce the field conditions for each experiment.

Simulated crop yields, as well as the N content of the resides were in a good agreement with the measurements (RMSE = 2.26 t DM ha^{-1} and 21.6 kg N ha^{-1}, respectively). The simulation of soil mineral N dynamics (NH_4 and NO_3) showed only a weak correlation for some experiments, due to limited data availability for soil parameterization, whereas soil water content (SWC) showed a general good agreement (R^2 up to 0.84). Both models were able to represent the dynamics of N_2O emissions over time at most of the experimental sites, as well as effects of different types of residue management ion soil N_2O emissions. 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 (RMSE = ranging from 0.3 to 3.3 kg N ha^{-1}). This study highlights that process-based biogeochemical models, (CERES-EGC and Landscape-DNDC) can be used to simulate the effect of residue management on crop yields and greenhouse gas emissions from a range of agro-ecosystems across Europe. However, longer and more detailed data series are needed for model calibration and testing. Such datasets would help to further assess the capability of the models to represent effects of agricultural management on soil N_2O emissions.

2. Introduction

Nitrous oxide (N_2O) is one of the most important greenhouse gases (GHGs), and it represents a quarter of the total greenhouse gases (CO_2eq) emitted by agriculture in EU-27 (FAOSTAT, 2021). The main sources are related to the application and the use of manure (43%) and synthetic fertilisers (36%), while N_2O emissions from management of crop residues contribute about 10% to total agricultural GHG emissions by European agriculture.

The source strength of agricultural soils for N_2O depends significantly on field management. Fertilizer as well as crop residue management are important factors affecting soil processes and associated N_2O emissions. E.g. reducing the input of nitrogen to soil can effectively mitigate direct emissions of N_2O from agroecosystems (Baggs et al., 2000). Crop residues, which represent a substantial input source of carbon and nitrogen to soils, can potentially increase carbon sequestration and fostering N_2O emissions (Rees et al., 2013). Consequently, knowing the effect of crop residue on N_2O emissions 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 (e.g., Huang et al., 2004), 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 (Muhammad et al., 2019). 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 (Pisante et al., 2015), most likely due to differences in climate and properties of soils (e.g. pH, texture, SOC) and residues between studies, i.e. factors which 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 (Hénault et al., 2012).

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.

Here we report on the ResidueGAS activity in which we used two state-of-the art biogeochemical process models and tested their suitability to simulate effects of crop residue management on soil N_2O fluxes. The field experiments were carried out at five sites in northern Europe. Moreover, this activity reports on simulation results testing the mitigating effect of different residue management strategies on soil N_2O emissions.

3. Materials and methods

3.1 Experimental sites

Data were provided from five experimental sites in northern Europe: Gleadthorpe (UK), Terrington (UK), Ås (NW), Lönnstrop (SW), and Foulum (DK). The characteristics of the sites are reported in Table 1.

Table 1. Name, length of measuring period and characteristics of sites used for model testing.

Site name	Experiment period	Temperature[a]	Precipitation[a]	Soil type[b]	Soil pH[b]	Bulk density[b]	SOC[b]	Fertilizer Amount[c]	Crop type
		°C	mm			t/m3	%	kgN/ha	
Ås	Sep 2018 - May 2019	6.4	875	Clay loam	5.57	1.18	2.88		Red clover
									Grass
									Fallow
Foulum	Sep 2012 - Sep 2013	9.3	961	Loamy sand	6.4	1.38	1.8	146 (CS)	Barley + clover
								146 (CS)	Barley + winter vetch
								146 (CS)	Barley + fodder radish
								146 (CS)	Barley + fallow
Gleadtorphe	Nov 2011 - Nov 2012	9.5	650	Sandy loam	6.1	1.23	1.61		Combinable Peas
									Peas vining
									Spring beans
								120 (AN)	Spring oils. rape +N
								120 (AN)	Sugar Beet +N
									Winter Beans
								160 (AN)	Winter Wheat +N
									Winter Wheat 0N
Lönnstrop	Oct 2018 - May 2019	9.2	535	Sandy loam	6.5	1.45	1.5		Sugar Beet
									Winter Wheat
Terrington	Sep 2012 - Nov 2013	10.1	667	Loam	8.1	1.22	1.8		Combinable Peas
									Peas vining
									Spring beans
								190 (AN)	Spring oils. rape +N
								120 (AN)	Sugar Beet +N
									Winter Beans

The Gleadtorphe and Terrington experimental sites have been subjected to the same treatments, i.e. testing incorporation *vs* removal of residues obtained from 7 crops, which resulted in 8 treatments, which were arranged in a split-plot design. At the Lönnstrop experimental site the removal *vs* incorporation of different amounts of residues (farmers practice and double amount of farmers practice) was tested. Residues originated from sugar beet and winter wheat. In a factorial experiment at the Foulom site effects of incorporation *vs* removal of residues was tested too. Residues here were derived from barley and treatments also included plots undersown with clover, barley and winter vetch, barley and fodder radish and a fallow treatment. At all sites, emissions of N_2O were measured discontinuously in weekly to monthly time steps, partly only during the cropping season (Gleadtorphe, 35 measurement days in 12 months; Terrington, 36 measurement days in 14 months; Foulum, 28 measerement days in 12 months; Lönnstrop, 39 measurement days in 6 months; Ås, 45 measurement days in 9 months).

Data regarding soil characteristics, meteorological conditions and management were directly provided by the site managers. Measurements of crop yield and N_2O were provided for all the sites. For most of the sites also information on soil moisture and soil mineral N dynamics and N content of residues were available.

3.2 Models overview

Simulations were performed by using two process-based biogeochemical models, CERES-EGC and LandscapeDNDC. The models were compared directly on one site, Lönnstorp, then applied to uniquely simulate the other sites. CERES-EGC was used to simulate Glentorphe, Terrington and Foulom, while LandscapeDNDC was used to simulate Ås.

CERES-EGC (Crop Environment REsource Synthesis - Environnement et Grandes Cultures; Gabrielle et al., 2005) is able to simulate the cycles of C, N and water for agricultural fields. The model simulates biogeochemical processes in soil, plant and atmosphere at daily time step at field scale. Regional simulations can be done by linking the model to a GIS database holding all relevant spatio-temporal information needed to initialize and drive the model. Inputs require meteorological and management data as forcing variables and soil and crop information as factors. Meteorological data are constituted by daily minimum and maximum temperature, precipitation, global solar radiation and wind speed. Management includes crop type and cultivar, date and type of tillage, irrigation volumes, N fertilisation amount, placement and type, information regarding crop sowing and crop residues management and placement. Soil is divided in sub-layers with specific physical and chemical characteristics.

LandscapeDNDC (Haas et al., 2013) is able to simulate C, N and water cycling within different ecosystems (arable, grassland and forest). This model has been applied for site and regional scale in various studies. LandscapeDNDC is composed by different modules integrating microclimate, water cycle, soil-biogeochemistry, plant physiological processes and growth by daily time step. Initialization of the model is based on site and soil information as latitude, physicochemical characteristics of soil profile (i.e., depth, humus type, clay content, organic C- and N-content, bulk density, saturated conductivity, gravel, pH, hydraulic parameters) as well as daily weather data (minimum and maximum air temperature, precipitation, global solar radiation, atmospheric CO_2 concentration). LandscapeDNDC is parameterised with crop type and management information i.e., crop species, tillage type, date of sowing and harvest, irrigation volumes and schedule, N fertilisation amount, type and placement, crop residue management and placement.

Both models simulate soil C and N dynamics in the ploughed layer, including the microbial N_2O source processes nitrification and denitrification as well as other N cycle processes such as immobilisation and mineralisation of N and the decomposition of soil organic matter (SOM). After simulated residue application, crop residues C and N fractions will be assigned to different C and N pools, which differ with regard to C to N ratios, principal chemical composition (e.g. lignin versus sugars) and rates of decomposition. Production (and in the case of denitrification also consumption) of microbial N_2O are calculated as potential rates in dependence of soil properties (e.g. texture, pH, SOC) and reduced by soil environmental factors such as soil water content, temperature and inorganic N availability. The performance of the models was evaluated using the coefficient of determination for linear models (R^2), modelling efficiency (Nash–Sutcliffe index, E), and root mean square error (RMSE). Values of E range between 1.0 (perfect fit) and $-\infty$, where a $E<0$ indicates that the mean value of the observed values would have been a better predictor than the model. RMSE represents the standard deviation of the residuals (prediction errors). Equations are reported by Bellocchi et al. (2002).

4. Results and discussion

4.1 Plant production

Models have been parameterised to allow the simulation of specific crop rotations and seasonal biomass production. As yields very much depend on used cultivars, crop growth parameters were partly adapted, so that realistic residue amounts, matching the quantities provided by the sites' managers, were simulated, and finally applied to soils. Fig. 1 shows reported versus simulated crop yields for various sites; for Ås no data on crop yields was available.

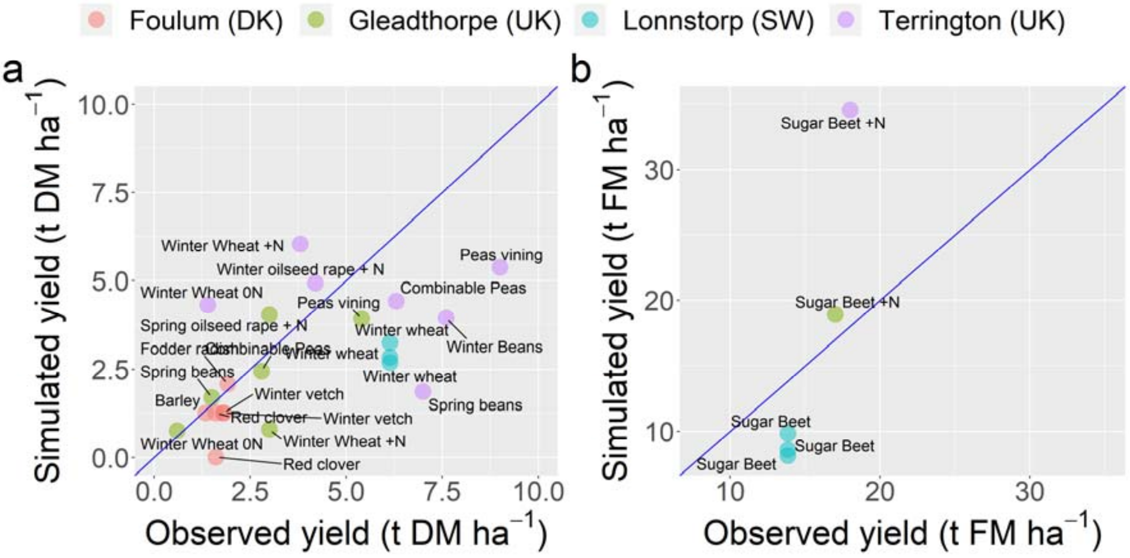


__Fig. 1.__ Reported versus simulated crop yields for various sites of ResidueGAS project (color coding), a) comparison of dry matter yields (DM), b) comparison of fresh matter yields (FM). The continuous line represents the 1:1 line.

The comparison between the simulated and measured yields showed some significant differences, which are likely due to uncertain parameterization of crop growth parameters. However, as information on many parameters was missing, a rather general parameterization scheme had to be used. Modelling efficiency was E=0.31, RMSE= 2.26 t DM ha^{-1} for crop yields reported as dry matter, and RMSE = 8.42 t FM ha^{-1} for crop yields reported as fresh matter. The coefficient of determination for the entire dataset was R^2=0.65. Generally, the models slightly underestimated yields, which as well introduces a source of uncertainty regarding the amount of residues being finally assumed for model simulations.

4.2 Soil mineral nitrogen and water content

The results of the comparison of measured versus simulated soil mineral N concentrations (NH_4 and NO_3) and volumetric soil water content (SWC) at 15 cm soil depth are reported in Fig. 2. The results shows, that the models often fail to capture the observed dynamics of soil ammonium, but do better with regard to soil nitrate concentrations. The models generally managed to simulate observed changes in soil moisture, except for the Ås site. For this site, models were challenged to accurately capture SWC under a snow cover.

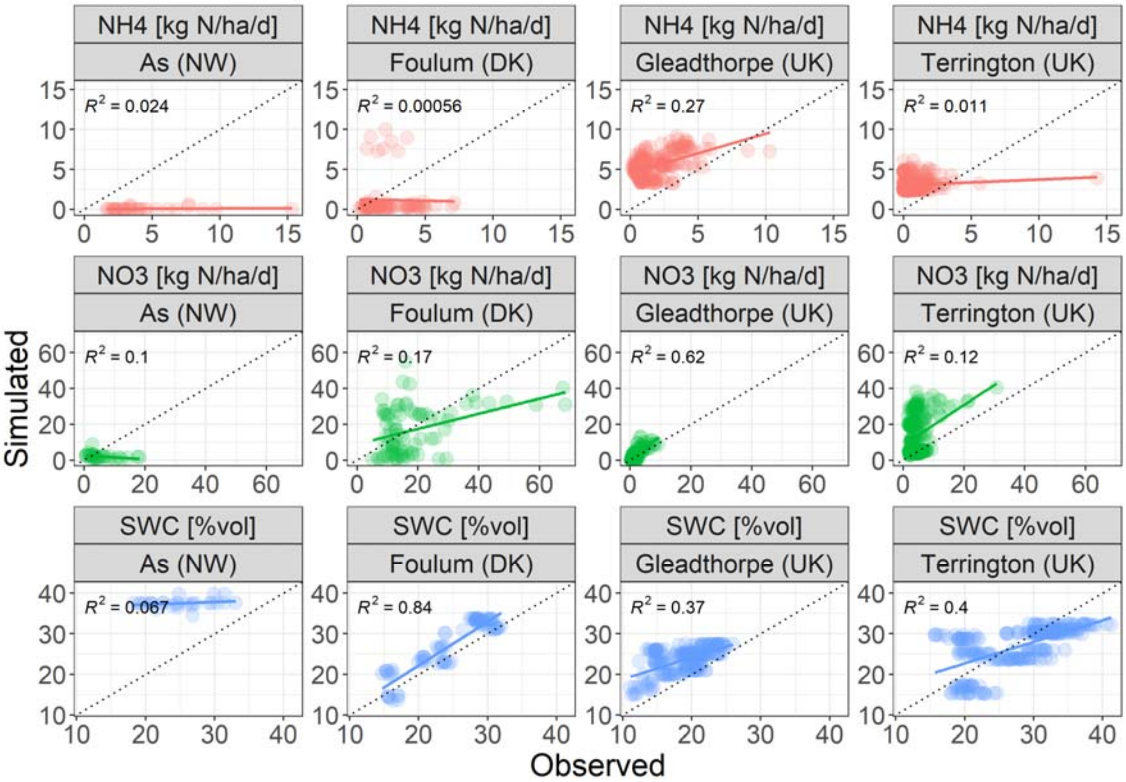
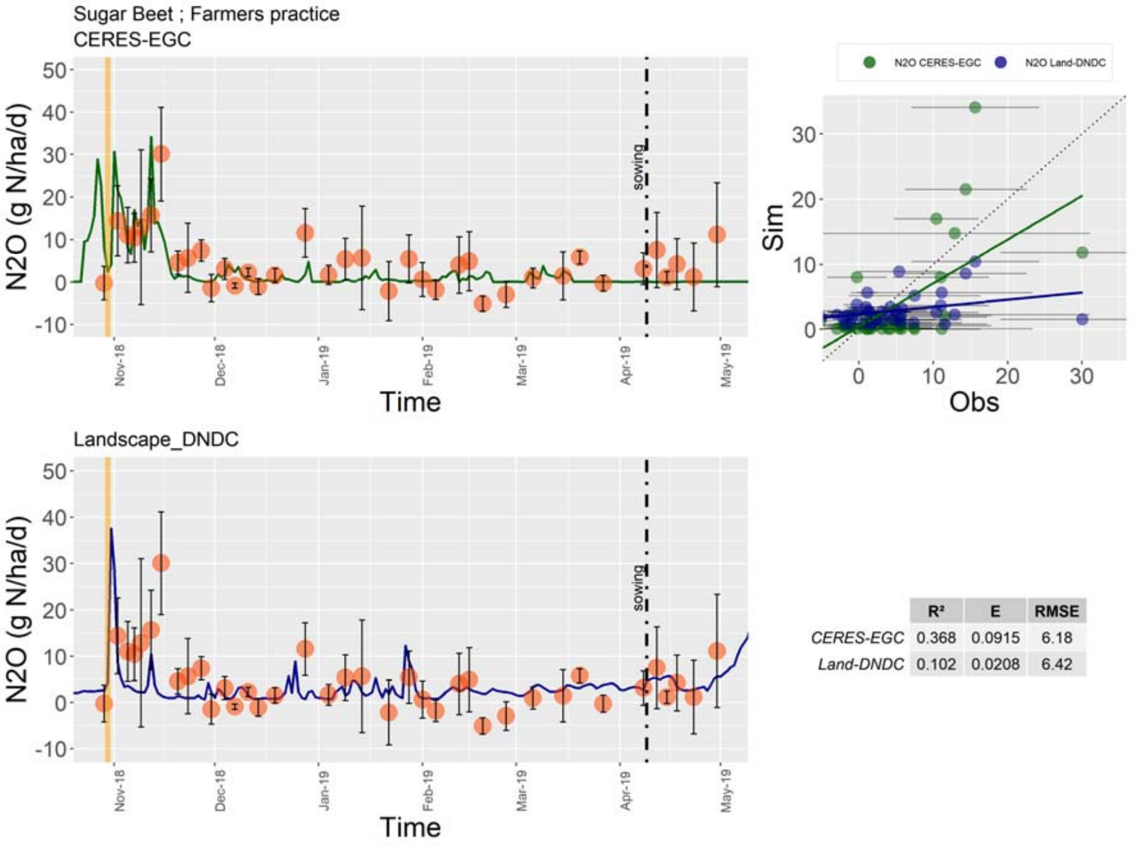


Fig. 2. Reported versus simulated soil ammonium (NH_4^+) and nitrate (NO_3^-) concentrations and volumetric soil moisture content (SWC) for 15 cm soil depth. The dashed lines represent the 1:1 line and the continuous lines represent the linear regression between simulated and observed data.

4.3 N_2O emissions

4.3.1 Agreement with models

The capability to simulate seasonal changes in soil N_2O fluxes by CERES-EGC and LandscapeDNDC was assessed for observations at the Lönnstorp site. Compared to all other datasets, a comparable high number of daily flux observations (N=39), covering a period of 6 months, was available for this site. The performance of both models was satisfying compared to the observations (E > 0 in 3 out of 6 experiments) with RMSE ranging from 6 to 10 g N ha^{-1} d^{-1} , but simulated daily emissions were generally within the confidence interval of the measurements (Fig. 3).



	R²	E	RMSE
CERES-EGC	0.368	0.0915	6.18
Land-DNDC	0.102	0.0208	6.42

Fig. 3. *Reported versus simulated N_2O emissions for one treatment in Lönnstrop site, sugar beet with conventional farmers practice. Red dots represent measures.*

It should be noted that an evaluation of the models conducted exclusively on point measurements may be inaccurate due to possible temporal gaps. In conclusion, a model evaluation with such a restricted dataset still remains challenging and inconclusive. Longer time series of flux measurements, also covering off-season fluxes are needed.

4.3.2 Long term cumulative emissions

The comparison between simulated and observed cumulative N_2O emissions over the entire measurement periods across all experimental sites and treatments are reported in Fig. 4. The simulated N_2O emissions agreed in magnitude and were within the uncertainty range of the measurements for most of the experiments. Cumulative observations were calculated by linear interpolation between sampling dates.

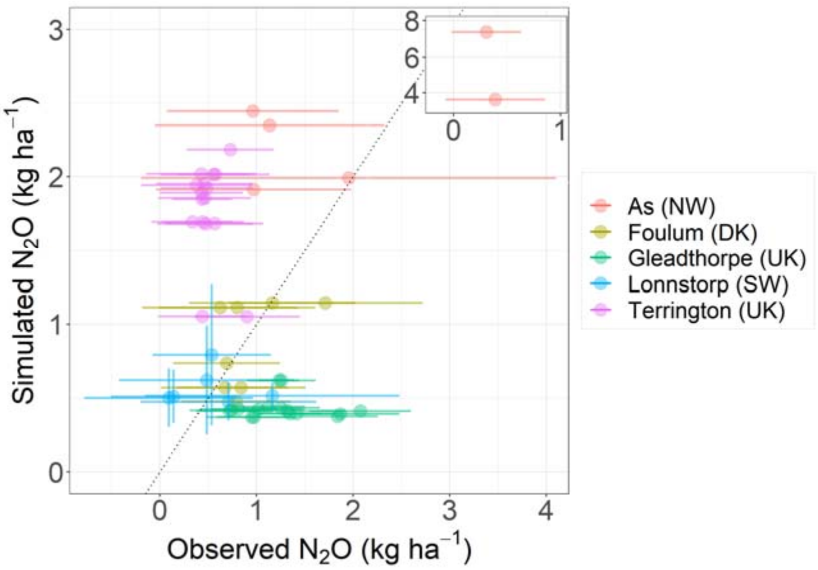


Fig. 4. *Comparison of measured and simulated cumulative N_2O emissions for the different sites (and treatments) used for model testing. Note that cumulative N_2O fluxes for measured values were obtained by linear interpolation between observation points, Error bars indicate the uncertainty of measured as well as of simulated cumulative emissions*

Generally, model simulations tended to overestimate cumulative N_2O emissions, specifically for the Ås and the Terrington site. However, it should be noted that the measured values have a high uncertainty due to high spatial variability of fluxes and the necessary interpolation procedure used for calculating cumulative values. RMSE values were in a range from 0.32 to 3.29 kg N ha^{-1}. These results highlight that due to missing site information and paucity of N_2O flux observations a full model testing remained extremely challenging demonstrating the necessity to collect more comprehensive datasets that allow for a complete model evaluation. The cumulated emission per site and experiment are reported in Appendix A.

5. Conclusions

Overall, both models, i.e. CERES-EGC and Landscape-DNDC, simulated magnitudes of residue effects on soil N_2O emissions reasonable and mostly within error margins of field observations. Nevertheless, it is also obvious that the datasets available on residue effects on soil N_2O emissions are short-term, often lack on necessary information for a valid model initialization (crop performance parameters, soil parameters), so that this modelling exercise somehow remained fragmentary and inconclusive. Longer time series are needed for model testing and this as well requires longer term funding schemes for such kind of research questions.

6. References

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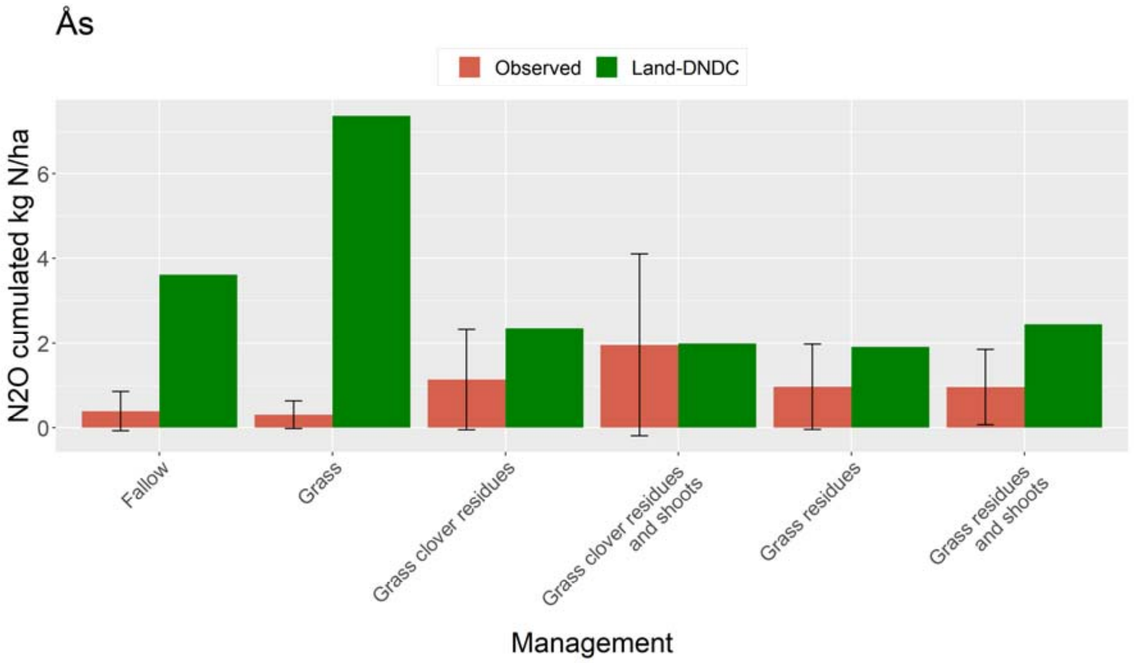
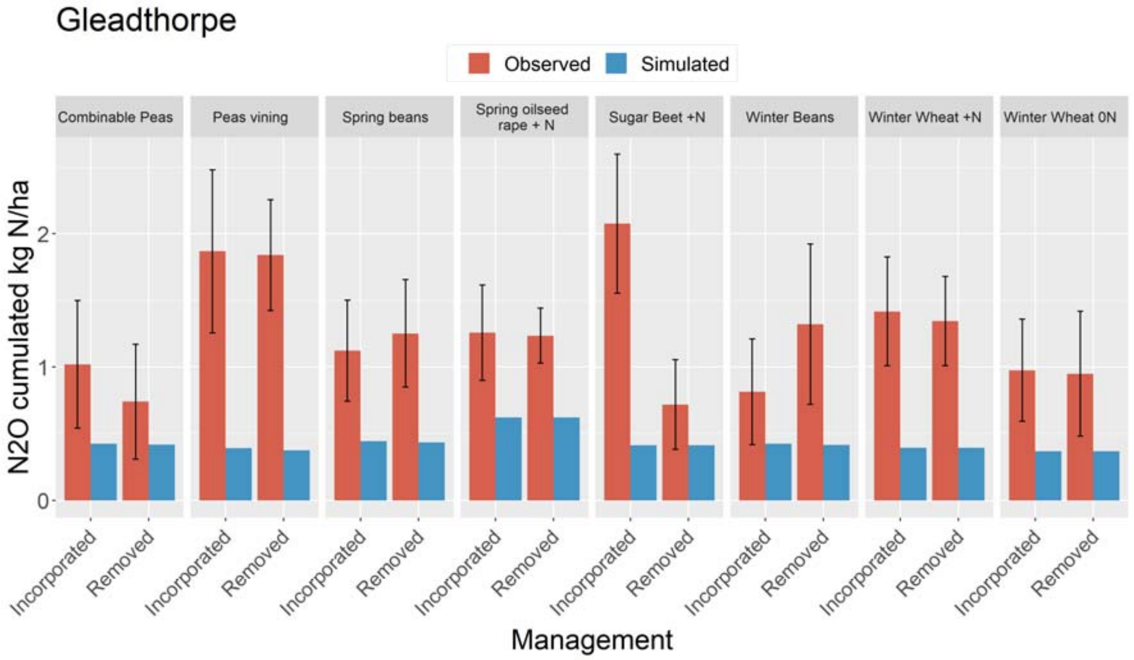
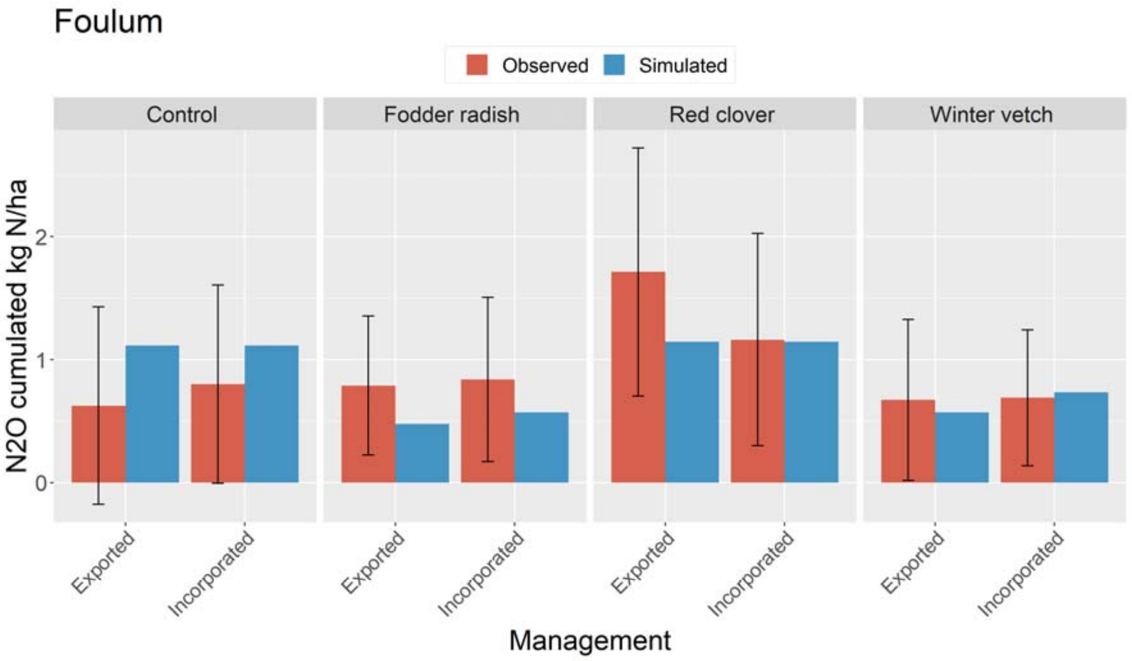
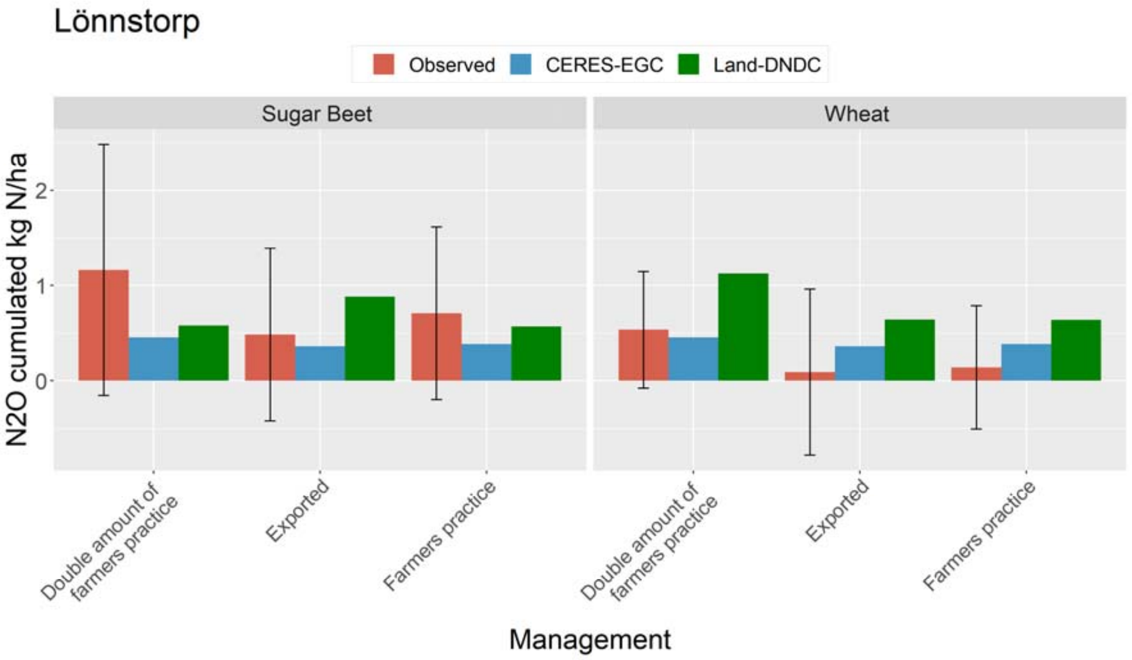
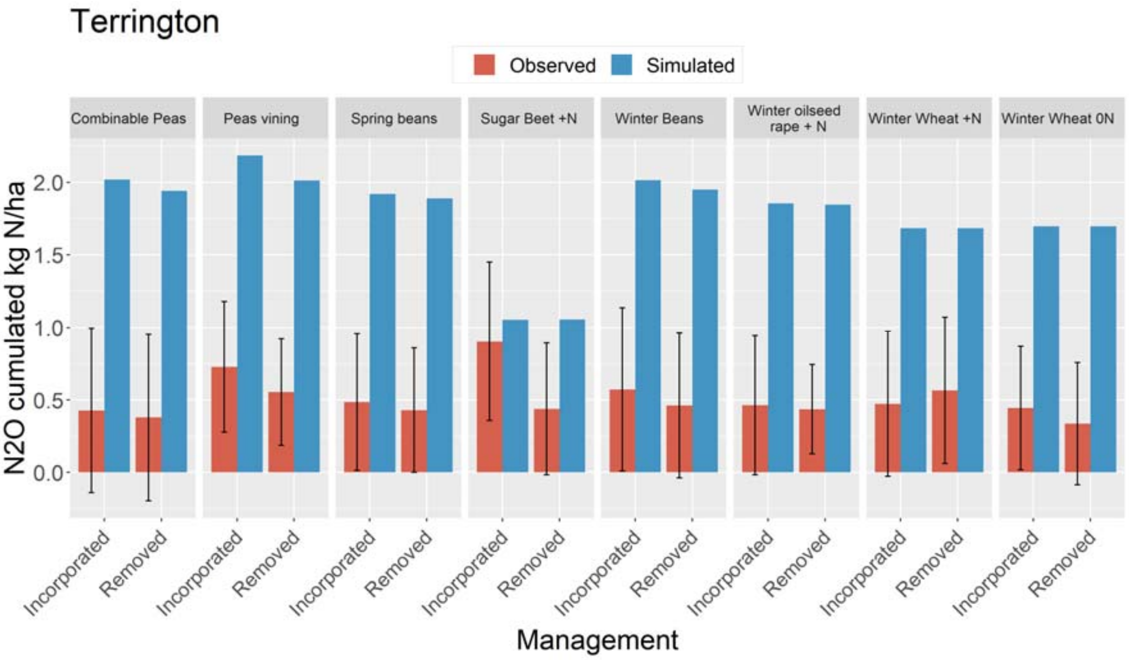
7. Appendix A


Ås
Observed
Land-DNDC
N2O cumulated kg N/ha
0
2
4
6
Fallow
Grass
Grass clover residues
Grass clover residues and shoots
Grass residues
Grass residues and shoots
Management


Gleadthorpe
Observed
Simulated
Combinable Peas
Peas vining
Spring beans
Spring oilseed rape + N
Sugar Beet +N
Winter Beans
Winter Wheat +N
Winter Wheat 0N
N2O cumulated kg N/ha
0
1
2
Incorporated
Removed
Management


Foulum
🟥 Observed
🟦 Simulated
Control
Fodder radish
Red clover
Winter vetch
N2O cumulated kg N/ha
0
1
2
Exported
Incorporated
Exported
Incorporated
Exported
Incorporated
Exported
Incorporated
Management


Lönnstorp
🟥 Observed
🟦 CERES-EGC
🟩 Land-DNDC
Sugar Beet
Wheat
N2O cumulated kg N/ha
0
1
2
Double amount of farmers practice
Exported
Farmers practice
Double amount of farmers practice
Exported
Farmers practice
Management


Terrington
Observed
Simulated
Combinable Peas
Peas vining
Spring beans
Sugar Beet +N
Winter Beans
Winter oilseed rape + N
Winter Wheat +N
Winter Wheat 0N
N2O cumulated kg N/ha
2.0
1.5
1.0
0.5
0.0
Incorporated
Removed
Management