ResidueGas DELIVERABLE NO. 4.2

Simulating Effects of Residue Management on Soil N_2O Emissions and Soil Carbon stock changes at European Scale

March 2021

Authors:

KIT: Klaus Butterbach-Bahl, Edwin Haas, Clemens Scheer

INRAE: Raia Silvia Massad, Marco Carozzi

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.

Carozzi, M., Haas, E., Massad, R.S., Scheer, C., Butterbach-Bahl, K., 2021. Simulating effects of residue management on soil N_2O emissions and soil carbon stock changes at European scale. ResidueGas Deliverable 4.2, April 2021.

Table of Contents

1. Summary

We developed a continental scale dataset for EU-27 on a grid of 0.25° x 0.25° spatial resolution including physicochemical soil properties, climate data with downscaled climate change projections (IPPC's scenarios RCP4.5 and RCP8.5) from 1951 to 2100, and arable management data such as chronological sequences of suitable crop rotations including synthetic and organic nitrogen fertilization. This dataset was used to compile various EU wide inventories of arable carbon and nitrogen cycling in agricultural ecosystems thereby assuming different residue management strategies.

Four management scenarios were simulated to assess the impact of residue management, especially on soil organic carbon sequestration and soil N_2O emissions, as well as crop yields. These residue management scenarios were: *Baseline* (residues incorporation as a function of crop type as reported by FAO), *Exported* (all aboveground residues removed from the field), *Surface* (all residues remain on the field, but are not incorporated → reduced tillage) and *Tillage* (all residues remain on the field, but will be ploughed into the soil after harvest).

Two process-based ecosystem models, CERES-EGC and LandscapeDNDC, were deployed to investigate the effects of the residue management scenarios on soil carbon sequestration and N_2O emissions. The residue scenarios were combined with two climate change projections, to compile EU-27 emission inventories for the period 1951 to 2100.

The inventory simulations allowed for the identification of hotspots and hot moments in carbon and nitrogen cycling in European arable ecosystems such as regions with high soil organic carbon losses and sequestration, strengths of soil N_2O emissions and their projection towards the year 2100.

Our findings show 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% SOC per year. These results support international initiatives such as the '4 per 1000' that promote 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. 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.

2. Introduction

Adaptation of agricultural practices may allow reduce the GHG footprint of food and feed production, as certain agricultural practices foster soil carbon (C) storage. Thus, agriculture may contribute to achieve long-term (*i.e.* 2100) climate objectives (Smith et al., 2013). Crop residue management is considered a key strategy to mitigate greenhouse gas (GHG) emissions from agriculture as it allows to promote soil C sequestration. Quality and composition of crop residues, management, soil and climatic conditions are considered the key controls affecting the accumulation soil organic carbon (SOC), although increases in soil organic carbon stocks may also increase soil nitrous oxide (N_2O) emissions (Li et al., 2016).

The interactions between agricultural practices and pedoclimatic conditions represent the main factors controlling the dynamics of the biogeochemical cycles of C and nitrogen (N), as well as crop production. Unfortunately, these interactions are not easy to determine via a simple approach. Simulation models represent a valuable tool to assess the impact of management practices on soil-plant-atmosphere exchanges (Ehrhardt et al., 2018). Recently, process-based models were used at regional scales to *e.g.* compute national GHG inventories (Smith, 2013). But major challenges still exist regarding the availability of spatially detailed input data (Lugato et al., 2017) and in the sensitivity of the models to changes of input parameters at spatial scale (Hoffmann et al., 2016). Moreover, simulating agricultural production with climatic projections, introduces an additional degree of uncertainty to the projections (Rosenzweig et al., 2013).

The aim of this research activity is to evaluate the long-term effects of different crop residue management practices on soil N_2O emissions and SOC storage capacity of European cropping systems. For this, we compiled detailed GHG budgets for European cropping systems, thereby assuming and testing different residues management strategies under climate change scenarios.

3. Materials and methods

3.1 Scenarios

Two ecosystem models, Landscape-DNDC (Haas et al., 2013) and CERES-EGC (Gabrielle et al., 1995), were applied to evaluate the effects of crop residue management scenarios on soil N_2O emissions and changes in soil organic stocks at the scale of EU-27. Models are detailed in Deliverable 4.1. Four different residue managements scenarios were defined and evaluated:

i) **Baseline**: this is the business as usual scenario. Residue management as a function of the crop species, according to FAO averages. Ratios [%] of residues removed / remaining on the field: cereals (50/50); grain maize, soya, potato, pulses, sugar beet, sunflower, rape seeds (20/80), silage maize (80/20). Soil tillage after harvest and before seeding.
ii) **Exported**: removal of the total aboveground residues, except stubbles, soil tillage as for the baseline.
iii) **Tillage**: all residues remain on the field, incorporation via tilling into the 20 cm topsoil, soil tillage as for the baseline.
iv) **Surface**: all residues remain on the field, but are were left on soil surface; no-tillage after harvest, though tillage is scheduled before seeding in spring of the following year.

3.2 Regional input data

Models were applied to a spatial dataset (0.25° × 0.25° latitude-longitude grid) composed by climate, soil and crop data. A historical weather dataset (1951-1999) in combination with two IPPC climate change projections to 2100 were used in our scenario studies: a “mild” scenario with robust actions to control GHG emissions, RCP4.5, and a “strong” scenario with no actions to counteract GHG, RCP8.5 (IPCC, 2013). Soil characteristics were extracted from the European Soil Database (Hiederer, 2013), selecting the most recurrent soil for the resolution of the simulation grid, accordingly with the elementary categories (texture, soil organic carbon, bulk density, soil depth and pH). This means that the selected soil represents the spatially most important soil for a given simulation unit.

Crop species and management data were obtained from a combination of the statistical crop distribution for EU-28 (Eurostat, 2019) and modelling (CAPRI model, Leip et al., 2008); details are reported in Wattenbach et al. (2015). This dataset consists of statistically derived crop rotations for the period 1978-2004 at a resolution of 1 km x 1 km. The dataset was extrapolated to the time period 1951 – 2100. Synthetic fertilizer N application rates were obtained from the above-mentioned statistics. Organic N fertilizer use was derived from FAOSTAT (last access 2020-10-06, “manure applied to soils (N content) - per country”). Organic N fertilizer was then spatially distributed to the grid cells according to the livestock density for cattle/swine from (“Gridded Livestock of the World – Latest – 2010 (GLW 3)”, https://dataverse.harvard.edu/dataverse/glw_3). Total N fertilization was applied to 91% of the cropping systems with a yearly average spanning from less than 20 to 370 kg N ha^{-1} y^{-1} (EU mean of 97 kg N ha^{-1} y^{-1}). In all scenario simulations, crops were irrigated according to their needs. Total area for arable lands in the EU-27 was derived from the Corine Land Use Map (AEE, 2018) and aggregated onto the input raster.

Figure 1 illustrates the distribution of arable land use across Europe and the N fertilization (urea as synthetic fertilizer and slurry as organic fertilizer) used for the inventory simulations.

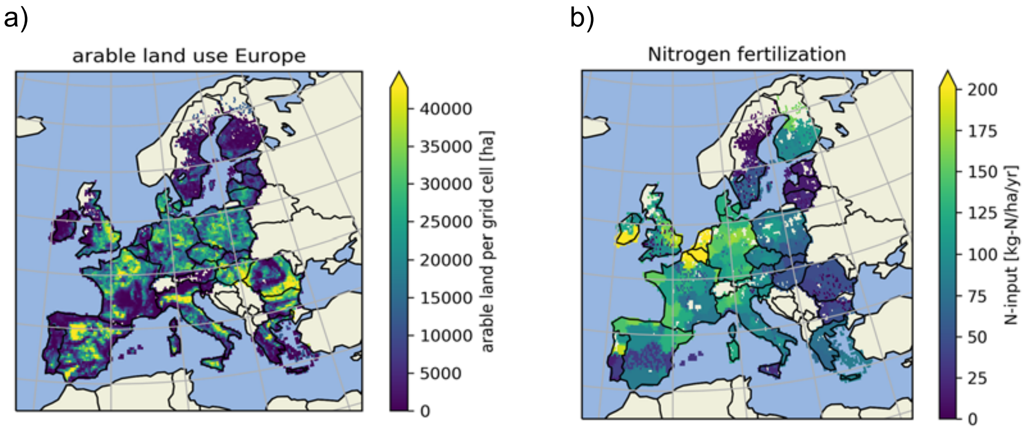


***Figure 1**. Arable land use across Europe with each 0.25° x 0.25° raster grid cell; b) Average N application (synthetic + organic nitrogen, averaging across 2000 – 2100) for arable agriculture in Europe.*

3.3 Simulation setup

To reduce the effects of the specific crop successions on the C and N cycle, the four most dominant crop rotations were selected per spatial grid cell and results of these four runs were weighted equally. The first 49 years (1951 - 1999) of the climatic data were used to spin-up the models and to bring all soil C and N pools into an equilibrium. The spin-up phase used the baseline management.

For assessing the global warming potential (GWP) the contribution of the biogenic GHG (CO_2, N_2O) is combined and normalised to CO_2-equivalents by using the relative global warming potential at the 100-year time horizon ($\gamma_{gas} = 298$ for N_2O and $\gamma_{CO_2} = 1$ for CO_2; IPCC, 2018)

$$GWP = \gamma_{N_2O} F_{N_2O} - \gamma_{CO_2} \Delta C$$

ΔC is the amount of organic C stored annually in the EU croplands in terms of CO_2. The GWP is identical to the net greenhouse gas emission (netGHG) [kg CO_{2eq} ha^{-1} yr^{-1}] used by Legato et al. (2018).

4. Results and discussion

Both ecosystem models simulated effects of residue management under historical and future climate conditions (RCP4.5 and RCP8.5) at the scale of EU27 using the four residue management scenarios.

4.1 Crop yields

Aggregated results for simulated crop yields are illustrated in **Figure 2**. Simulated yields for both models compare well over the entire simulation time span. The prediction agreement for crop yields is well in line with other model intercomparing studies such as FACCE JPI Macsur (Constantin et al., 2019) or AgMIP (Asseng et al., 2013, Ruane et al., 2016).

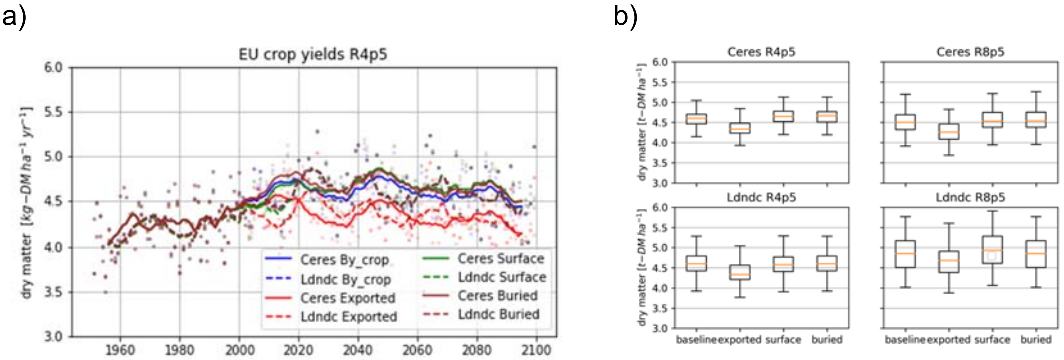


Figure 2. *a) Dynamics of averaged crop yields 1951 - 2100 for Europe; b) Crop yield distribution for the period 2000 - 2100 simulated by the two models under the different residue management and climate scenarios; "Buried" means "Tillage" scenario.*

In order to validate the simulated EU yield levels, the simulation results were compared with FAO NUTS2 species specific yield statistics across Europe (RMSE = 2.13 t ha^{-1}; MAE = 1.18 t ha^{-1}) (Figure 3). RMSE for each crop range from 12.8 to 38.6%. Figure 3 shows the N content in residues from simulated results and FAO data. The tendency is that simulations overestimate N for some crop (barley, potato, rapeseed, maize), with RMSE = 371 Tg N; CRM = - 0.54. Deviations and therefore uncertainties in simulated crop yields result most likely from EU wide model input data of arable land and fertilization management.

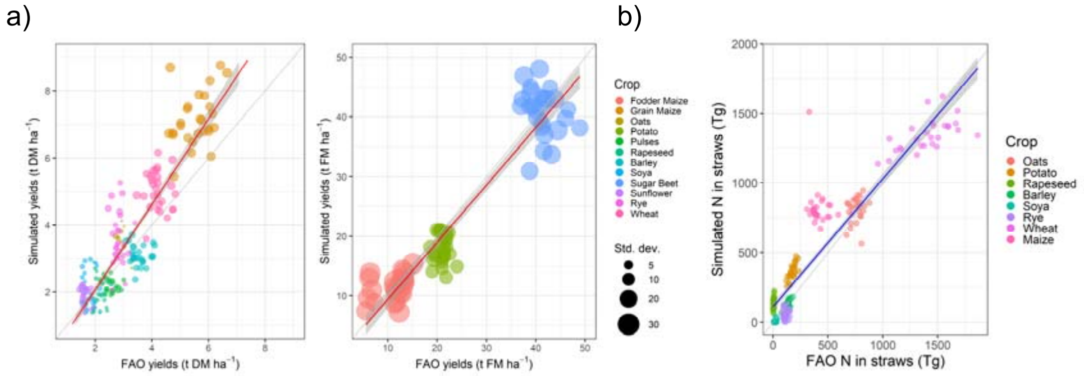


Figure 3. Model performance validation for simulation of a) crop yields and b) N content in residues across Europe. The overall accuracy of the simulated yields and N content compares well with the observations (FAO species specific yield statistics). Points represents yearly averages over EU-27 in the 1978-2004 period.

4.2 Soil carbon dynamics

Both models were initialized with the same soil organic carbon contents, which was distributed during model initialization into the internal carbon pools of the model. **Figure 4** a) and b) show the trend in aggregated soil carbon stocks over the simulation period 1951 - 2100 for all 8 inventory simulations (4 management scenarios with 2 climate scenarios). Both simulation models show consistent trends with respect to the 4 management scenarios. The Export scenario results in a significant loss of soil carbon relative to the Baseline simulation for both models. The Surface and Buried scenarios - in which 100% of the crop residues remain in the field in each case - lead to a significant increase in soil carbon with respect to the Baseline simulation. The differences in the simulated SOC levels between the models result from the fundamental different concepts in the soil biogeochemistry modules of the two models. Such differences have been observed before in other model intercomparing studies (Grosz et al., 2017, MACSUR, Riggers et al., 2020, AgMIP). **Figure 4** c) shows the topsoil (30 cm) SOC content in 1951 used for the model initialization and d) illustrates the regional distribution of the change in SOC for the baseline scenario and RCP8.5 thereby comparing SOC stocks in the year 2000 to the year 2100 (LandscapeDNDC inventory simulation).

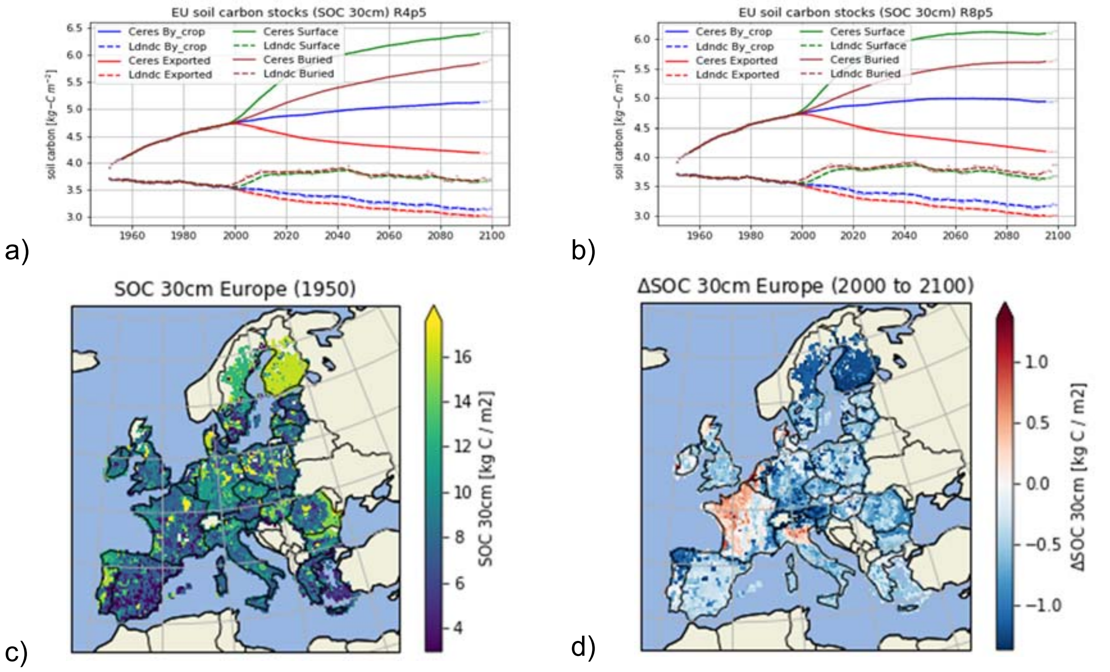


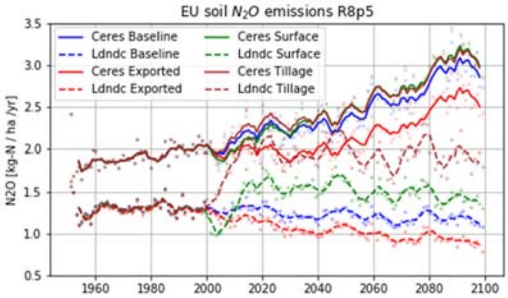
Figure 4. *SOC dynamics simulated for the residue management and climate change scenarios: a) RCP4.5 and b) RCP8.5. All inventory simulations assume Baseline arable management from 1951 – 1999 and transiently change to the four different residue management scenarios from 2000 – 2100. c) Initial topsoil (30 cm) SOC content in 1951 used for model initialization; d) regional distribution of ΔSOC for the Baseline scenario and RCP8.5 from 2000 to 2100 (LandscapeDNDC inventory simulation).*

Figure 6 summarizes the regional distributions of the effects of the different management scenarios from 2000 – 2100 on the SOC stocks. Each panel consists of a collection of four subfigures: upper left, absolute SOC changes; upper right, relative SOC changes (in %) between 2000 and 2100; lower left, absolute SOC; lower right relative SOC changes between the scenarios and Baseline scenario in the year 2100. Lugato et al. (2014) presented a similar study using the Daycent model focusing on different agricultural management options such as residues management to study their effect on the EU soil C sequestration potential. These authors report high soil C sequestration potentials on a moderate level in the East-European countries and higher levels in Central Europe (e.g. North-Italy, Austria, Germany, Czech Republic) and Western-European countries (e.g. Benelux and France). Magnitudes of the SOC changes are not comparable as the model SOC initialization may differ as well as the definition of the residue management scenarios.

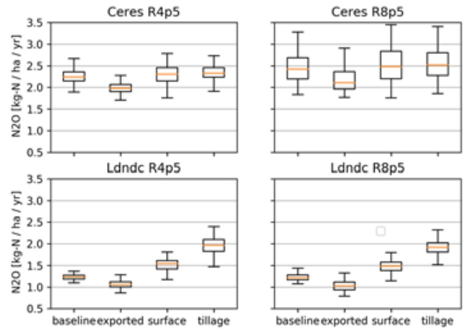
4.3 Soil nitrous oxide (N_2O) emissions

Figure 5 a) shows the dynamics of the spatially aggregated N_2O emissions over the simulation period 1951 - 2100 for the different residue management and the RCP8.5 climate change scenario simulations. Both models show good agreement for N_2O emissions compared to other model intercomparing studies (Erhardt et al., 2018; Fuchs et al., 2019). As with soil carbon, both models show consistent trends with reduced emission levels in the Export management scenario (lower biomass / nitrogen inputs from crop residues) and strongly increased emission levels in the Surface and Tillage management scenarios (increased biomass and nitrogen inputs from crop residues).

a)



b)



c)

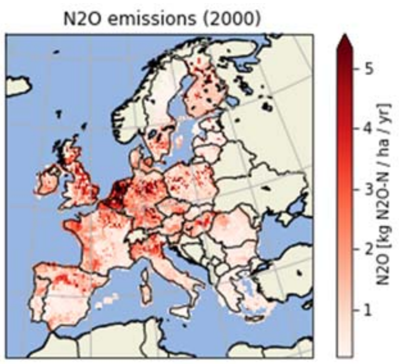


Figure 5 N_2O emission strength for the CERES-EGC and LandscapeDNDC inventory simulations for Europe under the residue management and climate change scenarios: a) Dynamics of average EU N_2O emission strength from arable soils under RCP4.5; b) Distribution of N_2O emissions (EU wide, 2000 – 2100); c) Regional distribution of N_2O emission strengths for 2000.

Guenet et al. (2021) reported global N_2O emissions strengths from synthetic and organic fertilizer use. Comparing our findings represented in Figure 5 c) for 2000 with Figure 3 in Guenet et al. (2021), the soil N_2O emission strengths from arable land use compare very well, even though all modelling data sources and inventory modelling concepts are fundamental different.

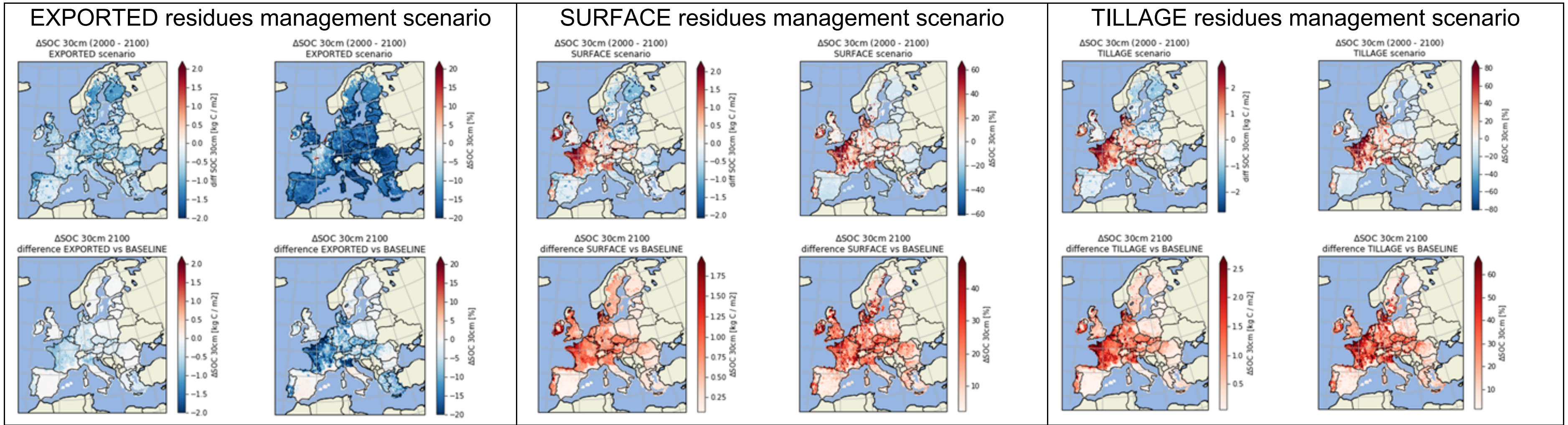


Figure 6 *SOC inventories under RCP8.5 climate change projections for Europe. Left panel: Exported scenario, Middle panel: Surface scenario and right panel: Tillage scenario; Each panel consists of a collection of four separate plot: Upper left: Absolute SOC changes and upper right: Relative SOC changes in [%] between 2000 and 2100; Lower left: Absolute SOC and lower right relative SOC changes between each scenario and Baseline scenario in the year 2100.*

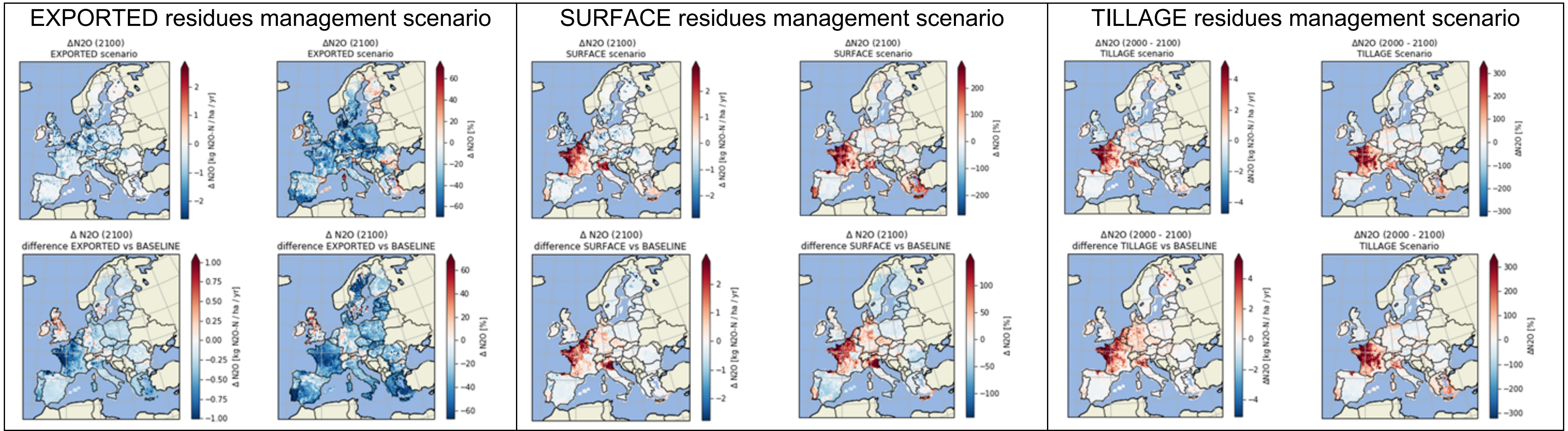


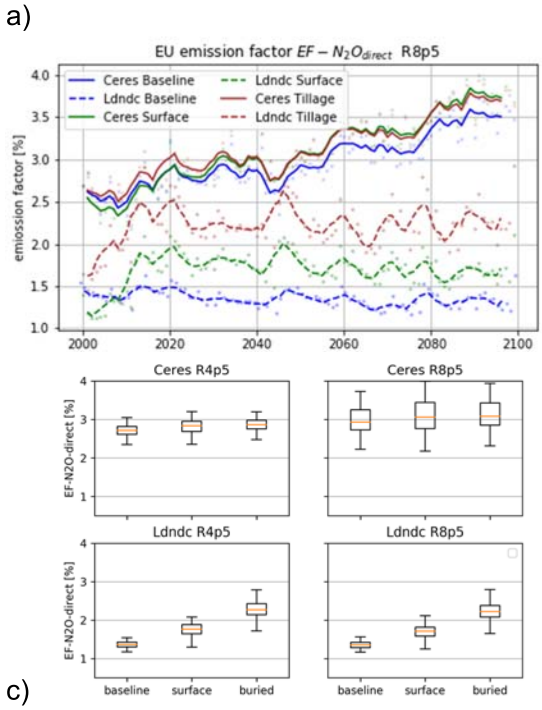
Figure 7 *Simulated N_2O inventories under RCP8.5 climate change projections for Europe, Panels and sub-figures same as in* ***Figure 6****.*

4.4 N_2O Emission factor of crop residues

Direct N_2O emission factor through nitrogen input via residues, as reported by the IPPC, is defined as

$$\mathrm{EF}_{\mathrm{N_2O}} = \frac{N_2O\ management\ - N_2O\ exported}{N\ added\ by\ straws}$$

where "*N_2O management*" is the N_2O assuming Baseline management. Tillage and Surface scenario refer to "*N added by straws*" and include the N (organic + mineral) added by the aboveground residues.



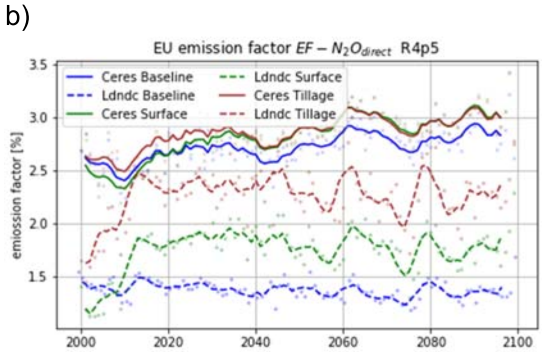


Figure 8. *Simulated emission factors for direct N_2O emissions from residues incorporation for a) RCP4.5 and b) RCP8.5 climate change projections 1951 – 2100; c) Distributions of simulated emission factors (2000 – 2100) for CERES-EGC and LandscapeDNDC inventory simulations.*

The resulting direct N_2O emission factors for N added with crop residues at the scale of EU 27 are shown in **Figure 8** a) and b) with regard to their temporal evolution and c) their distribution for 2000 - 2100. The differences in calculated emission factors between the models are based on the significant differences in the way soil N_2O production is simulated by the models: CERES-EGC simulates higher N_2O emissions but smaller differences between the different management scenarios, while LandscapeDNDC simulates lower N_2O emission levels but higher differences between the different management scenarios leading to higher emission factors compared to CERES-EGC. The resulting emission factors of the long-term simulations are all well above the IPCC Tier I emission factor of 1%. Derived emission factors are also higher compared with data from a global review by Charles et al. (2017) but compares well with simulated direct N_2O emission factors for the EU as obtained by the DNDC-Europe model (Leip et al., 2011).

Regional distributions of N_2O emission factors from crop residues from the inventory simulations are provided in the Appendix.

4.5 Global warming potential

To assess the GWP induced by a change in residue management (scenarios Exported, Surface, Tillage) for the 2000 – 2100 period, we considered the differences in soil carbon stocks and N_2O emissions by comparing residue management scenarios with the Baseline scenario. These differences are subsequently converted into GWP [kg CO_{2eq} ha^{-1} yr^{-1}]. Figure 9 a) illustrates changes in the GWP due to changes in SOC stocks (blue line), soil N_2O emissions (orange line) and the combination of the two (green line) exemplarily for the LandscapeDNDC inventory simulations (EU scale). For the scenario "Exported", the change in the GWP is dominated by the simulated reductions of soil N_2O emissions rather than by small changes in the SOC stocks. The Surface and Tillage scenarios both lead to increased SOC sequestration (see **Figure 4**) and enhanced soil N_2O emission rates (see Figure 5**Error! Reference source not found.**) compared to the Baseline scenario. This can be clearly seen in Figure 9 c) and e). For the Surface scenario the break-even of the GWP balance, i.e. GHG neutrality of the effect, will be after the simulation end in 2100, whereas for the Tillage scenario the simulated strong increase in soil N2O emissions cancel out wins due to increases in SOC stocks at around 2070, i.e. after this year residue incorporation will even stimulate total GHG emissions (as GWP).

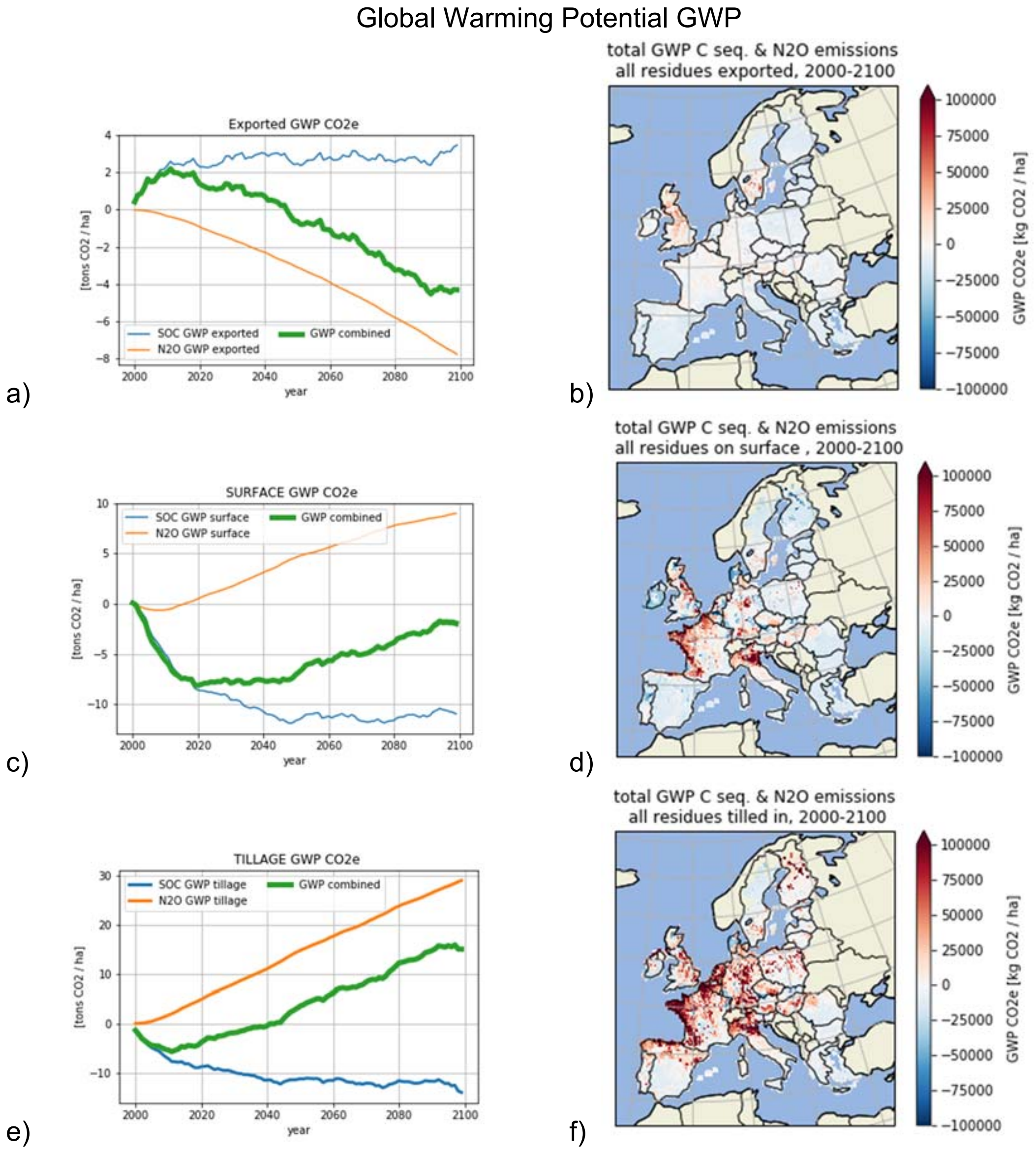


Figure 9 Derivation of the EU-27 global warming potential for the residue scenarios from C sequestration, N_2O emissions and their combination for the a) Exported, c) Surface and e) Tillage scenario; Regional distribution of the aggregated GWP values 2000 – 2100 for the b) Exported, d) Surface and f) Tillage scenario (All data shown: LandscapeDNDC inventory simulations, RCP8.5).

For all three scenarios, the regional distributions are illustrated in Figure 9 b), d) and f). The inventory simulations indicate hotspots of high aggregated GWP values in the Surface scenario in the regions of intense agriculture such as the coastal regions of France, North Italy and in Germany. For the Tillage scenario, hotspots with extreme high GWP values have been identified in regions with intense agriculture and therefore high nitrogen fertilization rates. Extreme GWP values have been identified in north of Spain, the coastal regions of France and Benelux, north of Italy (Po Valley), the intense agricultural regions in Germany and some regional hotspots in Czech Republic, Austria and Hungary. These regions correlate with intense SOC sequestration but also elevated soil N_2O emissions.

These identified regions need special attention as they are vulnerable to enhanced soil N_2O emissions, even though some of them clearly show high soil carbon sequestration rates (compare **Figure 6** and **Figure 7**).

Global warming potential (GWP)

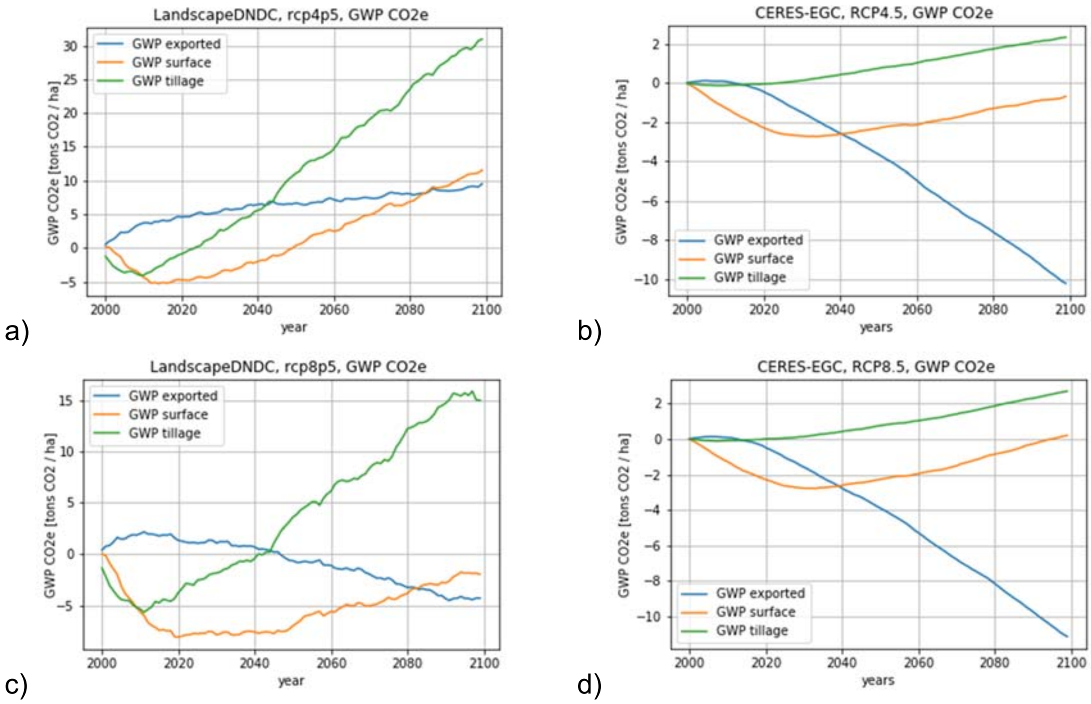


Figure 10 Global warming potential assessment across the residue management scenarios from C sequestration versus ‘N_2O emissions for the two models and climate change projections: a) LandscapeDNDC RCP4.5 b) CERES-EGC RCP4.5; c) LandscapeDNDC RCP8.5; d) CERES-EGC RCP8.5 ; Note: The magnitude of the four figures is different but the trend is similar.

Figure 10 summarizes all resulting GWP curves for the two models CERES-EGC and LandascapeDNDC for the RCP4.5 and RCP8.5 scenario. These findings agree very well with recent findings by Lugato et al. (2018), who simulated with the Daycent model approximately 8000 single sites across Europe based on the database of LUCAS soil information (Lugato et al., 2017). Both studies show an identical trend for GWP (comparing Figure 9 and Figure 10 with the net greenhouse gas emission flux Fig. 1 in Lugato et al. 2018) as well as very similar magnitudes for the GWP despite the fact that the data sources for the two independent studies are completely different.

The magnitude of the GWP values simulated by the two models differ in this study. However, both models came to an overall comparable trend, as can be seen in Figure 9. Even though the SOC dynamics and the N_2O emissions differ significantly in magnitude between both models, the combined GWP curves from C sequestration and soil N_2O emissions are coming to the same conclusion: increasing soil carbon sequestration by enhancing residues incorporation will be counterbalanced by elevated soil N_2O emissions resulting from the additional organic C and N inputs into the soil. Secondly, the elevated soil N_2O emissions dominate the GWP, as stated by Li et al. (2005) and recently discussed by Guenet et al. (2020). This becomes clear considering the Exported scenario, where the dramatic reduction in residue litter input significantly decreases the soil carbon content compared to the Baseline scenario, but as soil N_2O emissions decrease the same time, the overall effect is a reduction in total

GHG emissions. Contextually, the reduction of litter input into the soil reduced the N_2O emissions much stronger. This reduction becomes dominant in terms of GWP (see the Exported scenarios in Figure 10 b) and d) but also less pronounced in c)). Finally, the mitigation of climate change simulated with the Exported scenario may not be an adequate solution, as the reduction in litter input threatens soil fertility, soil health and food security. The opposing approach to follow the "*4 per 1000*" initiative and maximize the soil carbon sequestration even under reduced tillage practices (Surface scenario) will strengthen the soil C and N cycling with enhanced nitrification and denitrification leading to elevated soil N_2O emissions, as seen in Figure 5 for both models.

5. Conclusions

Although the two different simulation models showed good agreements for yield predictions, significant differences in SOC dynamics and N_2O emissions from soil were observed. The overall trend of the GWP assessment under the three residue management scenarios resulted in similar trends: for the Surface and Tillage scenarios the SOC sequestration was rapidly counterbalanced by elevated N_2O emissions from soil. The resulting GWP became positive (warming effect) as soon as the N_2O emissions from soil turned to be dominant. This could be estimated to 20 to 40 years after the change of residues management practice for the Tillage scenario. When the change of residues management practice went along with a reduction of tillage as seen in the Surface scenario, the counterbalancing of the soil carbon sequestration by elevated N_2O emissions takes a longer span, even more than 100 years.

These findings give evidence to support the "*4 per 1000*" initiative when residues were applied on the surface under a reduced tillage regime. When considering common agricultural practices with extensive soil tillage operations as weed control, our findings give more evidence to criticize the "*4 per 1000*" initiative, as soil N_2O emissions will counterbalance the soil carbon sequestration in short time leading to an enhanced GWP.

Overall, some uncertainties are assigned to the findings of this study. These result from structural differences between the two simulation models, general uncertainties in the regional data for model initialization (soil data) and data of regional agricultural management (crop cultivation and fertilization). These uncertainties may influence the simulated levels of soil organic carbon, soil N_2O emissions and resulting GWP values. On the other hand, the likelihood for the simulated trends in the results especially for the GWP remain very high.

6. References

Asseng, S., Ewert, F., Rosenzweig, C. et al. (2013) Uncertainty in simulating wheat yields under climate change. Nature Clim Change 3, 827–832, doi:10.1038/nclimate1916

Charles A, Philippe Rochette, Joann K. Whalen, Denis A. Angers, Martin H. Chantigny, Normand Bertrand, (2017) Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis, Agriculture, Ecosystems & Environment, Vol 236, doi:10.1016/j.agee.2016.11.021

Constantin J, Raynal H, Casellas E, et al., (2019). Management and spatial resolution effects on yield and water balance at regional scale in crop models. Agricultural and Forest Meteorology, Vol 275, doi:10.1016/j.agrformet.2019.05.013

EEA, 2018. European Environment Agency - Corine Land Cover (CLC) 2018, Version 2020_20u1. Dataset https://land.copernicus.eu/pan-european/corine-land-cover/clc2018

Ehrhardt, F., Soussana J.-F., Bellocchi G., et al., (2018) Assessing uncertainties in crop and pasture ensemble model simulations of productivity and N2O emissions. Global Change Biology, 24 (2), e603-e616, doi:10.1111/gcb.13965

Ehrhardt, F, Soussana, J-F, Bellocchi, G, et al. (2018) Assessing uncertainties in crop and pasture ensemble model simulations of productivity and N2O emissions. Glob Change Biol.; Vol 24, e603– e616, doi:10.1111/gcb.13965

Eurostat, 2019a. European Statistical Office database. Retrieved from: https://ec.europa.eu/eurostat/data/database

Fuchs K., Merbold L., Buchmann N., Bretscher, D., Brilli, L., Fitton, N., et al. (2020) Multimodel evaluation of nitrous oxide emissions from an intensively managed grassland. Journal of Geophysical Research: Biogeosciences, 125, doi:10.1029/2019JG005261

Gabrielle B., Da-Silveira J., Houot S., Michelin J., (2005) Field-scale modelling of carbon and nitrogen dynamics in soils amended with urban waste composts. Agriculture. Ecosystems & Environment 110, 289e299. doi:10.1016/j.agee.2005.04.015

Grosz B, Dechow R, Gebbert S, et al., (2017) The implication of input data aggregation on upscaling soil organic carbon changes. Environmental Modelling & Software, Vol 96, 361-377, doi:10.1016/j.envsoft.2017.06.046

Guenet, B, Gabrielle, B, Chenu, C, et al. (2020) Can N2O emissions offset the benefits from soil organic carbon storage? Glob Change Biol. 27: 237– 256. doi:10.1111/gcb.15342

Haas, E., Klatt, S., Fröhlich, et al., (2013) LandscapeDNDC: A process model for simulation of biosphere-atmosphere-hydrosphere exchange processes at site and regional scale. Landscape Ecology, 28 (4), pp. 615-636, doi:10.1007/s10980-012-9772-x

Hoffmann, H., Zhao, G., van Bussel, L., et al., (2015) Variability of spatial aggregation effects of climate data on regional yield simulation by crop models for a selected region in Germany. Climate Research 65, 53-69.

IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]

Leip A, Marchi G, Koeble R, Kempen M, Britz W, Li C, (2008) Linking an economic model for European agriculture with a mechanistic model to estimate nitrogen and carbon losses from arable soils in Europe, Biogeosciences 5: 73–94, doi:10.5194/bg-5-73-2008

Leip A, Busto M, Winiwarter W, (2011) Developing spatially stratified N2O emission factors for Europe (2011) Environmental Pollution, Vol 159, doi:10.1016/j.envpol.2010.11.024

Li C, Frolking S, Butterbach-Bahl K, (2005) Carbon Sequestration in Arable Soils is Likely to Increase Nitrous Oxide Emissions, Offsetting Reductions in Climate Radiative Forcing. Climatic Change 72, 321–338, doi:10.1007/s10584-005-6791-5

Li X., Sørensen P., Olesen J. E., Petersen S. O., (2016) Evidence for denitrification as main source of N2O emission from residue-amended soil. Soil Biol. Biochem. 92, 153–160, doi:10.1016/j.soilbio.2015.10.008

Lugato, E., Bampa, F., Panagos, P., Montanarella, L., & Jones, A. (2014). Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices. Global Change Biology, 20(11), 3557–3567. https://doi.org/https://doi.org/10.1111/gcb.12551

Lugato E., Paniagua L., Jones A., de Vries W., Leip A., (2017) Complementing the topsoil information of the Land Use/Land Cover Area Frame Survey (LUCAS) with modelled N2O emissions. PLoS ONE 12(4): e0176111, doi:10.1371/journal.pone.0176111

Lugato, E., Leip, A., & Jones, A. (2018). Mitigation potential of soil carbon management overestimated by neglecting N2O emissions. Nature Climate Change, 8(3), 219–223. https://doi.org/10.1038/s41558-018-0087-z

Riggers C, Poeplau C, Don A, et al., (2019) Multi-model ensemble improved the prediction of trends in soil organic carbon stocks in German croplands, Geoderma, Vol 345, doi:10.1016/j.geoderma.2019.03.014

Rosenzweig C., Jones J. W., Hatfield J. L., et al., (2013) The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. Agric. For. Meteorol., Vol. 170, pp. 166–172

Ruane AC, Hudson NI, Asseng S, Cammarano D et al., (2016) Multi-wheat-model ensemble responses to interannual climate variability, Environmental Modelling & Software, Vol 81, doi:10.1016/j.envsoft.2016.03.008

Smith P, Heberl H, Popp A, et al., (2013), 'How much land based greenhouse gas mitigation can be achieved without compromising food security and environmental goals?', Global Change Biology, vol. 19, no. 8, pp. 2285-2302. doi:10.1111/gcb.12160

Wattenbach, M., Lüdtke, S., Redweik, R., Van Oijen, M., Balkovic, J., Reinds, G., (2015) A generic probability based model to derive regional patterns of crops in time and space. Geophysical Research Abstracts, Vol. 17, EGU2015-13153, 2015

7. Appendix A

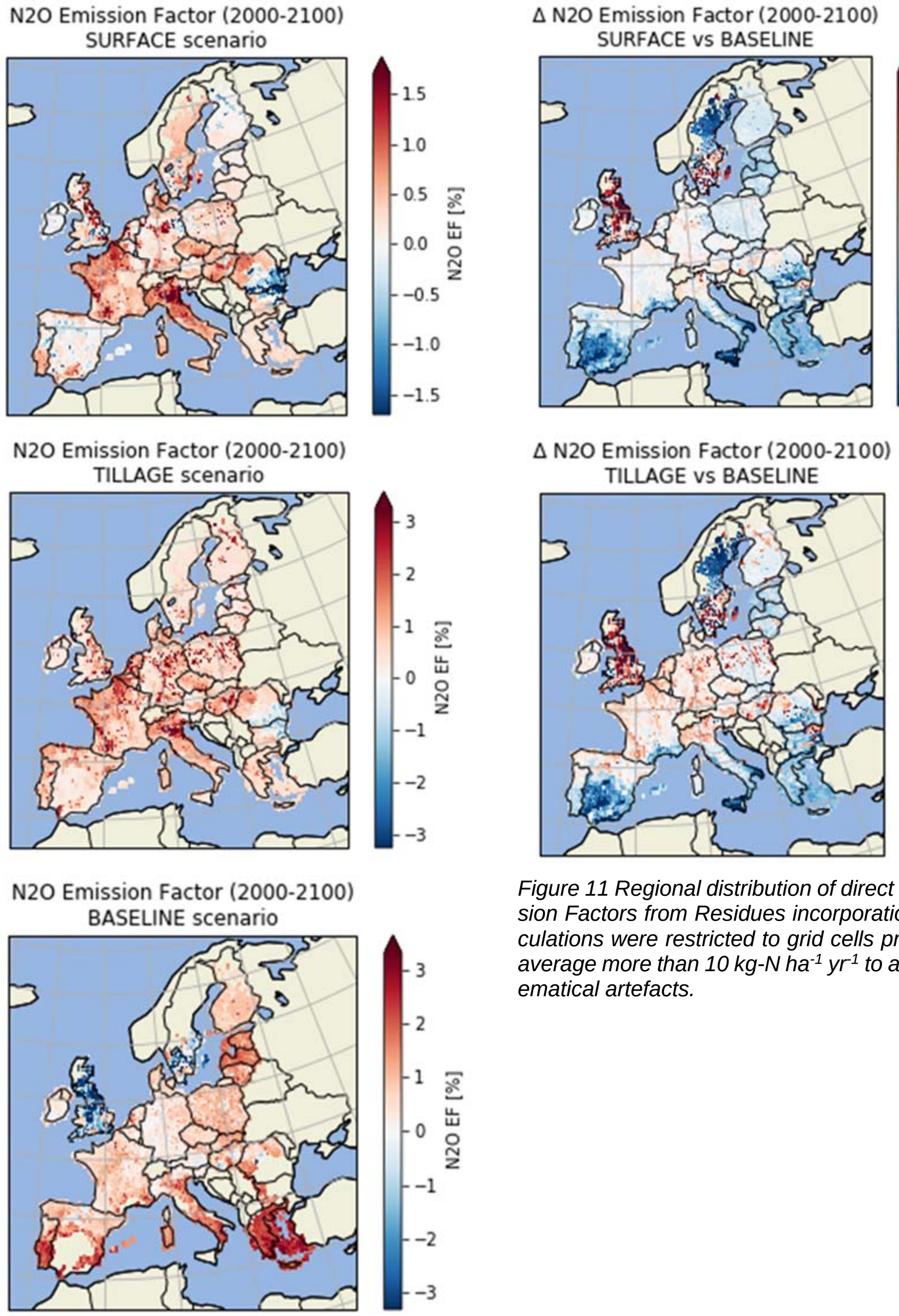


Figure 11 Regional distribution of direct N_2O Emission Factors from Residues incorporation; EF calculations were restricted to grid cells providing on average more than 10 kg-N ha^{-1} yr^{-1} to avoid mathematical artefacts.