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Significant offset of long-term potential soil carbon sequestration by nitrous oxide emissions in the EU

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Abstract

International initiatives such as the '4 pour 1000' are strongly promoting carbon (C) sequestration in soils, particularly in the agricultural sector where targeted management can mitigate greenhouse gas emissions. Changes in soil organic turnover have many feedbacks on the coupled nitrogen cycle, therefore any variation in soil nitrous oxides (N_2O) emissions could potentially offset or enhance any C sequestration actions. However, large-scale and dynamic temporal quantification of CO_2 and N_2O soil fluxes to guide policy-making decisions are still lacking. Here we ran a biogeochemistry model on approximately 8,000 soil sampling locations from the most extensive land use/soil inventory framework for the EU, to assess the net CO_2 equivalent (CO_2eq) flux associated with representative mitigating agricultural practices. We showed that practices based on integrated crop residue retention and lower soil disturbance did not increase N_2O emissions as long as C accumulation was continuing. By 2100 the N_2O-induced soil C sequestration offset (NCO) was 24%. The introduction of N fixing cover crops allowed higher C accumulation over the first 20 years but, beyond 2080, NCO values were over 100% even after reducing mineral N fertilizations proportionally. We conclude that significant CO_2 sequestration can be achieved in the initial 20-30 years of any mitigation scheme but, afterward, N inputs should be controlled through appropriate management.

Keywords: Carbon sequestration, N_2O emissions, agricultural soil, GHG, mitigation

Introduction, scope and main objectives

At the UNFCCC COP22 the '4 pour 100' initiative was launched, with the aim of implementing a multi-participatory program that demonstrates the potential role of agricultural soils in sequestering carbon. Under a legal framework in the European Union (EU), Member States have already started to account for soil organic carbon (SOC) changes, with a further proposal to include land use and land use change related emissions/removals in the Emission Trading System. The present emphasis on the role of agricultural soils in storing more carbon is, in fact, supported by a growing number of literature syntheses, showing SOC accumulation under targeted management practices. Even large-scale modelling studies have estimated a biophysical potential in the order of 0.5-2 Pg of CO_2eq in the EU, which is storable in a centennial time horizon by applying different sets of agricultural practices.

However, managements affecting the SOC cycle are likely to affect soil nitrous oxides (N_2O) emissions, as C and N biogeochemical cycles are strongly coupled. N_2O emissions are a very uncertain component of the soil greenhouse gas budget since they dynamically vary in space and time and our understanding of the process is still progressing. The existing monitoring measurements systems and available datasets do not allow for robust estimates of N_2O emissions and conclusions on the possible trade-off between N_2O emissions and C sequestration actions. This aspect is exacerbated by the fact that SOC sequestration reaches a saturation over time, while N_2O emissions can be constantly higher when comparing two management systems. Therefore, the overall mitigation effectiveness of possible SOC sequestration policies remains uncertain and new data and tools are needed, as presented in this work, to gain a higher level of confidence.

Methodology

Here we run the state-of-the-art biogeochemistry model DayCent, on about 8'000 soil sampling locations of the most extensive land use/soil EU inventory network, classified as arable. The model was driven by measured soil characteristics and complemented with updated datasets, including a RPC4.5 climate change scenario. A Montecarlo approach was used to quantify the uncertainty of the most sensitive and uncertain inputs. Our main idea was to quantify the net soil GHG emissions, simulating two representative mitigating practice options starting in 2016, in comparison with a baseline of current agricultural practices. The first scenario was an integrated crop residue retention and lower soil disturbance management (IRS) while, the second saw the introduction of N fixing cover crops incorporated before the successive main crop (CC), generally refereed as 'green manure'. In the latter scenario we reduced the N mineral fertilization by 75% of N fixed, assuming a lower efficiency of this biological form due to the lower synchronization with crop demand.

Results and Discussion

We found that IRS management asymptotically increased the SOC content by 2050, leading to a new steady-state equilibrium thereafter (Fig. 1). Average cumulative SOC gains were -7.9 and -10.8 Mg CO_2eq ha^{-1} at 2040 and 2100, respectively. Differences in N_2O emissions showed both positive (enhanced emissions) and negative (reduced emissions) changes during the period 2016-2040, with an average close to zero over all location. We defined the Nitrogen-induced Carbon sequestration Offset (NCO) as the ratio between cumulative changes in N_2O emissions and SOC sequestration (both expressed as CO_2 equivalent), where positive NCO indicates a reduction of the C sequestration effect by enhanced N_2O emissions, while negative values indicate an additional mitigation effect. We found about 50% of the sampling locations exhibited negative values in 2040. This indicates that IRS management reduced cumulative N_2O emissions in many locations compared to the baseline, while the complete NCO was reached only in a few points. Under the modelling framework, the soil C:N ratio of each organic C pool is highly constrained, reflecting what observed in the reality. Therefore, as long as the soil is accumulating organic C, it is also tightly incorporating N. Available mineral N can be taken from the inorganic pool and stabilized in direct association with C, reducing at the same time its availability as a substrate for nitrification and denitrification processes and the subsequent gaseous N losses.

Under the CC scenario, the soil fluxes were more contrasting than in IRS (Fig. 1). SOC sequestration was promoted by the additional C input provided by cover crops incorporated into soil, with an average SOC gains corresponding to -19.4 and -28.1 Mg CO_2eq ha^{-1} at 2040 and 2100 (Fig. 1). A recent meta-analysis on the effect of cover crop green manuring on SOC stocks reported annual changes between 0.09 and 0.68 Mg C ha^{-1} yr^{-1} (1th and 3dr quantile) when no-tillage studies were excluded, which is in the same order of our simulation with 0.11-0.30 Mg C ha^{-1} yr^{-1}.

The additional N coming from the cover crop fixation compared to the baseline, induced an increasing positive change in N_2O emissions. The higher N inputs into CC system derived not only by the fact that we partially replaced the mineral fertilization with the N-fixed, but also that in many locations the N fixation was higher than mineral fertilizations, leading to an average additional N of 41 kg N ha^{-1} yr^{-1} compared to the baseline. Since modelled nitrification and denitrification processes are functions of soil mineral N, this trend is not surprising. Moreover, modelled denitrification is also a function of the labile C availability which is strongly increased by the incorporation of fresh cover crops. This positive feedback is observed in many experimental studies, where higher N_2O emissions were recorded in SOC enriched soils. Besides that, the net cumulated soil GHG flux was lower (stronger sink) in CC than in IRS, with averages of -12.3 and -7.9 Mg CO_2eq ha^{-1} by 2040, respectively, and also with much more geographical variability (Fig. 1).

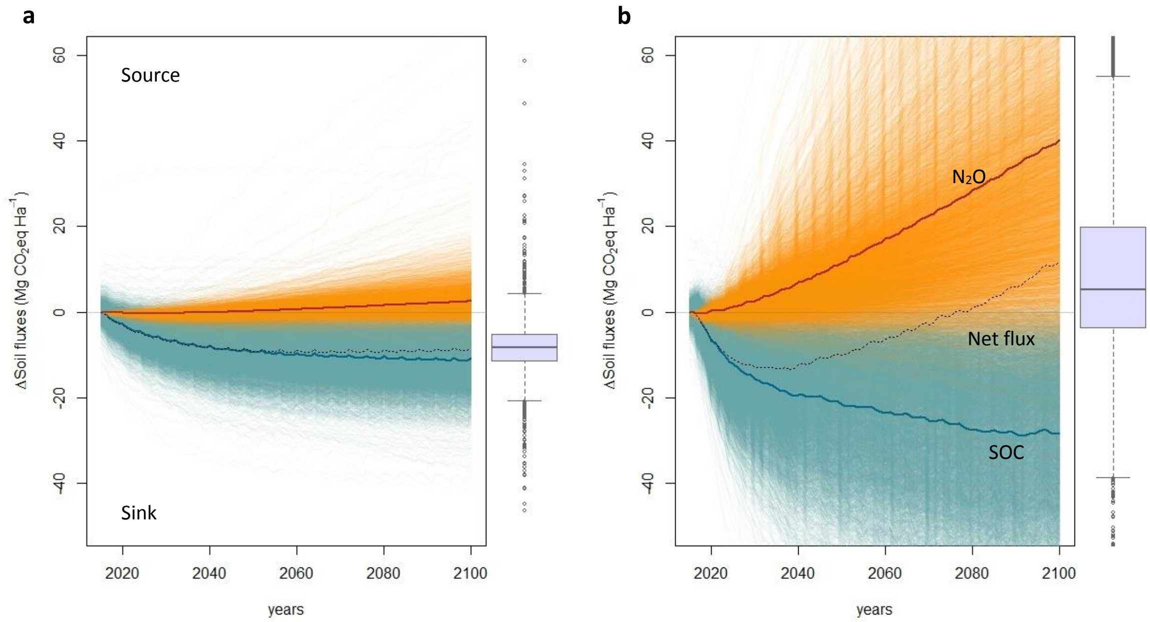

Fig. 1: Temporal trend of cumulative soil organic carbon sequestration, N_2O emissions and net soil fluxes under the mitigating practices in comparison with the baseline. a) scenario based on integrated crop residue retention and lower soil disturbance - IRS. b) scenario based on N fixing cover crop incorporated into soil (green manure) - CC. The y axis reports the differences in Mg CO_2eq ha^{-1} between mitigating practices and the baseline for soil organic carbon sequestration (blue line), N_2O emissions (red line) and net GHG fluxes (dark line). Thick lines are the averages of all 7804 locations simulated (thin lines).

When N fixing cover crops were present in the crop rotation, we observed an inverse relationship between yield changes compared to the baseline and N applications (Fig. 2). For application rates above 80 kg ha^{-1} of total N applied, we obtained frequent negative values (i.e. a yield reduction as compared to the baseline situation). Our results showed the same trends as observed in a meta-analysis investigating the same dynamics and, also, a positive relation between crop yield and N fixed, with a clear gain above 80 kg ha^{-1} of N fixed. The IRS management did not affect consistently the crop response and the yield change distribution was narrowly ranging across zero in the medium-term period (Fig. 2). Indeed, we saw a slightly positive yield response in the long-term as indicated by the distribution shifted towards positive values. This behavior was likely driven by the higher amount on N recycled into agroecosystems due to lower residue exportation, which was made available for plant uptake as limited competition for SOC build-up was occurring after 2050.

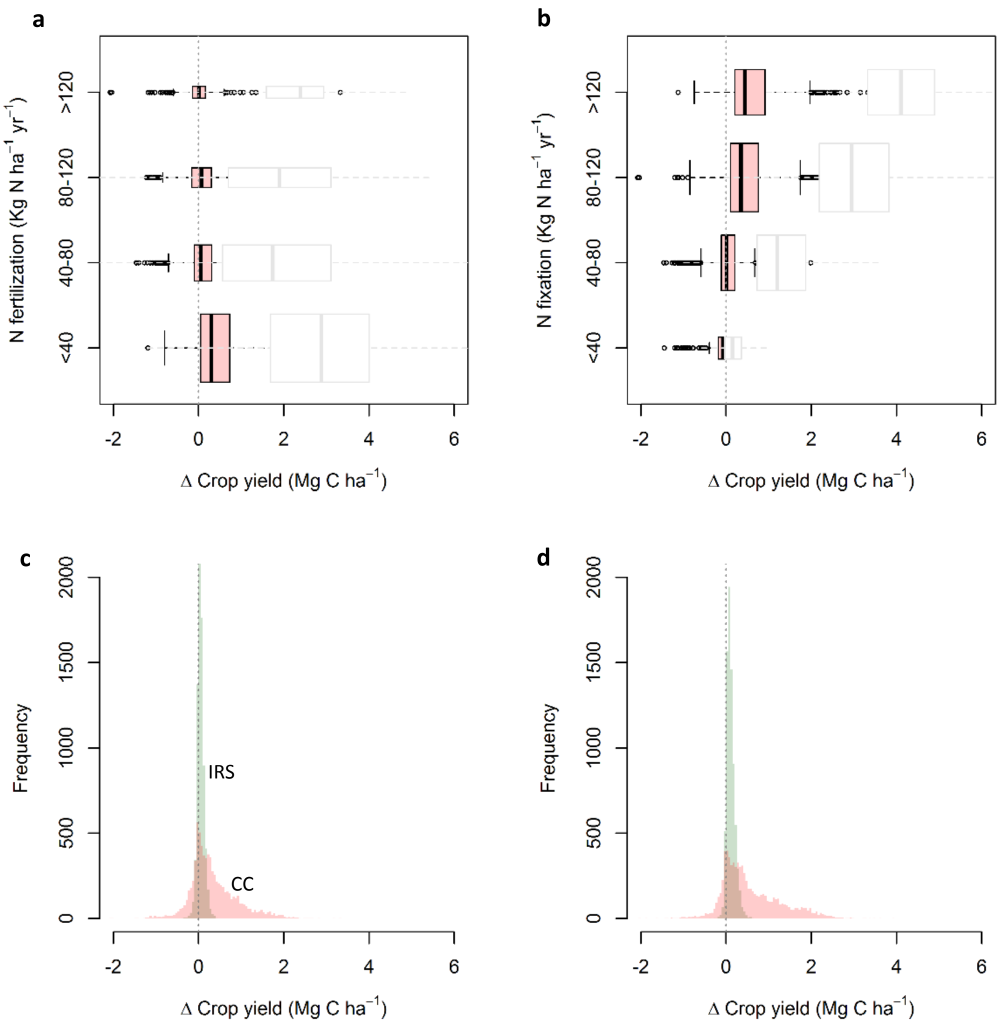

Fig. 2: Effect of mitigating practices on crop responses and relationship whit N input sources. a and b) Yield change distributions compared to the baseline in relation to total N fertilization and fixation, respectively, in the CC scenarios. Under this scenario we considered a reduction of N fertilizations equal to 75% of N fixed (assuming a low fertilization efficiency), with respect to the baseline; the box width is proportional to the locations number in that class. Grey boxes represent the difference in whole net primary productivity. c and d) Yield difference in the integrated crop residue retention-lower soil disturbance scenario (IRS - green histogram) and N fixing cover crops scenario (CC - red histogram), averaged for the period 2035-2040 (c) and 2095-2100 (d).

Conclusions

While existing data on C sequestration in agricultural soils are focusing on the C cycle, we showed that agricultural practices introducing additional N can potentially turn the agroecosystems to a net GHG source in the long-term. Process-based biogeochemistry models have proved to be a valid tool in order to provide quantitative and dynamic data about the agroecosystem mitigation potential. However, a better integration between management intervention and biogeochemical C and N cycles should be transferred to Earth System Models, as soil fluxes are still one of the most uncertain components and neglecting management induced-changes could confound the interpretation of land-atmospheric feedbacks. The potential SOC sequestration in arable soils is high as their general state is far from saturation and there is a high possibility to better adapt and rapidly change the management, in comparison with other land uses/classes. However, our results clearly highlight that any initiative or policy aiming at mitigating climate change should look at the coupled C and N cycles together.

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