

Response to Anonymous Referee #2

Overall response: We would like to thank referee 2 for these useful and constructive comments. These help improve the manuscript. Here we outline the point-by-point responses below in blue.

Dear Authors and Editor,

This manuscript targets a relevant and important topic and provides valuable insights into N₂O emissions dynamics in agriculture of relevance for GHG emissions monitoring and reporting as well as policy.

The paper is well-written. The introduction is clear and motivates the study well. The methods section is likewise clearly structured and the discussion brings up important uncertainties in the modelling approach.

Reply: We appreciate that the reviewer recognizes the value of our study.

However, I have a number of comments that the authors need to address before I can recommend it for publication, as outlined in the sections below.

Reply: Please find our point-by-point reply below.

Major comments:

1) Clarify the use of emission factors (EFs)

The authors use emission factors as one of the key output variables in their analysis. This is in the introduction motivated by the use of EFs in Tier 1 IPCC methodology for GHG reporting. However

1. The definition of EFs in this study deviates from the one used in IPCC guidelines (see detailed comment line 192). Please clarify why this alternative definition was what this means for the comparison between your derived EFs and the IPCC default ones.

Reply: We thank the reviewer for highlighting this distinction. We agree that the EFs derived from the modelling in our study are not defined exactly the same as the IPCC Tier 1 EFs. We clarify the definition and terminology.

In this study, we define a fertiliser-induced N₂O EF, calculated as the difference in simulated N₂O–N emissions between the baseline and “nofert” simulations (see our

response below), normalised by the amount of fertiliser N applied, as shown in Eq. 2. This approach is consistent with the commonly used concept of fertiliser-induced N_2O emissions, in which emissions from an unfertilised control are subtracted from emissions from a fertilised treatment and the difference is expressed relative to fertiliser N applied.

Our modelling-derived EFs, however, should not be interpreted as being equivalent to the IPCC Tier 1 EF. The objective is to investigate to which extent these modelling-derived EFs vary with space and time. Since the IPCC 1% Tier 1 EF applies to a broad set of N inputs including synthetic and organic fertilisers, we nevertheless use the IPCC EF as a reference because both quantities express N_2O emissions relative to fertiliser N inputs and therefore provide a useful common metric for illustrating differences between a fixed-factor inventory approach and a spatially and temporally explicit process-based modelling approach. The comparison is therefore intended as a contextual comparison of the resulting EFs and emission estimates, rather than as a direct validation of our model-derived EF against the IPCC default EF.

2. Clarify the intention of using EFs as a primary output variable for analysis. Is the goal to develop alternative EFs for use in GHG reporting or to facilitate comparisons?

Reply: In this study, the purpose of calculating the fertiliser-derived EFs is primarily to facilitate comparison and interpretation of the modelling results and to demonstrate an alternative process-based modelling approach for national-scale N_2O estimates, rather than to develop alternative EFs for direct application in national GHG reporting.

The motivation for including EFs is that they provide a commonly used metric for expressing the magnitude of agricultural N inputs that are eventually transformed to N_2O emissions (i.e., the relationship between applied N and N_2O emissions). Compared with the fixed EFs used in emission inventories, our process-based simulations explicitly represent variation in climate, soil conditions and agricultural management. So these modelling-derived EFs were used as a diagnostic output to illustrate how variable the relationship between N inputs and N_2O emissions are across Switzerland and over time. Instead of proposing a set of modelling-derived EFs as replacement EFs for national GHG reporting (could be a future direction but not for this study), we focused on demonstrating the differences between a Tier 1 approach and a process-based modelling approach (as discussed in L407-417) and emphasizing the very dynamic nature of N_2O emissions (e.g., as discussed in L373-377), highlighting that current 1% IPCC EF needs to be revised in order to capture the climatic effects.

We clarified our purpose in the Introduction.

2) Clarify development of background emissions

Background emissions of N₂O were derived from a counterfactual scenario where climate drivers were the same but fertiliser and manure N inputs were set to zero. It is however not clearly described how e.g. crop rotations and harvests are handled in this counterfactual. And won't these "background emissions" at least partly represent legacy emissions from SOM built up in the spin-up? See also my detailed comment on lines 186-190.

Reply: We thank the reviewer for pointing out this important aspect of the "nofert" scenario simulations. We agree that the term "background N₂O emissions" needs better clarification.

Background N₂O emissions are commonly defined as N₂O emissions from agricultural soils in the absence of current fertiliser N inputs (Bouwman 1996; Neftel et al. 2007; van Beek et al. 2011). Such emissions can originate from crop residues, SOM mineralisation, BNF and atmospheric deposition, and may also reflect residual N and soil conditions resulting from previous agricultural management (Bouwman 1996; Kim et al., 2013). Thus, "background" does not necessarily exclude all the influences of previous fertilisation or management.

In our "nofert" scenario, synthetic and organic fertiliser N inputs were set to zero, while other management practices, including crop rotations, planting, cultivation and harvest were kept identical to those in the baseline simulations, as described in L192-194. The baseline and "nofert" simulations also used the same spin-up. Consequently, the N₂O emissions simulated in the "nofert" scenario can retain "legacy effects" of previous fertilisation and management practices through the SOM established during spin-up. In addition, the exclusion of fertiliser inputs can alter crop growth and residual inputs, thereby affecting subsequent soil N cycling.

We clarify that "background N₂O emissions" represents the modelled N₂O flux under the zero fertilisation "nofert" scenario rather than the emissions completely independent of previous agricultural development. This provides a consistent baseline against which the incremental N₂O emissions resulting from fertiliser N inputs can be quantified.

We revised the definition of background N₂O emissions to improve clarity.

"F_{bg}, kg N ha⁻¹ yr⁻¹; defined as N₂O emissions from soils that are not fertilised **during the simulation period between 1981–2020 so that these emissions are from non-**

fertiliser N sources (e.g., biological N₂ fixation, atmospheric N deposition and return of crop residues) and SOM mineralisation, and may also reflect residual N and influences of previous agricultural management represented in the modelled soil pools.”

3) Revise statistical treatment of Monte Carlo results

Monte Carlo simulations were used by varying a set of influential model parameters around assumed distributions. From this a 95% confidence interval (CI) around the main results were calculated. However, it is not possible to derive confidence intervals from Monte Carlo simulations as the number of Monte Carlo runs will impact the width of the CI. So, increasing your Monte Carlo from 200 iterations to, say 400, would increase your perceived confidence. See e.g. von Brömssen & Rööß (2020) and my detailed comment on lines 242-243.

Reply: We thank the reviewer for pointing this out. We agree that our original use of the term “95% confidence interval” was inappropriate. The Monte Carlo simulations were not intended to provide an inferential confidence interval for the “true” total N₂O emissions or for the mean. Instead, the simulations propagate the prescribed uncertainty in selected DayCent N dynamic parameters through the model and generate an ensemble of possible national total estimates.

We revised the manuscript and replaced “95% confidence interval” with “95% uncertainty interval (defined by the 2.5th and 97.5th percentiles of the Monte Carlo simulations)”. The interval represents the central 95% of modelling results generated from the specified parameter uncertainty distributions.

We also agree that the number of Monte Carlo iterations determines how precisely the assumed output distribution is numerically represented. However, increasing the number of iterations does not reduce the underlying parameter uncertainty specified in the model; instead, it provides a more detailed numerical sampling of the prescribed distributions. In our analysis, 200 parameter sets were generated using Latin Hypercube Sampling (LHS), which provides more uniform coverage of the multidimensional parameter space than simple random sampling. We have clarified this distinction in the revised manuscript and have avoided any wording that might suggest that the number of simulations determines the level of statistical confidence in the resulting uncertainty range.

We believe that this revised interpretation more accurately describes the purpose and statistical meaning of our uncertainty analysis.

Detailed comments by line:

46: “Switzerland” appears a bit suddenly here. It comes in more naturally at line 60 so can be dropped here.

Reply: We removed “Switzerland” and rephrased the sentence.

“Many Annex I countries (i.e., industrialised countries and countries with economies in transition) **report annual N₂O emissions** to the United Nations Framework Convention on Climate Change (UNFCCC) predominantly based on Tier I methodologies (FOEN, 2026).”

49: Clarify that the 1% EF implies that 1% of N inputs is released as N₂O-N.

Reply: We revised the text to clarify the EF.

“...which estimate emissions as a fixed proportion of N inputs (i.e., a default aggregated EF of 1% for fertiliser-induced emissions **as N₂O-N** after accounting for soil organic matter turnover; Buendia et al., 2019).”

51-53: You write that “EFs are typically fixed in space and time” but in the same sentence that they still “partly represent” climatic conditions which seem like a contradiction. I am assuming that you refer to the disaggregation of default EFs for some climate conditions, but please clarify.

Reply: We revised the following text to avoid contradiction.

“However, because EFs are typically fixed in space **and time and do not take into account the influence of climatic conditions, soil properties, and local crop and field management on N₂O emissions, they only provide** a limited representation of spatial and temporal variability in emissions.”

73-74: Clarify “agricultural information” to show the detail of management variables included in the model

Reply: We revised the following text to provide details of model inputs and the datasets we used.

“We compiled spatially explicit datasets on climate (**temperature and precipitation**), soil properties (**soil texture, pH and organic matter**) and agricultural **management information (crop rotation and distribution, fertiliser application rates, and timing**

of planting and harvesting), and applied the well-calibrated and validated biogeochemical model DayCent at a high spatial resolution of 1 km×1 km.”

108-110: Please clarify the extent of this “evaluation” of the model to Swiss data and how this feeds into your work. Has this resulted in a Swiss calibration of model parameters that you use? How many crops have been evaluated and how representative are these to the total Swiss cropland? Does model evaluation cover the climatic, topographic and soil gradient in Switzerland?

Reply: We revised the text and added the following details of previous model evaluation.

“Previous studies have demonstrated that calibrations to site-specific soil and climate characteristics improved model performance in reproducing observed N₂O emission patterns (Del Grosso et al., 2000; Gurung et al., 2021; Laub et al., 2024; Necpalova et al., 2018). **For Switzerland, DayCent was calibrated and evaluated using experimental and measurement data from four long-term experimental sites in Switzerland (Therwil, Frick, Changins and Reckenholz), covering more than 14 major crops and a range of pedoclimate conditions (Emmel et al., 2018; Hüppi et al., 2015; Krauss et al., 2017; Mayer et al., 2015). The evaluation included crop productivity, soil carbon dynamics and soil N₂O emissions (Necpalova et al., 2018). DayCent was subsequently further calibrated and evaluated using Swiss (as well as French and German) cropland and grassland observations, with particular emphasis on key N dynamic parameters and their influences on observed N₂O emissions (Dos Reis Martins et al., 2022, 2024). Thus, the seven key N dynamic parameters used in this study were based on values that had been extensively calibrated and evaluated in these previous studies. These previous studies therefore provide a good basis for applying these parameter values across Switzerland, while acknowledging that the available sites do not cover the full climatic, topographic and soil conditions of the country.”**

128-131: How was data for the 24 agri-climatic zones resampled to the 1x1km grid?

Reply: Land use areas are available at a 1km × 1km resolution from Swiss Federal Statistical Office (BFS), whereas crop-specific areas and fertiliser application rates available for 24 agri-climatic zones were taken from Wüst-Galley et al. (2020). Each 1km × 1km grid was assigned to its corresponding agri-climatic zone, and the crop rotation scheme (as described in L149-156 and in Jiang et al. (2026)) was applied within each zone to distribute the reported cropland area among crop types. The annual mean fertiliser application rate for each individual crop within an agri-climate zone was then assigned to all 1km × 1km grids that belong to this zone.

We added the following texts in **Sect 2.4** to improve clarity.

“Our crop rotation scheme considers both nationwide recommendations for agricultural production and real practices sourced from farmers. **We applied this scheme to determine the most likely crop rotation through an iterative allocation procedure, in which cropland area was sequentially allocated to crop types according to their ranked areas, with crop types having larger areas allocated first (Jiang et al., 2026). This approach ensured that the modelled areas of individual crops were consistent with statistical data for the 24 agro-climatic zones (Wüst-Galley et al., 2020) and at the national level. This approach was adopted because spatially explicit crop rotation data are not available at the national scale, while allowing consistency with reported crop distributions across Switzerland at the agri-climatic zone level. Each 1km × 1km grid was assigned to its corresponding agri-climatic zone, and the annual mean crop-specific fertiliser application rate for that zone was assigned to all grids within the zone.**”

147-148: Clarify if the “fixed dates” were assumed to be the same across Switzerland or varied by agri-climatic zone

Reply: The static calendar with fixed dates were assumed to be the same across Swiss cropland. We revised the following text to clarify.

“...e.g., a static calendar **was used for the whole country**, which has fixed dates for each management practice rather than dynamic dates varying by years.”

186-190: In the “nofert” scenario I am assuming that net mineralisation of SOM will be higher than in the scenarios with continued fertilisation due to mineralisation of SOM built up from manure and crop C inputs in spin-up and the lower inputs of C in scenario with no manure application and reduced crop growth. So, is it really “background” N₂O emissions you observe or rather a combination of that and legacy N₂O emissions due to previous agricultural management? Or did you use a separate spin-up for the “nofert” scenario that did not include manure and fertilisers during spin-up?

Reply: We thank the reviewer for pointing this out. We reference our detailed answer to reviewer’s 2nd major point. To summarise briefly, we used the same spin-up for both baseline and “nofert” simulations, and we set the fertiliser N inputs to zero in “nofert” simulations while keep other variables (crop rotations, planting and harvest etc) identical.

We revised the definition of background N₂O emissions to improve clarity.

"F_{bg}, kg N ha⁻¹ yr⁻¹; defined as N₂O emissions from soils that are not fertilised during the simulation period between 1981–2020 so that these emissions are from non-fertiliser N sources (e.g., biological N₂ fixation, atmospheric N deposition and return of crop residues) and SOM mineralisation, and may also reflect residual N and influences of previous agricultural management represented in the modelled soil pools."

192: This definition of EF diverges from the definition of Tier 1 EF (i.e. EF1) in IPCC Guidelines for greenhouse gas inventories, which in addition to N in mineral and organic fertilisers also include N in crop residues and SOM mineralisation in the denominator. Please clarify and motivate why an alternative definition was used here as you relate your work to the default IPCC EFs in your introduction.

Reply: We reference our detailed answer to reviewer's 1st major point.

We revised the Introduction added the following text.

"We also calculated N₂O EFs from the difference in N₂O emissions between the baseline and no-fertiliser simulations relative to applied synthetic and organic fertiliser N. These modelling-derived EFs were compared with the IPCC Tier 1 EF, which is defined for a broader set of N inputs, including synthetic and organic fertilisers, crop residues and N mineralisation associated with changes in soil organic matter. We use our modelling-derived EFs as a diagnostic measure of the spatial and temporal variability in fertiliser-induced N₂O emissions."

235-236: Why does your default value differ from the calibrated mean?

Reply: The default values are original uncalibrated values prescribed in the DayCent model, whereas the calibrated mean values were used for the spatial simulations as "best estimates". We changed "Default" to "Default (uncalibrated)".

242-243: Am I correct to interpret this as that you calculated a confidence interval around the mean (or median) based on the Monte Carlo simulations? If so, that is not correct as the number of Monte Carlo runs performed (i.e. the number of "samples") will impact the width of the confidence interval. See e.g. von Brömssen & Rööß (2020).

von Brömssen, C., Rööß, E. Why statistical testing and confidence intervals should not be used in comparative life cycle assessments based on Monte Carlo simulations. *Int J Life Cycle Assess* **25**, 2101–2105 (2020). <https://doi.org/10.1007/s11367-020-01827-4>

Reply: We revised Section 2.7 Uncertainty evaluation to address the reviewer's concern.

“Uncertainty in modelled national N₂O emissions was evaluated using a Monte Carlo ensemble approach **based on 200 parameter realizations generated using Latin Hypercube Sampling (LHS)**, combined with the spatially explicit implementation of the DayCent model. We focused on quantifying the uncertainty arising from N cycle parameters in DayCent (details in Table S2), which have been shown to substantially influence model performance and cumulative N₂O emissions (Dos Reis Martins et al., 2022, 2024).

Uncertainty distributions for the selected model parameters were defined based on the default values and calibrated parameter ranges reported by Dos Reis Martins et al. (2022, 2024). A total of 200 parameter sets were generated using LHS to provide broad and approximately uniform coverage of the multidimensional parameter space.

The baseline simulations comprised more than 50’000 grids. Running 200 times over the full simulation domain was computationally expensive. We therefore used Conditioned Latin Hypercube Sampling (cLHS) to create a representative subset (n=400) of the simulated grids. The subset grids was conducted using key environmental and management variables that influence N₂O emissions, including MAT, MAP, SOM, soil pH, soil clay content, fertiliser intensity and organic fertiliser fraction. The selected grids were used to represent the multivariate heterogeneity of environmental conditions and management practices from the full simulation domain. For each of the 200 parameter sets, DayCent was run independently for all representative grids.

The ensemble of these modelled N₂O emission estimates was summarized using its empirical percentiles. The 2.5th and 97.5th percentiles were used to define a 95% simulation interval, representing the central 95% of modelled emission outcomes generated by propagating the prescribed parameter uncertainty through the DayCent model. This interval represents uncertainty associated with the selected DayCent N cycle parameters rather than a statistical confidence interval for the true N₂O emissions or their mean (von Brömssen and Röö, 2020). The uncertainty analysis does not account for uncertainties associated with model structure, climate inputs, soil datasets or management data.”

252-253: Consider the wording “despite declining fertiliser inputs” which indicate that reduced fertiliser inputs are expected to reduce EFs, but that’s not the case right?

Reply: We removed the phrase to avoid misunderstanding.

271: See comment above.

Reply: We removed the phrase to avoid misunderstanding.

360-361: What does “spatial increases” mean?

Reply: As shown in Fig. 5 e&f, the relative increases of N₂O due to climate change are generally larger in grassland (12–18%) than cropland (3–9%) spatially. We revised the text to improve clarity.

“...modelled decadal mean N₂O emissions increased by 5.7% in croplands and 13.6% in grasslands between 2011 and 2020 due to the climatic effect (difference between “baseline” and “clim1980” simulations), with **larger relative increases found in grassland across the country** (Fig. 5f).”

422: Clarify if the 25% reduction refers to total national use or per hectare application rate.

Reply: The 25% reduction refers to national total fertiliser use. We revised the following text.

“Total fertiliser application (including both synthetic and organic) in Switzerland decreased by ~25% over the studied period (Figs. S2c).”

424: Change “in line with” to “along with”

Reply: We changed the text as suggested.

503: Missing “have” in “can have”

Reply: We added the missing “have” in the sentence.

505-506: Clarify what you mean by “substantial shifts”

Reply: We thank the reviewer for pointing this out. We realise that the phrase “substantial shifts” was not clear. We revised the following text.

“Thus, as extremes (heatwaves, droughts or compound events) are expected to become more frequent under climate change (Calvin et al., 2023), the magnitude of N₂O emissions and their changes can vary depending on the timing, intensity and concurrence of temperature and precipitation anomalies.”

531-532: You do not show that climate change “renders mitigation measures less effective” but rather that climate-induced N₂O emission increases offsets some of the reduction from mitigation.

Reply: We thank the reviewer for pointing this out. We agree that, from a biophysical perspective, our results do not demonstrate that climate change renders the mitigation measure itself less effective. Our original statement was intended from a policy perspective, where the relevant consideration is the net emission outcome of mitigation under a changing climate. In this context, climate-induced increases in N₂O emissions partially offset the reductions achieved through lower fertiliser inputs, resulting in a smaller net reduction than would occur in the absence of the climate-induced increase. To avoid ambiguity, we removed the original statement.

536-537: Would be interesting if you could elaborate on what “site-specific mitigation strategies” might be. What strategies could be suitable in one place but not another due to pedoclimatic conditions?

Reply: We thank the reviewer for this helpful suggestion. We revised the text and elaborate

“Second, the effects of management practices are spatially variable and context specific. Existing experimental and modelling studies demonstrated inconsistent effectiveness of mitigation measures at different places. **For example, nitrification inhibitors applied with fertiliser are found generally effective in reducing agricultural soil N₂O emissions, whereas other practices such as manure substitution (full or partial), reduced- or no-tillage and irrigation have shown variable effects, with both increased and decreased N₂O emissions reported (Charles et al., 2017; Mei et al., 2018; Van Kessel et al., 2013; Velthof & Mosquera, 2011; You et al., 2024).** This implies that generalized scenarios for N₂O reduction might be insufficient given the varying pedoclimatic conditions, management practices, and highly dynamic nature of N₂O fluxes. Therefore, site-specific mitigation strategies developed from monitoring, process-based modelling and field experiments should be considered.”

553-554: Related to my comment on lines 531-532 this is not really a trade-off but rather that some of the gains from mitigation are offset by climate-induced emissions increases resulting in lower absolute emissions reductions. However, from your results I can't see that they show that this compromises the effectiveness of mitigation measures (here reduced fertiliser N inputs), but rather that it's a battle up-hill.

Reply: We revised the text to address this point.

“These findings highlight that climate-induced increases in N₂O emissions can partially offset the reductions achieved through declining fertiliser inputs, resulting in smaller net reductions in N₂O emissions than would occur in the absence of the climate change.”

Reference:

Charles, A., Rochette, P., Whalen, J. K., Angers, D. A., Chantigny, M. H., & Bertrand, N. (2017). Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. *Agriculture, Ecosystems & Environment*, 236, 88–98. <https://doi.org/10.1016/j.agee.2016.11.021>

Mei, K., Wang, Z., Huang, H., Zhang, C., Shang, X., Dahlgren, R. A., Zhang, M., & Xia, F. (2018). Stimulation of N₂O emission by conservation tillage management in agricultural lands: A meta-analysis. *Soil and Tillage Research*, 182, 86–93. <https://doi.org/10.1016/j.still.2018.05.006>

Van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M. A., Linnquist, B., & Van Groenigen, K. J. (2013). Climate, duration, and N placement determine N₂O emissions in reduced tillage systems: A meta-analysis. *Global Change Biology*, 19(1), 33–44. <https://doi.org/10.1111/j.1365-2486.2012.02779.x>

Velthof, G. L., & Mosquera, J. (2011). The impact of slurry application technique on nitrous oxide emission from agricultural soils. *Agriculture, Ecosystems & Environment*, 140(1–2), 298–308. <https://doi.org/10.1016/j.agee.2010.12.017>

You, L., Ros, G. H., Chen, Y., Zhang, F., & De Vries, W. (2024). Optimized agricultural management reduces global cropland nitrogen losses to air and water. *Nature Food*, 5(12), 995–1004. <https://doi.org/10.1038/s43016-024-01076-w>