Response to Anonymous Referee #1

Overall response: We would like to thank referee 1 for these useful and constructive comments. These help improve the manuscript. Here we outline the point-by-point responses below in blue, and the relevant tables and figures are attached. Line numbers given in the response refer to the revised manuscript with track changes.

The manuscript, "**Warming-induced agricultural nitrous oxide emissions can offset mitigation benefits of fertiliser management**" by Jiang et al., is interesting and addresses a **scientifically important question**. However, I would recommend **major revisions** before acceptance.

The topic is timely and important. The manuscript addresses a strong research question with potentially important implications for agricultural climate mitigation. The combination of high-resolution, process-based explicit modelling with a valuable national-scale dataset/model framework is a major strength. The manuscript is also transparent about several limitations of the modelling framework.

The scientific results are presented clearly and concisely.

We thank that the reviewer for recognizing the value of our study.

However, I have substantial concerns regarding the representation of **agricultural management dates and fertiliser timing, land-use change, and biological nitrogen fixation (BNF)** in the scenario study.

Please find our detailed reply below.

Major comments

1. Representation of management dates and fertiliser timing

The authors state that they use static/fixed management calendars rather than dynamically varying management dates between years. For a 40-year climate-change analysis, this could be important because warming may affect planting and harvest dates, growing-season duration, mowing and grazing dates, and plant N demand, among other processes.

If fertilisation occurs on a fixed calendar date despite a progressively earlier growing season, the model may create an artificial mismatch between N fertilisation and plant N demand. This mismatch could itself affect simulated N_2O emissions. Similarly, keeping mowing dates fixed could affect plant residue inputs and SOM mineralisation. The conclusion that warming increases N_2O emissions may therefore partly reflect the interaction between warming and fixed management schedules. I suggest that the authors quantify the effect of climate-responsive management dates for fertilisation, mowing, and other relevant management activities, in order to demonstrate whether the main conclusions remain robust when management responds to climate change.

We thank the reviewer for highlighting this important point. We agree that climate change may have influenced the timing of planting, fertilisation and harvest in Swiss agriculture, and that farmers may have adapted local management practices accordingly. However, historical records of field-specific management dates are not available, thus we cannot construct yearly climate-responsive crop calendars. Developing such a dynamic crop calendar is also beyond the scope of this study. We would like to mention that, although management operations were prescribed according to fixed crop calendars, crop growth and N uptake are simulated dynamically in DayCent in response to environmental conditions, such as temperature, soil moisture and nutrient availability.

We examined the available observational records. Records from an intensively managed grassland at Chamau, Switzerland, show that fertilisation dates varied among years but generally followed a regular pattern, without an apparent trend towards earlier or later applications between 2006 and 2020 (Fig. R1). For croplands, records from a long-term trial in Therwil, Switzerland (see Table R1), do not exhibit a consistent temporal trend in planting dates for silage maize or winter wheat. By contrast, potatoes were planted 20 days earlier in 2009 than in the earlier observed years (1985, 1992 and 1999) and the corresponding harvest dates were also earlier, but this information does not provide sufficient evidence to reconstruct systematic historical changes in management timing at the national scale.

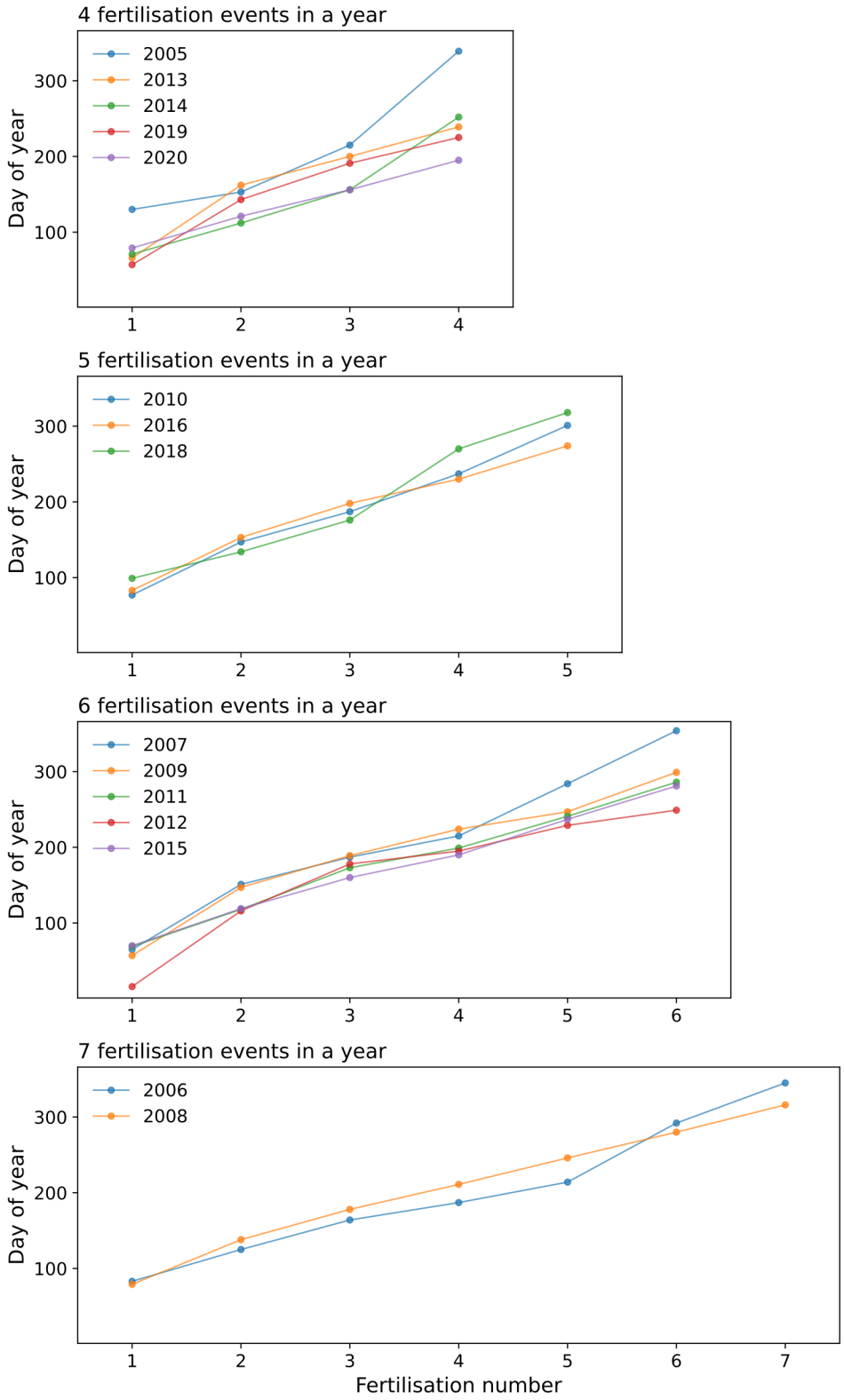


Figure R1. Fertilisation dates of an intensively managed grassland in Chamau, Switzerland between 2005 and 2020.

Table R1. Planting, harvest and fertilisation dates of three major crops of a long-term trail in Therwil, Switzerland. *Winter wheat is harvested in the following year after planting.

Crop	Year	Planting	Harvest	Fertilisation
Potato	1985	112	240	109
	1992	112	246	146
	1999	119	235	113, 151, 140
	2009	99	211	97, 128, 140
Silage maize	2002	130	261	119, 168, 176
	2006	144	272	109, 135,166, 185
	2013	148	268	133, 168, 183, 190
Winter wheat*	1995	286	207	73, 129
	2000	286	203	75, 116
	2003	303	196	79, 107, 132
	2007	299	195	65, 100, 136
	2010	288	201	82, 110, 139

To address the reviewer's concern, we conducted two additional rounds of sensitivity tests to assess the sensitivity of N_2O emissions and the estimated climatic effect to alternative management timings. For croplands, planting, fertilisation and harvest dates were advanced by a) 7 and b) 14 days for all spring crops relative to the prescribed crop calendar. For winter crops, autumn planting dates were kept identical to those in the baseline simulations, while fertilisation and harvest dates in the following year were advanced by a) 7 and b) 14 days. This treatment avoids introducing an additional shift in autumn establishment while testing the sensitivity of N_2O emissions to earlier management during the growing season. For grassland (excluding SPA), where mowing occurs 3-7 times throughout the year and the timing was constrained by satellite-derived observations for 2019–2022, fertilisation and mowing dates were shifted by ±14 days. The rescheduled management practices were applied only to the baseline simulations. We retained the original fixed crop calendar in the clim1980 simulations because this scenario is designed to represent agricultural production under a fixed climate representative of the 1980s, for which a fixed management calendar is internally consistent. The sensitivity tests therefore assess whether the estimated climate-induced increase in N_2O emissions is sensitive to the assumed timing of management practices under the changing climate.

We found that the alternative management timings changed simulated N_2O emissions by 0.5–2.2% in croplands and by -0.6% to 0.3% in grassland relative to the baseline simulations. Across these sensitivity tests, the estimated climatic effect remained positive, with simulated N_2O emissions increasing by 3.5–5.2% in croplands and 13.0–13.9% in grasslands. These results indicate that the direction of the climatic effect and our overall conclusions are robust to the tested changes in management timing.

We revised the manuscript accordingly and added the following text.

In Section 2.6 L271–277, we added,

"Because comprehensive historical records of field-specific fertilisation, planting and harvest (mowing) dates were unavailable, we could not reconstruct year-specific management timing. We therefore conducted two additional rounds sensitivity tests in which dates of management practices were rescheduled. For croplands, planting, fertilisation and harvest dates were advanced by a) 7 and b) 14 days for spring crops relative to the prescribed crop calendar, whereas autumn planting dates of winter crops were kept identical to those in the baseline simulations and fertilisation and harvest dates in the following year were advanced by 7 and 14 days. For grasslands, fertilisation and mowing dates were shifted by ±14 days to assess the sensitivity of N_2O emissions to management timing.

In Section 3.4 L425–427, we revised,

"Based on the difference between the baseline simulations and the scenario simulations with time-varying fertiliser but fixed climate representative for the 1980s (clim1980; Table 1), modelled decadal mean N_2O 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). Across the management-timing sensitivity tests, the estimated climatic effect ranged from 3.5% to 5.2% in croplands and from 13.0% to 13.9% in grasslands."**

In Section 4.4 L556–563, we added,

"Under the prescribed fertilisation and management schedules, our results indicate that N_2O emissions would have increased by 5.7% in croplands and 13.6% in grasslands due to warming and changes in precipitation patterns between 2011 and 2020 (Fig. 5a, b). We found that advancing management timing resulted in 0.5% to 2.2% lower N_2O emissions in croplands and changes of −0.6% to 0.3% in grasslands relative to the baseline simulations. The simulated increase

in N_2O emissions associated with the changing climate remained positive across all tested management-timings, ranging from 3.5% to 5.2% in croplands and from 13.0% to 13.9% in grasslands. These results indicate that the direction and estimated climate-induced increase in N_2O emissions are robust across the tested changes in management timing."

In Section 4.5 L609–615, we added,

"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 N_2O 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 N_2O 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 N_2O reduction might be insufficient given the varying pedoclimatic conditions, management practices, and highly dynamic nature of N_2O fluxes. Therefore, site-specific mitigation strategies developed from monitoring, process-based modelling and field experiments should be considered. **Our management-timing sensitivity tests further suggest that advancing planting and fertilisation dates under a changing climate could reduce simulated N_2O emissions, highlighting the potential role of adaptive management timing as part of climate change mitigation strategies.**"

2. Land-use change and fertiliser inputs (Lines 200–201)

The authors state that "total fertiliser inputs also depend on land use areas which changed land use over the past 40 years, especially for croplands." How have the authors addressed this issue? Were land-use areas kept static, as in Figure S1?

If land-use areas were kept static, please quantify the impact of this assumption on the study outcomes. In particular, how does it affect the partitioning of national total fertiliser inputs among different crops?

We thank the reviewer for this comment. Land use areas were not kept static in our simulations. Instead, temporal changes in cropland and grassland areas were represented in our simulations, as shown in Table S3 (in the Supplementary Material) and described in Sect. 4.2 (L487-489). The corresponding land use are for each year was used to calculate the simulated national N_2O emissions as specified in Eq. (1).

Meanwhile, the national fertiliser inputs and their partitioning among crop types also reflect the temporal changes in the corresponding land use areas.

"Annual total N_2O emissions from Swiss croplands and grasslands ($E_{N2O,total}$, kt N yr^{-1}) were calculated using the following equation,

$$E_{N_2O,total} = \sum_{i=1}^{N} F_{N_2O,i} \cdot A_i, \quad (1)$$

where N is total number of grid cells belong to any given land use (N is 14'926 and 36'140 for croplands and grasslands, respectively). $F_{N2O,i}$ is the N_2O flux in grid i (kg N ha^{-1} yr^{-1}), and A_i is the **time-varying** area of cropland or grassland in grid i (ha). "

We revised the Methods L240–242 to clarify this point.

"Note that the national total fertiliser inputs also depend on land use areas which changed land use over the past 40 years, especially for croplands. **Our simulations accounted for these temporal changes in land use areas, and the corresponding land use area in each year was used to calculate the national N_2O emissions as specified in Eq. (1).**"

3. Biological nitrogen fixation (Lines 440–441)

The authors state that "BNF became an increasingly important N input in unfertilised grasslands, potentially contributing to an increase in modelled background emissions under warming conditions." Is temporal variation in the area undergoing BNF included in the DayCent simulations? If so, please show the variation in BNF area over time and report the simulated contribution of BNF to total N inputs for both cropland and grassland. This would help determine whether the increasing grassland background N_2O emissions shown in Fig. 1b are driven, at least partly, by changes in BNF.

We thank the reviewer for pointing out this issue regarding simulated BNF under the "nofert" scenario. We examined the temporal variation in simulated BNF and its contribution to total N inputs (without fertilisation) for both croplands and grasslands. We found that neither simulated BNF nor its contribution to total N inputs showed substantial temporal changes over the study period (Fig. R2). Thus, changes in BNF do not appear to explain the increasing background N_2O emissions from grasslands shown in Fig. 1b. We removed the original statement accordingly. The increase in background N_2O emissions from grasslands is primarily associated with increased SOM mineralisation under changing climatic conditions.

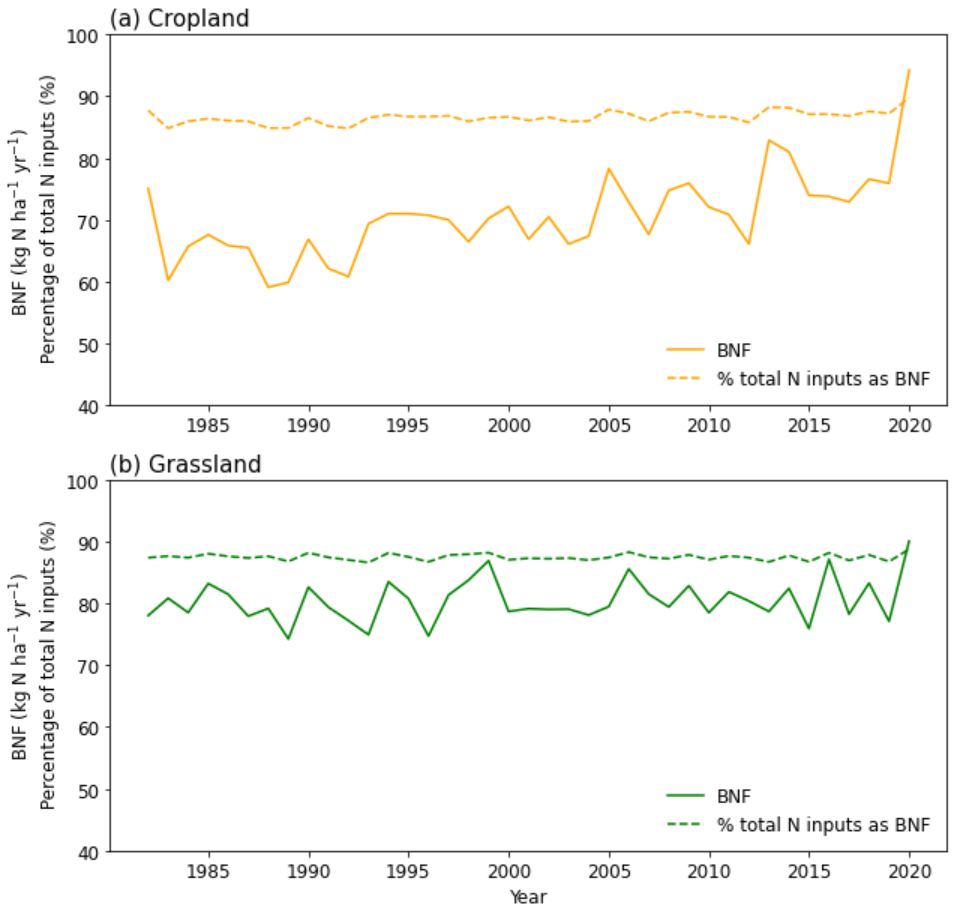


Figure R2. Simulated biological N_2 fixation and its contribution to total N inputs (BNF and atmospheric N deposition) for unfertilised (a) croplands and (b) grasslands in Switzerland between 1991 and 2020.

4. Synthetic versus organic fertiliser N inputs

I think Fig. 1c and the description of fertiliser N inputs would benefit from separating synthetic and organic N inputs for both cropland and grassland. I suggest showing separate time series for synthetic and organic fertiliser N inputs for cropland and grassland, for example by adding these results to Fig. S6. This would clarify whether the reported decline in fertiliser N inputs is primarily attributable to changes in synthetic fertiliser, manure/organic fertiliser, or both.

We thank the reviewer for this helpful suggestion. We updated Fig. S6 to show both synthetic and organic fertiliser N inputs for cropland and grassland over the study period. The Mann–Kendall trend tests indicate that the decline in total fertiliser N

inputs in both croplands and grasslands was associated with significant decreases in both synthetic and organic fertiliser N inputs.

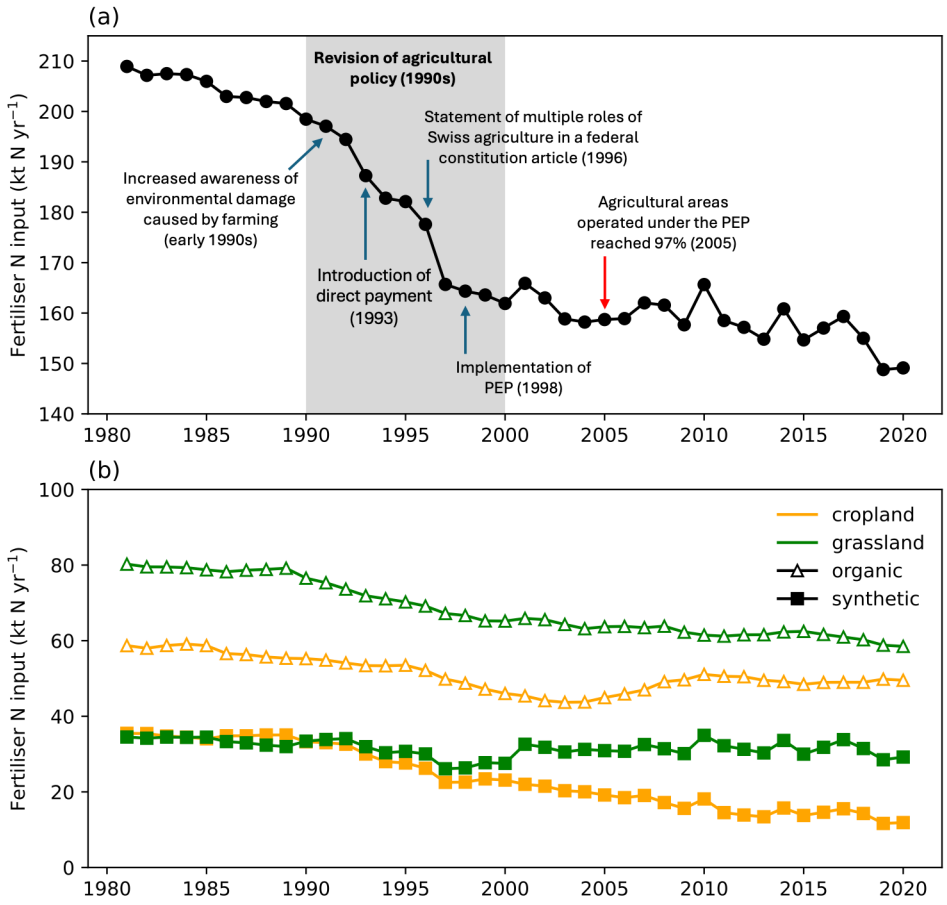


Figure S6. Nitrogen inputs from fertilisers to agricultural land in Switzerland. Fertilisers include organic (livestock manure applied to field and manure deposited during grazing) and synthetic fertilisers. Values from compiled datasets (see Methods). Shaded grey area in panel (a) represents the period in the 1990s when national policies and measures were implemented in the agricultural sector, prior to changing the Federal Constitution. Important events are shown along the timeseries of fertiliser nitrogen inputs. Values in parenthesis are corresponding years. Note that the y-axis starts from 140 kt N yr^{-1}. PEP is Proof of Ecological Performance. Panel (a) is taken from Jiang et al. (2026). Panel (b) shows that both types of fertiliser inputs declined in cropland and grassland, determined by Mann-Kendall Trend test.

5. Suggested modification of the title

I suggest modifying the title to: "**Climate** warming-induced agricultural nitrous oxide emissions can offset mitigation benefits of fertiliser **reduction**"

This would clarify that the study specifically concerns climate warming and reductions in fertiliser N inputs.

We revised the title to "**Climate warming-induced agricultural nitrous oxide emissions can offset mitigation benefits of fertiliser reduction**".

Minor comments

6. Please clarify in the caption whether "Fertilizer N inputs" in Fig. 1c includes both synthetic and organic fertilisers, as well as manure deposited during grazing.

We updated the caption of Figure 1 to clarify the fertiliser N inputs shown in Fig. 1c.

"Figure 1. … (c) Fertiliser N inputs per unit area (kt N ha^{-1} yr^{-1}) to agricultural land based on national statistics, **including both synthetic and organic fertilisers**. **Manure deposition to pastures during livestock grazing is accounted.** "

7. How is fertilisation distributed among crops in the model setup? Are synthetic and organic fertilisation data available separately for individual crops? Please specify this in the Methods section.

We thank the reviewer for this question. Fertiliser N inputs were distributed among individual crops and managed grasslands in the model setup, with organic and synthetic fertilisers estimated separately. For organic fertilisers, manure inputs (including slurry and solid manure) allocated to individual crops and managed grasslands were obtained from Wüst-Galley et al. (2020), following the methodology described in L155-160 and also used in our companion study (Jiang et al., 2026). The spatial allocation accounts for farm-level preferences for applying different types of manure to different crop groups and for the fertiliser requirements of grassland types across different elevation (Sinaj et al., 2017; Wüst-Galley et al., 2020).

For synthetic fertilisers, national annual fertiliser import statistics were used as the constraint on total synthetic fertiliser N inputs. We assumed all imported synthetic fertilisers were used in the corresponding year. For each crop and managed grassland, we first estimated a provisional synthetic fertiliser application rate as the difference between the recommended N application rate in the Swiss fertilisation guidelines and

the mineral N supplied by organic fertilisers. We then summed these provisional N requirements across all crops and managed grasslands and compared the resulting national total with the amount of synthetic fertiliser imported in that year. A correction factor was calculated as the ratio between these two quantities and applied uniformly to the provisional application rates. This approach ensured that the estimated synthetic fertiliser application at the national scale was consistent with the corresponding statistical data.

We revised the Method L162–171 and added the following text.

"Synthetic fertiliser inputs were derived from national import statistics (FOEN, 2026) and assumed to be applied as ammonium nitrate, which is a major type of fertiliser used in Switzerland. **All imported synthetic fertiliser was assumed to be applied in the corresponding year. For each crop and managed grassland, a provisional synthetic fertiliser application rate was estimated as the difference between the recommended N application rate specified in the Swiss guidelines "Principles for the fertilisation of agricultural crops in Switzerland" (Sinaj et al., 2017) and the mineral N supplied by organic fertilisers (assuming 50% of N in organic fertilisers is in mineral form). The provisional application rates were summed across all crops and managed grasslands to obtain a national synthetic fertiliser requirement in each year. We then calculated a correction factor as the ratio of the total annual amount of imported synthetic fertiliser to the national annual requirement. This correction factor (~1.7 for the 1980s and ~1.3 for the 2010s; indicating declined excessive N inputs through synthetic fertilisers) was applied uniformly to the provisional application rates, ensuring that the resulting national synthetic fertiliser use was consistent with the corresponding statistical data.**"

8. Please specify whether the nofert scenario also sets grazing-derived N inputs to zero. This could be clarified in the text, for example around Lines 186–189.

Grazing-derived N inputs were set to zero in the "nofert" scenario. We revised the Methods section L226–229.

"**Synthetic and organic fertilisers (including manure N deposition during grazing) were set to zero in the "nofert" scenario, while the other practices (e.g., planting, cultivation, harvest) specified in DayCent schedule files were the same as the baseline simulations. Subsequently, the following equation is used to** calculate modelling-derived EF (EF_{N_2O})"

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. Line numbers given in the response refer to the revised manuscript with track changes.

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 an motivates the study well. The methods section is likewise clearly structured and the discussion brings up important uncertainties in the modelling approach.

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.

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.

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 N_2O EF, calculated as the difference in simulated N_2O–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?

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 L474–484) and emphasizing the very dynamic nature of N_2O emissions (e.g., as discussed in L439–

446), highlighting that current 1% IPCC EF needs to be revised in order to capture the climatic effects.

We clarified our purpose in the Introduction L77–82.

2) Clarify development of background emissions

Background emissions of N2O were derived from a counterfactual scenario where climate drivers where 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.

We thank the reviewer for pointing out this important aspect of the "nofert" scenario simulations. We agree that the term "background N_2O emissions" needs better clarification.

Background N_2O emissions are commonly defined as N_2O 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. The baseline and "nofert" simulations also used the same spin-up. Consequently, the N_2O 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 N_2O emissions" represents the modelled N_2O 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 N_2O emissions resulting from fertiliser N inputs can be quantified.

We revised the definition of background N_2O emissions in L223–226 to improve clarity.

"F_{bg}, kg N ha^{-1} yr^{-1}; defined as N_2O 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 N_2 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 & Röös (2020) and my detailed comment on lines 242-243.

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 N_2O 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 2.5^{th} and 97.5^{th} 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 (L279–300) 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.

We removed "Switzerland" and rephrased the sentence in L47–48.

"**Many Annex I countries** (i.e., industrialised countries and countries with economies in transition) **report annual N_2O 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.

We revised the text to clarify the EF in L50.

"…which estimate emissions as a fixed proportion of N inputs (i.e., a default aggregated EF of 1% for fertiliser-induced emissions **as N_2O-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.

We revised the following text to avoid contradiction in L53–54.

"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 N_2O 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

We revised the following text to provide details of model inputs and the datasets we used L74–76.

"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?

We revised the text in L116–126 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 N_2O 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 (Büchi et al., 2017; Hüppi et al., 2015; Krauss et al., 2017; Mayer et al., 2015). The evaluation included crop productivity, soil C dynamics and soil N_2O emissions (Necpalova et al., 2018). DayCent was subsequently further calibrated and evaluated using Swiss (as well as French and German) cropland and grassland observations (Ammann et al., 2007, 2009 2020; Emmel et al., 2018; Feigenwinter et al., 2023a; Fuchs et al., 2018; Merbold et al., 2021), with particular emphasis on key N dynamic parameters and their influences on observed N_2O 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?

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 L179–180 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** L180–187 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

The static calendar with fixed dates were assumed to be the same across Swiss cropland. We revised the following text in L174 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?

We thank the reviewer for pointing this out. We reference our detailed answer to reviewer's 2nd major point on page 14. 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 N_2O emissions in L223–226 to improve clarity.

"F_{bg}, kg N ha^{-1} yr^{-1}; defined as N_2O 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 N_2 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.

We reference our detailed answer to reviewer's 1st major point on page 13.

We revised the Introduction added the following text in L77–82.

"**We also calculated N_2O EFs from the difference in N_2O 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 N_2O emissions.**"

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

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 & Röös (2020).

von Brömssen, C., Röös, 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

We revised Section 2.7 Uncertainty L279–300 evaluation to address the reviewer's concern.

"Uncertainty in modelled national N_2O 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 N_2O 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 N_2O 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 N_2O emission estimates was summarized using its empirical percentiles. The 2.5^{th} and 97.5^{th} 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 N_2O emissions or their mean (von Brömssen and Röös, 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?

We removed the phrase to avoid misunderstanding.

271: See comment above.

We removed the phrase to avoid misunderstanding.

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

As shown in Fig. 5 e&f, the relative increases of N_2O due to climate change are generally larger in grassland (12–18%) than cropland (3–9%) spatially. We revised the text in L426 to improve clarity.

“…modelled decadal mean N_2O 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.

The 25% reduction refers to national total fertiliser use. We revised the following text in L489.

“**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”

We changed the text as suggested.

503: Missing “have” in “can have”

We added the missing “have” in the sentence.

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

We thank the reviewer for pointing this out. We realise that the phrase “substantial shifts” was not clear. We revised the following text in L581–582.

“Thus, as extremes (heatwaves, droughts or compound events) are expected to become more frequent under climate change (Calvin et al., 2023), **the magnitude of N_2O 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.

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 N_2O 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?

We thank the reviewer for this helpful suggestion. We revised the text in L609–615 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 N_2O 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 N_2O 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 N_2O reduction might be insufficient given the varying pedoclimatic conditions, management practices, and highly dynamic nature of N_2O 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.

We revised the text in L635–637 to address this point.

"These findings **highlight that climate-induced increases in N_2O emissions can partially offset the reductions achieved through declining fertiliser inputs, resulting in smaller net reductions in N_2O 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 N_2O 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., Linquist, B., & Van Groenigen, K. J. (2013). Climate, duration, and N placement determine N_2O 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