

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.

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.

Reply: 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.

Reply: 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 N₂O emissions. Similarly, keeping mowing dates fixed could affect plant residue inputs and SOM mineralisation. The conclusion that warming increases N₂O 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.

Reply: 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.

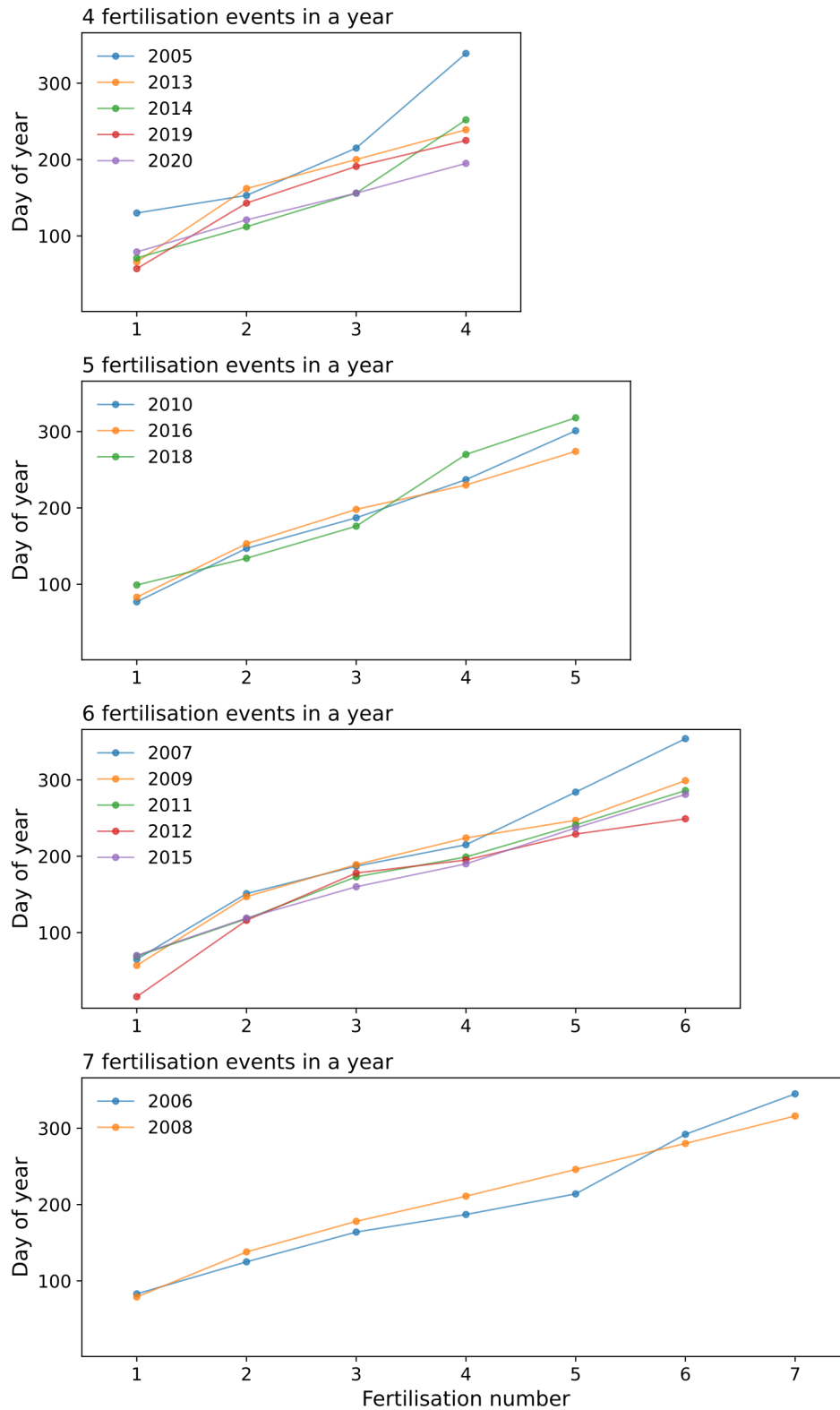


Figure R1. Fertilisation dates of an intensively managed grassland in Chamau, Switzerland between 2005 and 2020.

Table R1. Planting, harvest and fertilisation dates of three major crops of a long-term trial 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 N₂O 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 N₂O 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 N₂O emissions is sensitive to the assumed timing of management practices under the changing climate.

We found that the alternative management timings changed simulated N₂O 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 N₂O 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 2.7, 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 N₂O emissions to management timing.

In Section 3.4, 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 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). 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, we added,

“Under the prescribed fertilisation and management schedules, our results Our results indicate that N₂O 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 N₂O emissions in croplands and changes of -0.6% to 0.3% in grasslands relative to the baseline simulations. The simulated increase

in N₂O 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 N₂O emissions are robust across the tested changes in management timing.”

In Section 4.5, 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 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. **Our management-timing sensitivity tests further suggest that advancing planting and fertilisation dates under a changing climate could reduce simulated N₂O 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?

Reply: 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 (L418-419). The corresponding land use are for each year was used to calculate the simulated national N₂O 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. We revised the Methods to clarify this point.

“Annual total N₂O emissions from Swiss croplands and grasslands ($E_{N_2O, total}$, 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). $F_{N_2O, i}$ is the N₂O 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). ”

“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 N₂O 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 N₂O emissions shown in Fig. 1b are driven, at least partly, by changes in BNF.

Reply: 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 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 N₂O emissions from grasslands shown in Fig. 1b. We removed the original statement accordingly. The increase in background N₂O emissions from grasslands is primarily associated with increased SOM mineralisation under changing climatic conditions.

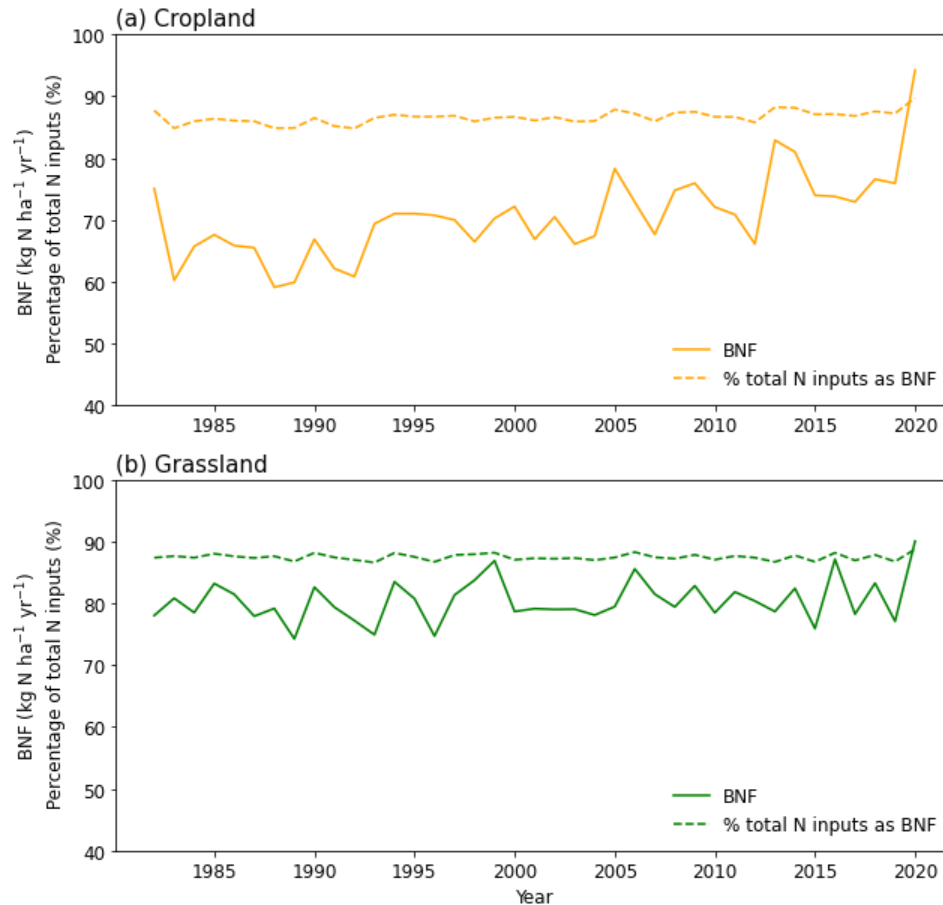


Figure R2. Simulated biological N₂ fixation and its contribution to total N inputs for (a) croplands and (b) grasslands in Switzerland between 1991 and 2020.

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.

Reply: 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.

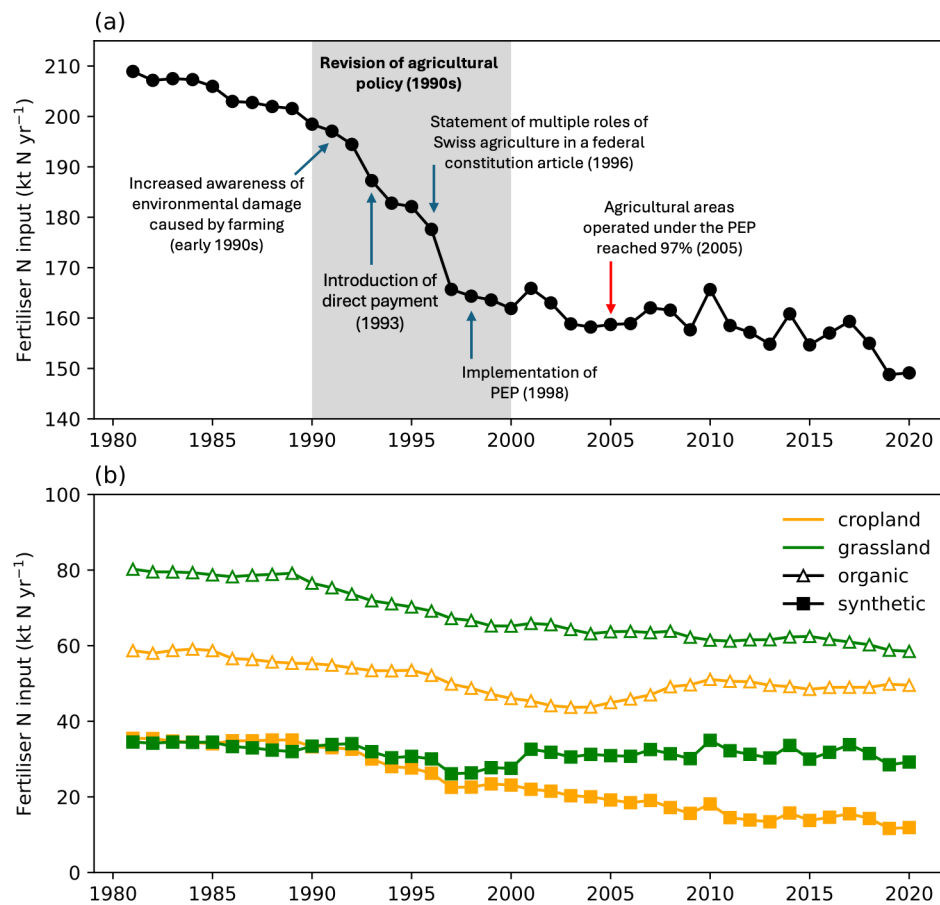


Figure S6. Nitrogen inputs from fertilisers to agricultural land in Switzerland. Fertilisers include organic (livestock manure applied to field and manure deposited during grazing) and synthetic fertilisers. Values from compiled datasets (see Methods). Shaded grey area in panel (a) represents the period 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.

Reply: 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.

Reply: 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 ($\text{kt N ha}^{-1} \text{ yr}^{-1}$) 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.

Reply: 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 L137-142 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 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.

Reply: Grazing-derived N inputs were set to zero in the “nofert” scenario. We revised the Methods section.

“Synthetic and organic fertilisers (including manure N deposition during grazing) were set to zero in the “nofert” scenario. Subsequently, the following equation is used to calculate modelling-derived EF (EF_{N_2O})”