Response to Zimeng Wang (Referee 1)

Overall response: We would like to thank Prof Zimeng Wang (referee 1) for these insightful 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.

Comment: This manuscript uses the Swiss agricultural system as a case study and applies the DayCent biogeochemical model to reconstruct nitrogen budgets for croplands and managed grasslands from 1981 to 2020 at a 1 km × 1 km resolution. The study focuses on evaluating N inputs, N outputs, nitrogen use efficiency, N losses, and soil N balance. The core contribution of the manuscript is that it integrates NUE, N losses, and soil N stock dynamics into a single framework for assessing agri-environmental performance. The authors show that Swiss agri-environmental policy reforms improved nitrogen use efficiency and reduced N losses, while also indicating that cropland soil N stocks may have experienced long-term depletion. This perspective has strong policy relevance and methodological significance.

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

Comment: The title of the manuscript is "Balancing nitrogen use efficiency, losses and soil nitrogen depletion to evaluate agri-environmental performance across spatial scales over 40 years". Overall, the title is accurate. It captures the three core variables of the study: NUE, N losses, and soil N depletion, and it also reflects the long-term and spatial dimensions of the work. However, one aspect of the title could be further improved. The phrase "across spatial scales" is somewhat broad. The study was actually conducted at the national scale with 1 km × 1 km spatially explicit simulations, rather than comparing multiple spatial scales in a strict sense, such as field, regional, national, or continental scales. Therefore, I suggest that the authors revise the title to make it more precise.

Reply: We revise the title to "**Balancing nitrogen use efficiency, losses and soil nitrogen depletion to evaluate national scale agri-environmental performance over 40 years**".

Comment: L35: The overall logic of the Introduction is clear, but the background and rationale for the key evaluation indicators could be strengthened. NUE is an important assessment metric in this study, but the Introduction does not provide a sufficiently detailed explanation of this concept. The authors should better justify why NUE was selected as a core indicator for evaluating N balance and N losses.

Reply: We thank Prof Wang for identifying this potential weakness. We added the following text to more clearly explain NUE and the rationale of using it as a core indicator for evaluating N performance in our study.

"**To evaluate the N performance of a system and the associated environmental impacts, N use efficiency (NUE) is a widely used indicator. NUE is defined as the ratio of N outputs to N inputs, with higher NUE indicating more of the inputs going toward their intended use. For cropping systems, NUE is calculated as the N in harvested products divided by total N input (i.e. synthetic and organic fertilizers, biological N fixation and atmospheric N deposition). It is usually reported with other indicators describing the magnitude of N use, such as N yield or N surplus (difference between the N inputs and outputs). The NUE approach can be extended to the national and global level to track efficiency changes over time. It has been reported that global average NUE declined from 68% to 45% between 1961 and 1980 and subsequently stabilized over the next three decades (Lassaletta et al., 2014).** In many countries, marked reductions in NUE resulted from intensified fertilization, which also led to elevated N losses (Lassaletta et al., 2014)."

Comment: L15: The term grasslands in this manuscript actually refers to managed meadows, excluding managed pastures and summer pastures. Although this is explained in the Methods and figure legends, for example, "Grasslands in Switzerland are categorised into three major types: 1) meadows, 2) pastures and 3) summer pastures. In this study, we focused on meadows, which are managed for grass production for livestock feed", the direct use of "grasslands" in the Abstract may lead readers to assume that the study covers all Swiss grasslands. I suggest that the authors define this more clearly when the term first appears in the Abstract.

Reply: We revised the Abstract and more explicitly clarified the term "grasslands" as permanent managed meadows.

"Nitrogen (N) is essential for agricultural productivity, but excessive N inputs result in substantial losses to the environment. Conducting N assessments at national scales is challenging because observational data are limited, especially over long time periods. Here we compiled detailed datasets and performed high-resolution biogeochemical modelling to quantify N budgets for Switzerland's diverse agricultural ecosystems over four decades, **with a focus on croplands and grasslands (i.e., permanent managed meadows used for livestock feed).** Between the 1980s and the 2010s, N use efficiency improved from 47% to 57% in croplands and from 63% to 71% in grasslands, while losses through leaching and gas emissions decreased by 24% in croplands and 4% in grasslands. These improvements are closely linked to the implementation of national-scale agri-environmental policies that reduced fertilizer use in the 1990s.

However, despite increased efficiency, cropland soils experienced substantial N depletion between 1995 and 2011 (–23 kg N ha^{-1} yr^{-1}) in croplands. Our results demonstrate that policy reforms have improved agricultural system functioning and reduced losses, but also reveal risks associated with unbalanced soil N, underscoring the need for integrated N management for sustainable agriculture."

Comment: L93: "Inputs of site-specific soil properties such as soil texture (sand, silt, clay), soil pH and soil organic matter (SOM)". The main research focus of the manuscript is "Balancing nitrogen use efficiency, losses and soil nitrogen depletion". However, the model input data do not include any soil N-related indicators, such as TN. If soil N is generated internally by the model, I think the authors should provide a more detailed description of the relevant model processes and initialization.

Reply: DayCent model has its own carbon and nitrogen module, which simulates soil organic matter formation and decomposition. The initialization was performed by carrying out spin-up simulations that comprised of five phases representing the evolution of Swiss agriculture (Lee et al., 2020a, b), as described in Section 2.3. We agree with Prof Wang that a more detailed description of these modules and relevant processes would be helpful for clarification.

We revised the Method.

"In this study, we used the DayCent17centEVI model version to quantify N budgets for two Swiss land ecosystems: a) croplands and b) grasslands. **DayCent has a mechanistic representation of the terrestrial carbon (C) and nitrogen cycle. The SOM in DayCent is split into three compartmental pools, namely active, slow and passive, with different potential decomposition rates. These SOM pools receive plant materials from above and belowground litter. Simulated N flows follow C flows depending on the C:N ratio which varies from 15 to 3 for the active pool, from 20 to 12 for the slow pool, and from 10 to 7 for the passive pool. For newly formed surface biomass, the C:N ratio is a function of the N content of the decomposed material, with higher C:N ratio for lower N content. The model accounts for both organic and mineral N and the relevant processes, including mineralization-immobilization turnover, nitrification and denitrification.** These transformations are regulated by environmental factors such as temperature, soil moisture, soil texture, SOM content and oxygen availability. **Nitrogen input flows are modelled through simulated atmospheric deposition and biological N fixation, and through input data to the model that record application of organic and synthetic fertilizers. Simulated losses are outgassing of N_2O, N_2, NO and NH_3 to the atmosphere and leaching (e.g., nitrate and organic forms).** It is crucial to acknowledge that NH_3 volatilization in DayCent is not sophisticated, which may lead to underestimation of NH_3 emissions and overestimation of nitrate leaching."

Comment: L95: In the Abstract, the method is described as "high-resolution biogeochemical modelling". However, in the specific description of Model input data, the 1 km × 1 km high-resolution dataset refers to weather data, while the site-specific soil properties were originally provided at 30 m × 30 m resolution and were then resampled to 1 km × 1 km using the conservative remapping method in Climate Data Operator (CDO). I am not fully convinced about the accuracy of this resampling approach across such a large resolution difference. The authors should provide a more detailed description and justification of this method.

Reply: We revised the manuscript to provide a clearer description and justification of the resampling procedure for soil inputs. Specifically, soil data originally available at 30 m resolution were aggregated to the 1 km model grid using conservative remapping in CDO, which preserves area-weighted means. This step was necessary to ensure consistency with the 1 km modelling framework and other input datasets (e.g. meteorological variables), and has been used in other studies, e.g., (Hashimoto et al., 2025). Performing simulations at a higher spatial resolution (e.g., 30m x 30m) would not be computationally feasible in our case. We acknowledge that this procedure smooths fine-scale spatial heterogeneity in soil properties, but the general features at the national scale were preserved (as shown in Fig. R1).

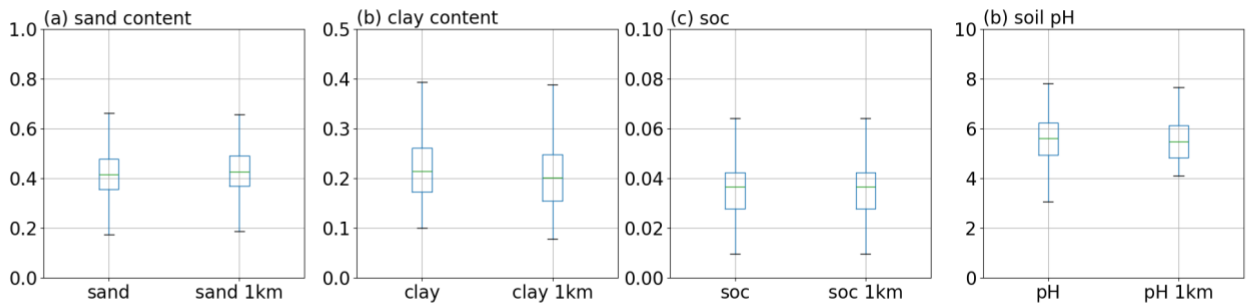

Figure R1. Comparison of the variability in soil data between the original data (30 m) and resampled data (1 km) for four soil properties.

We have added this clarification in the revised Methods section.

"Soil properties originally available at 30 m × 30 m resolution were aggregated to the 1 km model grid using conservative remapping implemented in the Climate Data Operator (CDO). This approach preserves area-weighted means and is useful in upscaling environmental datasets to coarser modelling resolutions

(Hashimoto et al., 2025). Because the model operates at 1 km spatial resolution, harmonization of all input datasets was required to ensure consistency across input variables. While this aggregation inevitably smooths fine-scale heterogeneity in soil properties, the most prominent features of the geospatial distribution of soil variables at the national scale are preserved."

Comment: L175: A similar issue applies here. "The total N inputs include organic and synthetic fertilizers, biological N fixation and atmospheric N deposition". The authors do not clearly describe the source of the N deposition input data. In addition, it is unclear whether the BNF referred to in the manuscript represents ecosystem-level BNF, and whether it includes both plant-associated and soil-based biological nitrogen fixation.

Reply: We thank Prof Wang for pointing out the ambiguity of the description. The total N inputs mentioned in the original texts are the term used for calculating N budget, and are not model inputs. The DayCent model simulate non-symbiotic soil N fixation, symbiotic plant N fixation and atmospheric N deposition. DayCent relies on a simple linear equation to estimate N deposition from precipitation data. We have revised the Method to clarify these points.

"The total N inputs (T_{in}) **to agricultural systems (croplands and grasslands)** include organic (N_{org}) and synthetic fertilizers (N_{syn}), biological N fixation (N_{BNF}) and atmospheric N deposition (N_{dep}). **As mentioned in Section 2.1 and 2.2, BNF (including both non-symbiotic soil N fixation and symbiotic plant N fixation) and atmospheric deposition are simulated by the DayCent model, whereas organic and synthetic fertilizers are model inputs."**

Comment: L285: The soil N balance data for grassland in 1981–1990 in Table 2 need to be checked. According to the definition provided in the Methods:

N input=124+57+60+12=253

N output=158+35+24=217

Δsoil N=253−217=36

However, the Δsoil N value reported in the table is 25 kg N ha^{-1} yr^{-1}. If this is a calculation error, it should be corrected.

Reply: We have corrected the error and further checked the calculation. Here is the updated Table 2.

Updated Table 2. Nitrogen budgets and soil N balance of Swiss agroecosystems. Nitrogen inputs include livestock manure, synthetic fertilizers, BNF and atmospheric N deposition. Nitrogen outputs include N removal through harvest, gaseous emissions and leaching. Soil N balance is N inputs minus N outputs. All variables are decadal mean for the 1980s and the 2010s, and have the unit kg N ha^{-1} yr^{-1}. Values in parenthesis are uncertainty (95% confidence interval) due to model parameters estimated from the Monte Carlo approach.*Grasslands refer to managed meadows only, while managed pastures and summer pastures for grazing are not included.

	Period	N input				N output			Δsoil N
		N_{org}	N_{syn}	N_{BNF}	N_{dep}	N_{yield}	N_{gas}	$N_{leaching}$	
Cropland	1981-1990	132	80	18	11	113 (112-115)	24 (21-27)	107 (93-116)	-4 (-19-7)
	2011-2020	129	36	27	11	115 (114-121)	22 (20-25)	78 (70-85)	-12 (-15 - -4)
Grassland*	1981-1990	124	56	59	12	158 (154-168)	34 (30-40)	23 (14-30)	36 (29-46)
	2011-2020	88	53	63	12	155 (153-162)	34 (30-39)	21 (12-27)	6 (2-14)

Comment: L305: In Figures 5 and 6, total N input is expressed in kg N ha^{-1} yr^{-1}, whereas the other variables are expressed as percentages of total N input. This design is useful, but it may also cause confusion. I suggest that the authors clearly label the units in the figures, for example, "Fertilizer N: % of total N input". Alternatively, the percentage calculation rules should be explicitly described in the Methods, especially for Δsoil N%.

Reply: We revised the Method section to explicitly describe the calculation of percentages for each N flow.

"**Specifically, N flows expressed as percentages of total N inputs were calculated as:**

$$\%N_{flow} = \frac{N_{flow}}{N_{in}} \times 100 \quad (7)$$

Similarly, the relative changes in soil N stock were calculated as:

$$\%\Delta \text{soil N} = \frac{\Delta \text{soil N}}{N_{in}} \times 100 \quad (8)$$

These results are shown in Figs. 5 and 6."

Comment: L435: The Uncertainty section identifies three sources of uncertainty: input data, model parameters and processes, and spatial application of the model. However, the discussion remains mainly qualitative. As this is a model-driven study, I suggest that the authors provide quantitative uncertainty ranges for the key conclusions. In particular, cropland soil N depletion is one of the main findings of this study, and it strongly depends on modelled N loss, especially nitrate leaching. The authors also acknowledge limitations in DayCent's representation of water movement and NH_3 volatilization, which may affect estimates of leaching and gaseous N losses. For example, the manuscript states that "DayCent lacks a sophisticated scheme for NH3 volatilization, leading to substantially underestimated NH3 fluxes". I think the authors should add an assessment of uncertainty in N loss and provide uncertainty ranges for soil N balance.

Reply: We agree with Prof Wang that a quantitative uncertainty analysis would be helpful. Therefore, we conducted an uncertainty assessment using a Monte Carlo approach. Due to the large number of simulations, we applied this approach on a representative subset of all simulated grids. The following new sub-section is added in the Method, with uncertainty shown in updated Table 2.

"**We used a Monte Carlo ensemble approach (200 iterations) to quantify the uncertainty in simulated N losses, NUE and soil N balance arising from key processes represented in DayCent. Nine model parameters regulating N leaching, nitrification and denitrification were selected for the analysis (details are presented in Table S2). Parameter ranges were defined using probability distributions based on the default values and calibrated ranges reported in previous studies (Dos Reis Martins et al., 2022, 2024). Because these parameters also influence plant N uptake through their effects on N loss pathways, plant-specific parameters were not evaluated separately.**

To reduce the computational burden associated with the large number of simulations, we created a representative subset of grid cells using Conditioned Latin Hypercube Sampling (cLHS). This subset (n=400) preserved the spatial variability of climate, soil properties, and fertilization intensity across Switzerland. For each Monte Carlo iteration, DayCent was run for all selected grid cells using a unique set of parameter values. Simulated N losses,

NUE, and soil N balance were then calculated and compared with the baseline simulation. Uncertainty in national-scale estimates was quantified from the distribution of ensemble results and reported as 95% confidence intervals (CI).″

New Table S2. Selected model parameters in DayCent used for uncertainty analysis in this study. N cycle Parameter values were taken from Dos Reis Martins et al. (2022, 2024). *Calibrated parameter values were derived from multiple sites across Switzerland and Germany for [a]croplands and [b]grasslands. Leaching parameters were tested with a range of ±20% of the default value.

Parameter	Description	Unit	Default	Calibrated mean*	95% CI
Fleach(1)	Intercept value for a normal day to compute the fraction of mineral N, P, and S which will leach to the next layer when there is a saturated water flow	unitless	0.50	None	[0.40–0.60][a,b]
Fleach(2)	Slope value for a normal day to compute the fraction of mineral N, P, and S which will leach to the next layer when there is a saturated water flow	unitless	0.50	None	[0.40–0.60] [a,b]
Ncoeff	Minimum water and temperature limitation coefficient for nitrification	unitless	0.03	0.027[a] 0.031[b]	[0.022–0.043][a] [0.022–0.038][b]
N2Oadjust_fc	Maximum proportion of nitrified N lost as N_2O at field capacity	unitless	0.025	0.07[a] 0.022[b]	[0.019–0.187][a] [0.020–0.031][b]
N2Oadjust_wp	minimum proportion of nitrified N lost as N_2O at wilting point	unitless	0.02	0.016[a] 0.009[b]	[0.009–0.027][a] [0.009–0.027][b]
MaxNitAmt	Maximum daily nitrification amount	$g\ N\ m^{-2}\ d^{-1}$	1.5	3.7[a]	[0.9–5.2][a]
netmn_to_no3	Coefficient to control the fraction of new net mineralization that goes to nitrate	unitless	0.2[a] 0.15[b]	0.36[a] 0.2[b]	[0.08–0.81][a] [0.045–0.232][b]
wfpsdnitadj	Adjustment on inflection point for the water filled pore space effect on denitrification curve	unitless	1.0[a] 1.04[b]	1.3[a] 1.06[b]	[0.74–1.44][a] [0.53–1.14][b]

N2N2Oadj	N_2/N_2O ratio adjustment coefficient	unitless (0.1–2.0)	1.0	1.16[a] 1.03[a]	[0.64–1.80][a] [0.66–1.80][b]

Here is the updated Table 2.

Updated Table 2. Nitrogen budgets and soil N balance of Swiss agroecosystems. Nitrogen inputs include livestock manure, synthetic fertilizers, BNF and atmospheric N deposition. Nitrogen outputs include N removal through harvest, gaseous emissions and leaching. Soil N balance is N inputs minus N outputs. All variables are decadal mean for the 1980s and the 2010s, and have the unit kg N ha^{-1} yr^{-1}. Values in parenthesis are uncertainty (95% confidence interval) due to model parameters estimated from the Monte Carlo approach.*Grasslands refer to managed meadows only, while managed pastures and summer pastures for grazing are not included.

	Period	N input				N output			Δsoil N
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Section 5 which explicitly discuss the uncertainty in a qualitative manner is therefore removed. The following texts were integrated into Discussion.

"The Monte Carlo analysis showed that the uncertainty associated with simulated NUE, N losses, and soil N stock changes was generally smaller than the observed long-term trends, increasing confidence that the reported temporal changes are robust. Nonetheless, the quantified N budgets in this study were estimated primarily using a modelling approach so that the results (and the associated uncertainty) should be interpreted with caution. In addition to the evaluated model parameters, other sources of uncertainty were not quantified, such model inputs (e.g., livestock C and N data, and soil data). It is also worths noting that DayCent uses a simple "tipping bucket" module to represent water movement in soil layers, which can overestimate percolation fluxes (i.e., predict quicker drainage). This influences soil water content and consequently affects water-dependent processes (such as crop N uptake, leaching and N_2O production). Moreover, DayCent lacks a sophisticated scheme for NH_3

volatilization, leading to substantially underestimated NH_3 fluxes. This can result in a larger soil nitrate pool because more ammonium is available for nitrification, subsequently enhancing nitrate leaching.

Overall, our results and findings are robust and provide valuable insights for agricultural policy implementation and the assessment of agri-environmental performance. This work also demonstrates the feasibility of spatially explicit N flow quantification. Future work on monitoring national N use (e.g., constructing N budgets and calculate N balance) can incorporate biogeochemical modelling as part of the methodology. Importantly, long-term monitoring of soil N stock should also be integrated into future soil samplings and surveys."

Comment: Overall, this manuscript is innovative, particularly in integrating NUE, N losses, and soil N balance into a unified framework for assessing agricultural nitrogen management. The use of high-resolution DayCent simulations to reveal changes in nitrogen cycling following Swiss agri-environmental policy reforms is also valuable. However, the authors need to further strengthen the methodological description and uncertainty analysis, especially regarding soil N depletion. My recommendation is minor revision.

Reply: We thank again Prof Zimeng Wang for the positive feedback on our study and these useful comments. We revised the manuscript to address all the points. We hope that the revised manuscript can meet the requirements for publishing in Biogeosciences.

Response to Referee 2

Overall response: We would like to thank Referee 2 for these insightful and constructive comments. These help improve the manuscript. Here we outline the point-by-point responses below in blue, and the relevant figures are attached.

The manuscript provides an assessment of changes in Nitrogen status in Swiss grasslands between 1981 and 2020 as simulated by DayCent model. The authors propose 3 indicators – Nitrogen use efficiency (NUE), N loss, and soil N stock as a comprehensive framework for evaluating N response to changes in agricultural management and policy. The study incorporates a multitude of data sources to deliver spatially explicit modelling of N dynamics over Swiss grasslands. The main findings are: NUE improvement in croplands and grassland mainly due to reduction in N fertilizer application; N loss reduction proportionally to the reduction in N input; and N stock depletion in croplands. The main contribution of this research is the spatially comprehensive assessment of different aspects of N dynamics which provides detailed national picture of long-term results of the policy change.

Reply: We thank Referee 2 for recognizing the value of our study.

Since the comprehensive results were obtained entirely through modeling, the validity of the conclusions fully relies on the model formulation and parametrization. In particular, the 3 indicators selected by authors: NUE, N loss, and N stock are a result of a simulation by the DayCent model, therefore their apparent change is not something that was observed in reality, but rather a consequences of the model structure, parameters, and drivers (drivers being based on the observational data). While the authors argue that their findings “highlight the importance of policy intervention for agricultural N management” the link between policy changes, model drivers and/or parameters, and output is not sufficiently established throughout the manuscript.

Reply: We believe that conducting such high-resolution spatially explicit simulations using a process-based model can be useful for assessing the agricultural productivity, N loss and soil N changes, which has important implications for long-term decision making. We acknowledge that there are limitations and uncertainty associated with a modelling approach. We revised the Method section to more explicitly describe how policy changes are reflected in our simulations. We improved the analysis of policy-driven changes in the Results and Discussion sections. Please see our detailed responses for each comment below.

The authors acknowledge the inherent uncertainty of modeling results and list uncertainty sources it in the discussion. While modelled yields and soil N changes are compared to the observed data (Supplementary Figures S2, S3, S5), no quantitative assessment of modelling error and uncertainty is provided.

Reply: We conducted the required quantitative uncertainty assessment using a Monte Carlo approach. Due to the large number of simulations, we applied this approach on a representative subset of all simulated grids. A new sub-section describing the Monte Carlo approach is added in the Method with uncertainty range presented in updated Table 2. In addition, we updated Figs. S3 and S5, and provided a set of metrics (r^2, rRMSE and Mean Bias) for model evaluation. Please see our detailed response for the corresponding comment below.

Overall, more information is needed for the readers to understand where the results come from and make a conclusion about their robustness. Therefore, I suggest making the following changes to the manuscript:

1. Add a more detailed description of how policy reforms of 1990s and changes in farmers' practices were reflected in the model drivers, i.e. fertilization, crop rotations, tillage, etc.

Reply: The policy reforms in the 1990s had led to substantial reduction in fertiliser use, resulting from the implementation of subsidies. Meanwhile, livestock productivity (particularly milk yield) significantly increased during this period, which decreased livestock population without lowering production, leading to substantially lower N inputs from livestock manure. These aspects are reflected in the fertilizer (both synthetic and organic) inputs to DayCent. In addition, policy reforms also introduced the use of cover crops to reduce soil erosion and nutrient leaching. However, we do not have statistical data with regard to this measure so that it was not addressed in the model. Other agricultural practices such as crop rotations and tillage did not change considerably. We added the following texts to the Method section.

"During the 1990s in Switzerland, important nationwide agri-environmental policy reforms introduced subsidy schemes in order to mitigate nutrient losses. Meanwhile, there was a significant increase in livestock productivity (i.e., milk yield) during this period and in line with decreased livestock population without lowering production, resulting in decreased N inputs from livestock manure. These led to substantial reductions in synthetic and organic fertilizer application to agricultural soils. The fertilizer input data we used record these changes, which were specified in DayCent's schedule files. In addition, the use of cover crops also forms part of the agri-environmental

policy that was implemented in the late 1990s, with the aim of reducing soil erosion and nutrient leaching, particularly in winter months. However, this potentially relevant measure was not covered by our study due to insufficient statistical data. Other agricultural practices were also assumed to remain unchanged."

The impact of not including the cover crops is considered limited and discussed in the following text.

"Another uncertainty is related to absence of representing cover crops in the model, which have been found to improve multiple ecosystem functions, including total soil N (Liu et al. 2025) at a global level. For Switzerland, Herzog et al. (2005) estimated that the increased use of cover crops since the late 1990s reduced farm-level nutrient balances by 10% until 2005. In this study, we do not include the use of cover crops driven by the national policy implementation because of no available data. The impact of not including them in this study is that we potentially underestimated the reduction in nitrate leaching and therefore also in NUE, but based on the above-mentioned study, the impact is not high."

2. Add a sensitivity analysis, illustrating and comparing NUE, N loss and N stock sensitivity in croplands and grasslands to changes in drivers over the course of the simulation: both drivers affected by policy change, and unrelated to policy change – e.g. temperature and moisture regimes. This will illustrate the comparative importance of factors in the model and provide a clear interpretation of simulation results.

Reply: We carried out additional sensitivity tests and scenario simulations to demonstrate how model drivers affect NUE, N loss and soil N changes. These drivers include temperature, precipitation, fertilizer type and fertilizer rates. We believe these are helpful for interpreting simulations results. That said, we prefer to show these additional modelling outputs in the Supplementary Materials to avoid detracting our main findings and conclusions. We added the following text to the Method section that describes the sensitivity tests and scenario simulations.

"To better understand the sensitivity of simulated N dynamics to environmental conditions, we conducted a series of one-factor-at-a-time sensitivity tests using the baseline simulation as a reference. To assess the influence of meteorological drivers, we applied uniform changes of (i) ±2°C in air temperature and (ii) ±20% in precipitation, while keeping all other inputs

unchanged. Air temperature and precipitation were selected because they are the primary meteorological drivers controlling plant growth and soil C and N cycling in DayCent.

In addition, we performed three fertilizer management scenarios: (i) replacement of all organic fertilizer with synthetic fertilizer while maintaining the same total N application rate, (ii) replacement of all synthetic fertilizer with organic fertilizer while maintaining the same total N application rate, and (iii) a 20% reduction in both synthetic and organic fertilizer application rates. Each scenario was simulated independently, with all other model inputs and management practices identical to those of the baseline simulation. Changes in total N input, N harvest, NUE, total N losses and soil N stock change were evaluated relative to the baseline simulation."

New Table S3. Results of sensitivity tests of environmental variables and scenario simulations of fertilizer management for their effects on NUE, N loss and soil N changes in the model. Changes were calculated using the national annual total values averaged over the simulated 40 years. *These changes are relative values.

Variable	Value change	Δ N input (%)		ΔN harvest (%)		ΔNUE (%)		ΔN loss (%)		Δsoil N (%)	
		CL	GL	CL	GL	CL	GL	CL	GL	CL	GL
Air temperature	+2 ºC	1.6	-0.6	4.1	-2.0	2.5	-1.4	5.5	16.4	57.6	-41.5
	–2 ºC	-1.8	-0.3	-6.6	0.8	-4.9	1.1	-4.5	-17.9	-66.6	44.2
Precipitation	+20%*	1.5	0.3	-0.6	-0.6	-2.0	-0.9	4.9	4.1	14.1	-4.0
	–20%*	-2.3	-0.5	-0.9	0.5	1.4	1.1	-6.7	-5.9	-28.8	7.2
Fertilizer N input	only synthetic[a]	-2.2	-1.0	0.1	3.5	2.4	4.5	2.9	1.2	62.3	-44.9
	only organic[b]	-0.5	-0.3	-1.0	-2.2	-0.4	-1.9	-2.8	-6.8	-23.3	35.8
	–20% rate[c]	-14.0	-11.5	-3.2	-6.0	12.5	6.2	-20.5	-20.3	22.3	-30.1

3. Add a quantitative uncertainty analysis, estimating uncertainty of simulated NUE, N loss and N stock due to uncertainty in parameter estimation. Currently, authors describe parameters as being based on several experimental studies in Switzerland, however, the uncertainty of it, and how it translates into the uncertainty of this paper's results is unclear.

Reply: We performed the uncertainty evaluation and revised the manuscript accordingly.

"We used a Monte Carlo ensemble approach (200 iterations) to quantify the uncertainty in simulated N losses, NUE and soil N balance arising from key processes represented in DayCent. Nine model parameters regulating N leaching, nitrification and denitrification were selected for the analysis (details are presented in Table S2). Parameter ranges were defined using probability distributions based on the default values and calibrated ranges reported in previous studies (Dos Reis Martins et al., 2022, 2024). Because these parameters also influence plant N uptake through their effects on N loss pathways, plant-specific parameters were not evaluated separately.

To reduce the computational burden associated with the large number of simulations, we created a representative subset of grid cells using Conditioned Latin Hypercube Sampling (cLHS). This subset (n=400) preserved the spatial variability of climate, soil properties, and fertilization intensity across Switzerland. For each Monte Carlo iteration, DayCent was run for all selected grid cells using a unique set of parameter values. Simulated N losses, NUE, and soil N balance were then calculated and compared with the baseline simulation. Uncertainty in national-scale estimates was quantified from the distribution of ensemble results and reported as 95% confidence intervals (CI)."

New Table S2. Selected model parameters in DayCent used for uncertainty analysis in this study. N cycle Parameter values were taken from Dos Reis Martins et al. (2022, 2024). *Calibrated parameter values were derived from multiple sites across Switzerland and Germany for [a]croplands and [b]grasslands. Leaching parameters were tested with a range of ±20% of the default value.

Parameter	Description	Unit	Default	Calibrated mean*	95% CI
Fleach(1)	Intercept value for a normal day to compute the fraction of mineral N, P, and S which will leach to the next layer when there is a saturated water flow	unitless	0.50	None	[0.40–0.60][a,b]
Fleach(2)	Slope value for a normal day to compute the fraction of mineral N, P, and S which will leach to the next layer when there is a saturated water flow	unitless	0.50	None	[0.40–0.60] [a,b]

Ncoeff	Minimum water and temperature limitation coefficient for nitrification	unitless	0.03	0.027[a] 0.031[b]	[0.022–0.043][a] [0.022–0.038][b]
N2Oadjust_fc	Maximum proportion of nitrified N lost as N_2O at field capacity	unitless	0.025	0.07[a] 0.022[b]	[0.019–0.187][a] [0.020–0.031][b]
N2Oadjust_wp	minimum proportion of nitrified N lost as N_2O at wilting point	unitless	0.02	0.016[a] 0.009[b]	[0.009–0.027][a] [0.009–0.027][b]
MaxNitAmt	Maximum daily nitrification amount	$g\ N\ m^{-2}\ d^{-1}$	1.5	3.7[a]	[0.9–5.2][a]
netmn_to_no3	Coefficient to control the fraction of new net mineralization that goes to nitrate	unitless	0.2[a] 0.15[b]	0.36[a] 0.2[b]	[0.08–0.81][a] [0.045–0.232][b]
wfpsdnitadj	Adjustment on inflection point for the water filled pore space effect on denitrification curve	unitless	1.0[a] 1.04[b]	1.3[a] 1.06[b]	[0.74–1.44][a] [0.53–1.14][b]
N2N2Oadj	N_2/N_2O ratio adjustment coefficient	unitless (0.1–2.0)	1.0	1.16[a] 1.03[a]	[0.64–1.80][a] [0.66–1.80][b]

Here is the updated Table 2.

Updated Table 2. Nitrogen budgets and soil N balance of Swiss agroecosystems. Nitrogen inputs include livestock manure, synthetic fertilizers, BNF and atmospheric N deposition. Nitrogen outputs include N removal through harvest, gaseous emissions and leaching. Soil N balance is N inputs minus N outputs. All variables are decadal mean for the 1980s and the 2010s, and have the unit kg N ha^{-1} yr^{-1}. Values in parenthesis are uncertainty (95% confidence interval) due to model parameters estimated from the Monte Carlo approach.*Grasslands refer to managed meadows only, while managed pastures and summer pastures for grazing are not included.

	Period	N input				N output			Δsoil N
		N_{org}	N_{syn}	N_{BNF}	N_{dep}	N_{yield}	N_{gas}	$N_{leaching}$	
Cropland	1981-1990	132	80	18	11	113 (112-115)	24 (21-27)	107 (93-116)	-4 (-19-7)
	2011-2020	129	36	27	11	115 (114-121)	22 (20-25)	78 (70-85)	-12 (-15 - -4)
Grassland*	1981-1990	124	56	59	12	158 (154-168)	34 (30-40)	23 (14-30)	36 (29-46)

	2011-2020	88	53	63	12	155 (153-162)	34 (30-39)	21 (12-27)	6 (2-14)

Section 5 which explicitly discuss the uncertainty in a qualitative manner is therefore removed. The following texts were integrated into Discussion.

"The Monte Carlo analysis showed that the uncertainty associated with simulated NUE, N losses, and soil N stock changes was generally smaller than the observed long-term trends, increasing confidence that the simulated temporal changes are robust. Nonetheless, the quantified N budgets in this study were estimated primarily using a modelling approach so that that the results (and the associated uncertainty) should be interpreted with caution. In addition to the evaluated model parameters, other sources of uncertainty were not quantified, such model inputs (e.g., livestock C and N data, and soil data). It is also worths noting that DayCent uses a simple "tipping bucket" module to represent water movement in soil layers, which can overestimate percolation fluxes (i.e., predict quicker drainage). This influences soil water content and consequently affects water-dependent processes (such as crop N uptake, leaching and N_2O production). Moreover, DayCent lacks a sophisticated scheme for NH_3 volatilization, leading to substantially underestimated NH_3 fluxes. This can result in a larger soil nitrate pool because more ammonium is available for nitrification, subsequently enhancing nitrate leaching.

Overall, our results and findings are robust and provide valuable insights for agricultural policy implementation and the assessment of agri-environmental performance. This work also demonstrates the feasibility of spatially explicit N flow quantification. Future work on monitoring national N use (e.g., constructing N budgets and calculate N balance) can incorporate biogeochemical modelling as part of the methodology."

4. Discussion needs to be reframed to clearly interpret simulation output with respect to model drivers and parameters, while making a connection to real-life processes via referencing robust parameterization based on observational and experimental studies. The interpretation of results would also benefit from a discussion of the N-cycle processes that may be significant for the N cycle response to policy change but are not represented in the DayCent model.

Reply: We thank the reviewer for this valuable comments. Please see our detailed replies below.

Additional minor concern:

The spatial aspect of the simulations allows for analysis of regional differences within Switzerland, but there is no discussion of such differences.

Reply: We thank the reviewer for comment. We agree that the spatially explicit simulations enable us to investigate regional differences in N dynamics across Switzerland. However, the primary objective of this study was to conduct a national-scale assessment of NUE, N losses and soil N balance through spatially explicit simulations using a biogeochemical model, with emphasis on long-term temporal trends and differences between cropland and grassland ecosystems rather than regional variability.

To avoid over expanding the manuscript, we did not undertake a detailed regional analysis of the simulated spatial patterns. We have, however, added a brief statement discussing the spatial variability and acknowledging that the spatially explicit simulations could be further exploited to investigate regional differences.

"The spatially explicit simulations showed that higher N losses and negative soil N balances were mainly associated with intensively managed agricultural regions dominated by croplands, where fertilizer inputs and harvest removal were higher (Fig. 5). In contrast, grassland generally exhibited lower N losses and mostly positive soil N balance (Fig. 6), consistent with higher N retention associated with continuous vegetation cover. Although the simulations were conducted at a fine spatial resolution that enables analysis of regional differences across Switzerland, the primary objective of this study was to assess national-scale temporal trends and compare two agricultural systems. A more detailed investigation of regional hotspots of NUE, N losses and soil N changes represents an important direction for future research."

Specific comments

Title: "Balancing nitrogen use efficiency, losses and soil nitrogen depletion to evaluate agri-environmental performance across spatial scales over 40 years"

Different spatial scales were not discussed in the manuscript, so I suggest changing it to "national scale".

Reply: We revised the title to "**Balancing nitrogen use efficiency, losses and soil nitrogen depletion to evaluate national scale agri-environmental performance over 40 years**".

L338: "Our results also indicate that NUE increases with BNF-derived N and decreases with fertilizer N (Fig. 8A, B). Under present conditions, the type of N input (i.e. BNF or fertilizer) has no significant influence on relative N losses (%Nloss; Fig. 8C, D)."

Most probably, the fact that type of N input affects NUE but does not affect N loss is a consequence of the model structure. A sensitivity analysis could answer this question. Another question is whether BNF-derived N is negatively correlated to fertilizer N. The reasons for these relationships should be made clear to the readers.

Reply: We thank the reviewer for this insightful comment. We agree that the simulated relationships partly reflect the underlying model structure and should be better explained. The newly conducted sensitivity tests and scenario simulations offer additional information on these effects. We revised the manuscript and made the following changes.

"**Within the current model framework, our simulation results demonstrate at the national scale that NUE increases with a greater contribution of BNF-derived N and decreases with increasing fertilizer N (Fig. 8A, B). In DayCent, symbiotic N fixation occurs only when mineral N is insufficient to satisfy plant demand, leading to an inverse relationship between BNF-derived N and fertilizer N inputs. Although the model does not distinguish the source of mineral N during plant uptake or loss processes, the scenario simulations indicate that replacing fertilizer sources by only applying a single type of fertilizer results in modest changes in total N losses (ranging from -7 to 3%), whereas reducing the total fertilizer input substantially decreases N losses by ~20% (as presented in Table S3). These findings suggest that the amount of N input is a stronger determinant of N losses than the source of N input.**"

L341: "Importantly, $\%N_{loss}$ correlated negatively with soil N change, indicating that reducing N losses is crucial for preventing soil N depletion in agricultural land (Fig. 8E)."

The observation that N loss is negatively correlated to N change is self-evident. It would be more meaningful to compare the relative influence of N loss vs N input on the N change

Reply: As illustrated by the scenario simulations, soil N stock changes are jointly controlled by N inputs, N removal through harvests and N losses. Although reducing fertilizer application by 20% decreased total N losses by approximately 20%, the accompanying reduction in total N inputs resulted in slightly greater soil N depletion in croplands and reduced soil N accumulation in grasslands. These results suggest that maintaining soil N stocks requires balancing reductions in N losses with sufficient N inputs, rather than minimizing N losses alone. We revised the manuscript.

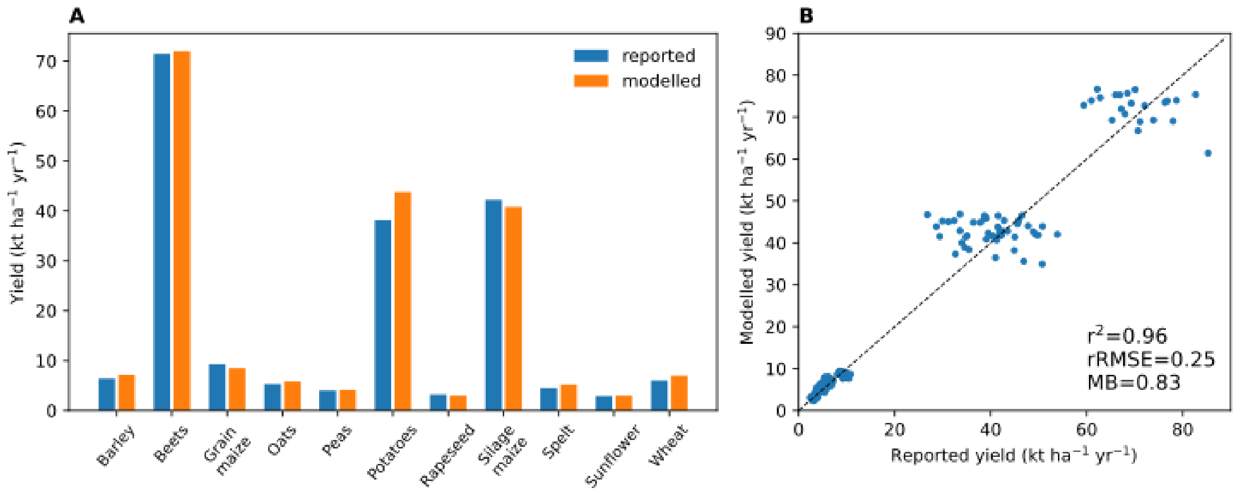
"**Although lower simulated relative N losses were associated with more positive soil N balances (Fig. 8E), the scenario simulations demonstrates that soil N stock changes are determined by the combined effects of N inputs, harvest removal, and N losses (Table S3). A 20% reduction in fertilizer application decreased total N inputs by only 11–13% because increased BNF partially compensated for lower fertilizer inputs (Table S3). Nevertheless, soil N depletion in croplands increased slightly and soil N accumulation in grasslands declined, indicating that reductions in N losses alone are insufficient to maintain soil N stocks if accompanied by reduced N inputs. These findings highlight the need to optimize both N inputs and N retention when improving N management."**

L354: "Using national-scale simulations evaluated against observational data…"

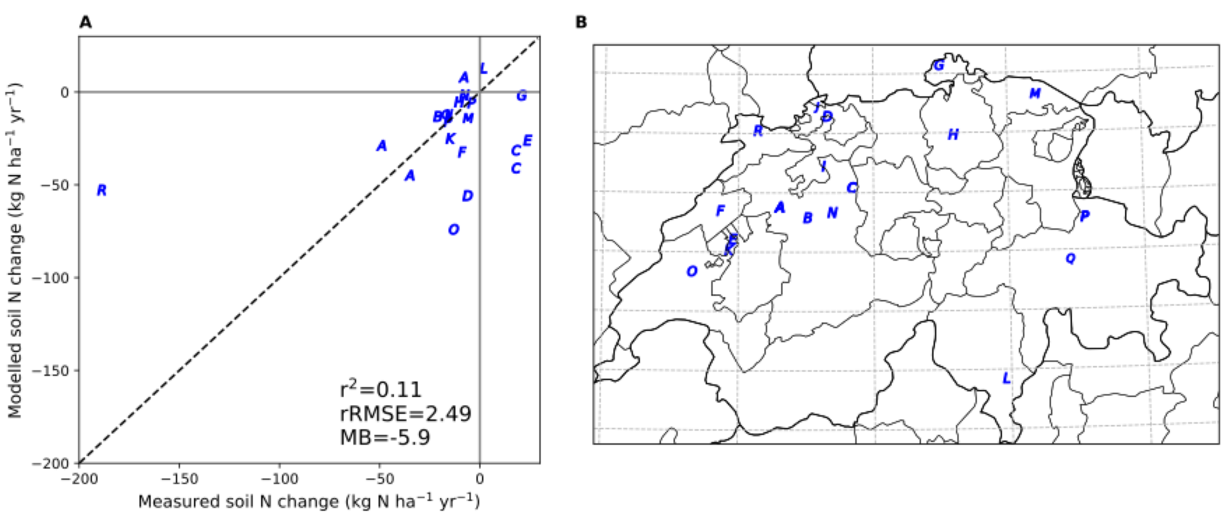
Quantitative evaluation of simulation results against observational data should be added and referenced here.

Reply: We added a set of metrics (r^2, rRMSE and Mean Bias) for model evaluation in updated Figs. S3 and S5 (as shown previously). We referenced these figures in the revised text.

"Using national-scale simulations evaluated against observational data **(Figs. S2, S3 and S5),** we construct spatially explicit N budgets over the past four decades and show that Switzerland's cropland and grassland systems have undergone profound transformations."



Updated Figure S3. Comparisons between modelled and reported yields for 11 crops from 1991 to 2013 in Switzerland. All yields are national mean expressed on a wet matter basis at harvest.



Updated Figure. S5. (A) Comparisons between modelled and measured soil N change (kgN ha^{-1} yr^{-1}) in croplands. (B) Locations of measuring sites. Measurements are from NABO long-term soil monitoring data. Multiple occurrences of the same symbol in panel a represent soil N changes in different time periods at the same location. There are 18 sites and 22 site-year measurements (n=22) chosen for comparison. DayCent simulations capture 77% of the trend (soil N depletion or soil N accumulation) correctly, with 50% modelled values within a factor of 2 (FAC=0.5) compared with measurements.

L358: "These findings can largely be explained by policy reforms in the 1990s."

Figure 2C and Supplementary Figure S4A do show a visible change of slope for croplands occurring in the 1990s, but same cannot be claimed about grasslands. Either more evidence is needed to support the policy effect claim for grasslands, or more discussion about the lack of such effect should be added.

Reply: We thank the reviewer for pointing out this overgeneralization. We agree that the evidence for a policy-related shift is much stronger for croplands than for grasslands. We have therefore revised the Discussion to distinguish between the two systems.

"**During 1981–2020, the simulations reproduced stable agricultural production despite declining fertilizer N inputs, accompanied by increasing NUE and reduced N losses, particularly in croplands. The timing of these changes is consistent with the implementation of agricultural policies promoting less fertilizer use during the 1990s. However, the responses differed between ecosystems. In croplands, fertilizer reductions primarily involved synthetic fertilizers (Table 2), which likely contributed to the marked increase in NUE and decline in N losses. In contrast, grasslands experienced little change in N losses. This can be partly explained by fertilizer reductions dominated by decreases in organic fertilizer, while synthetic fertilizer inputs remained relatively stable. (Table 2).**"

L380: "In this study, we noticed a decoupling of yields from fertilizer inputs with increased NUE in both ecosystems between the 1980s and the 2010s, i.e. yields do not exhibit a linear dependence on N input."

The relationship between N inputs and yields is not something to be noticed in the results – it is a direct consequence of the crop simulation parameters that were input in DayCent, presumably based on the long-term experiments. Therefore, the argument should follow the logic: experiments showed a certain relationship between fertilization and yield -> the model was parameterized based on this relationship -> at the national scale model output showed...(maybe some spatial differences or any added information compared to what already went in the model parametrization).

Reply: We agree with the reviewer that the nonlinear relationship between N inputs and crop yields has been well established in experimental studies and is represented within the process-based structure of DayCent. Our intention was not to present this as a new discovery, but to highlight that the national-scale simulations reproduced a progressive decoupling between fertilizer N inputs and agricultural production over the study period. To clarify this point, we revised the manuscript and made the following changes.

"**At the national scale, the simulations reproduced a progressive decoupling between crop yields and fertilizer N inputs from the 1980s to the 2010s. The simulated increasing NUE over recent decades reflects not only improvements in N management but also the diminishing marginal yield response to additional fertilizer inputs that exceed the agronomic optimum. This pattern is consistent with the well-established nonlinear response of crop yield to N fertilization, which indicates that further increases in fertilizer inputs are unlikely to translate into significant yield gains, suggesting that Switzerland has moved beyond the stage of input-driven intensification. The scenario simulations further support this interpretation: reducing fertilizer application rates by 20% results in only modest reductions in simulated N harvest (3–6%) while substantially decreasing N losses (~20%), suggesting considerable opportunity to further improve environmental performance without compromising agricultural production.**"

L388: "Our modelling results show that N losses decreased only in absolute terms due to lower N inputs, while relative N losses show less significant reductions in croplands and even increased in grasslands (Table 2 and Fig. S4A in Supplementary Materials). Increases of relative N losses in grasslands might be attributed to the unstable N accumulation in soils that causes higher gaseous N emissions resulting from legacy effects (Qian et al., 2025)"

Logically, the reasons for model output can only include processes that are reflected in the model. Is "unstable N accumulation" something that is represented in DayCent and could affect the simulation results? If so, how? The reasoning here may need updating based on the sensitivity analysis.

Reply: Based on the sensitivity tests, we found that simulated N losses increased by 6% in croplands and by 13% in grasslands under a uniform 2C increase in temperature. We revised the manuscript.

"**Although absolute N losses declined with decreasing fertilizer inputs, relative N losses showed only modest reductions in croplands and even increased in grasslands. Our sensitivity analysis suggests that the weaker reduction in relative N losses in grasslands may partly reflect the greater sensitivity of grassland N cycling to increasing temperatures, which offset part of the**

reduction expected from lower fertilizer inputs. A uniform 2°C increase in air temperature increased simulated N losses by approximately 6% in croplands and 13% in grasslands, indicating that warming enhances soil N turnover and gaseous N emissions in DayCent. Consequently, the reduction in N losses resulting from lower fertilizer inputs may have been partially offset by temperature-driven increases in N cycling, particularly in grasslands. In addition, reducing fertilizer application substantially decreased absolute N losses but also altered BNF and soil N dynamics in DayCent, demonstrating that relative N losses are governed by the interaction among N inputs, plant response and internal soil N cycling rather than by fertilizer inputs alone.”

L403-409: The N losses in the output can be and should be definitively attributed to certain drivers used in the simulation and then compared to domain knowledge and observational studies which would corroborate or contrast the simulation results.

Reply: We agree that the Discussion should first explain the simulated N losses using processes explicitly represented in DayCent before relating the results to previous studies. Accordingly, we have substantially revised this section.

“**Our simulations, supported by sensitivity analyses, indicate that soil N dynamics are governed by the combined effects of N inputs, harvest removal, climate and internal N cycling, rather than by any single environmental or management factor. Maintaining soil N stocks therefore requires balancing N inputs with harvest removal against N losses. Sensitivity analyses further showed that although reducing fertilizer application substantially decreased N losses, the accompanying reduction in total N inputs slightly accelerated soil N depletion. Moreover, increasing temperature enhanced simulated N losses, suggesting that climate warming may have partially offset improvements associated with reduced fertilizer use. Our simulations identified nitrate leaching as the dominant N loss pathway (Fig. 5F, Table 2; Fig. S6 in Supplementary Materials), explaining the persistence of N losses despite declining fertilizer inputs. This simulated pattern is consistent with previous studies showing that cropland systems are particularly susceptible to N losses because annual cultivation disturbs soil structure and periods of bare soil increase vulnerability to nitrate leaching (Porwollik et al., 2022; Rupp et al., 2024). Excessive fertilizer application, especially in the form of nitrate, significantly increases leaching risk and thereby degrades groundwater quality (Misselbrook et al., 1996; Shepherd et al., 2001; Vinten et al., 1994), reflected by the widespread (~35%) exceedance of groundwater nitrate guidelines (>25mg/L) across the Swiss Plateau (Covatti et al.,**

2025). In addition, wheat as the second most widely cultivated crop in Switzerland, is known to extract large amounts of soil N (Kraaijvanger & Veldkamp, 2020), suggesting that harvested crops can represent a substantial pathway of N export. Together, these factors can contribute to a negative N balance in croplands."

Overall, this paper shows a promising and innovative approach to national assessments of N balance and long-term policy effects. However, quantitative sensitivity and uncertainty analyses, as well as a clear link between observation, model parametrization, and interpretation of the output are necessary. My recommendation is a major revision.

Reply: We thank again Referee 2 for the positive feedback on our study and these useful comments. We revised the manuscript to address all the points. We hope that the revised manuscript can meet the requirements for publishing in Biogeosciences.