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).

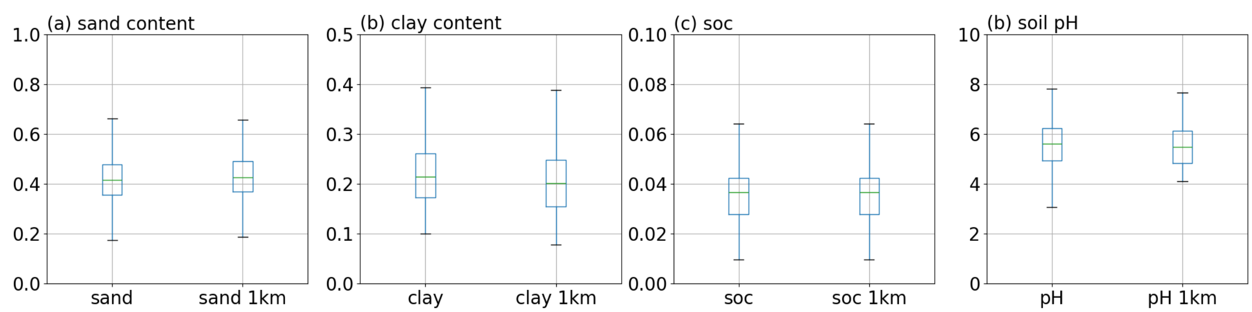

Figure R1. Comparison of the variability in soil data between the original data (30 m) and resampled data (1 km) for four soil properties.

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:

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

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

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

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.

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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.