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Warming-induced agricultural nitrous oxide emissions can offset mitigation benefits of fertiliser management

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Abstract. Agriculture is the dominant source of anthropogenic nitrous oxide (N_2O), a potent greenhouse gas with a high global warming potential. In Switzerland, substantial changes in fertiliser use alongside climatic conditions have occurred over the past four decades, yet the relative contributions of management practices versus environmental change to long-term N_2O emission trends remain incompletely understood. Here, we applied the biogeochemical model DayCent at 1 km resolution across Switzerland, integrating spatially explicit datasets on climate, soil properties and agricultural management, to quantify N_2O emissions for the period 1981–2020 from croplands and grasslands and attribute emission changes to management versus climate drivers. Simulated national N_2O emissions from agricultural soils declined by roughly 5% from 4.0 to 3.8 kt N yr^{-1} between the 1980s and 2010s, primarily due to a 25% reduction in N fertiliser use. Our attribution simulations suggested that under real climate conditions, such a decrease in fertiliser N inputs (–25%) over the period studied lowered emissions by 15.2% in croplands and by 12.0% in grasslands (including permanent meadows and pastures, and high alpine summer pastures). However, compared to a control scenario (in the absence of climate change), rising temperatures over the past 40 years offset these gains, increasing emissions by 5.7% in croplands and 13.6% in grasslands. These results show that warming-induced N_2O emissions partially negate mitigation from improved fertiliser management, highlighting the need for integrated agricultural N_2O mitigation strategies that are resilient to future warming.

1 Introduction

Nitrous oxide (N_2O) is both a potent greenhouse gas (GHG) and an ozone-depleting substance (Ravishankara et al., 2009). With a 100-year global warming potential approximately 273 times that of carbon dioxide (CO_2), it accounts for 6.4% of the total global radiative forcing during 1750–2022 (IPCC, 2021). Since pre-industrial times, atmospheric N_2O concentration has increased from 270 ppb in 1750 to 338 ppb in 2024 (Ghosh et al., 2023; Zhu et al., 2025), with the rate of increase accelerating in recent years, from 0.82 ± 0.33 ppb yr^{-1} (1980–2020) to 1.15 ± 0.12 ppb yr^{-1} (2021–2024) (Ghosh et al., 2023; Zhu et al., 2025). Agriculture is the primary source of anthropogenic N_2O, contributing more than half of global emissions (Tian et al., 2020), largely through nitrogen (N) inputs such as field application of synthetic fertilisers, livestock excreta and

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other reactive N (N_r) sources (Tian et al., 2020, 2024; Zhu et al., 2025). As global food demand continues to rise, regulating agricultural N_2O emissions has become increasingly critical for climate change mitigation (Davidson, 2012; Reay et al., 2012).

Quantifying N_2O emissions from agricultural soils remains challenging due to the complex underlying processes. Mechanistically, N_2O is primarily produced through two key processes: nitrification and denitrification (Butterbach-Bahl et al., 2013). Microbial activities responsible for both processes are controlled by environmental factors such as temperature, soil moisture, soil N and oxygen levels, and soil pH (Butterbach-Bahl et al., 2013; Flechard et al., 2007; Skiba and Smith, 2000). In addition, agricultural practices including fertiliser application and harvesting also influence N_2O fluxes. In particular, fertiliser application elevates soil N availability and is a primary driver of increased agricultural N_2O emissions. Alteration of soil structure, such as by compaction and drying-rewetting cycles, affects N_2O production through their impacts on soil water content and aeration status (Beare et al., 2009; Decock et al., 2015; Liu et al., 2018). Interactions among these factors often result in very dynamic N_2O emissions, characterised by spatial "hotspots" and temporal "hot moments" (Butterbach-Bahl et al., 2013; Groffman et al., 2009). This intrinsic variability makes it difficult to derive reliable estimates from directly upscaling field measurements for larger spatial and temporal scales.

National greenhouse gas (GHG) inventories commonly rely on emission factor (EF) approaches to estimate N_2O emissions from agricultural soils. In Switzerland, as in many Annex I countries (i.e., industrialised countries and countries with economies in transition), annual reporting of N_2O emissions to the United Nations Framework Convention on Climate Change (UNFCCC) is predominantly based on Tier I methodologies (FOEN, 2026), which estimate emissions as a fixed proportion of N inputs (i.e., a default aggregated EF of 1% for fertiliser-induced emissions after accounting for soil organic matter turnover; Buendia et al., 2019). These approaches provide a transparent and consistent framework for estimating management-related emissions at the national scale. However, because EFs are typically fixed in space and time, they only partly represent the influence of climatic conditions, soil properties, and local crop and field management on N_2O emissions, and therefore provide a limited representation of spatial and temporal variability in emissions. In contrast, process-based models explicitly represent the mechanisms governing soil N dynamics and simulate the responses of processes such as nitrification and denitrification to environmental drivers and management practices. As a result, they offer the possibility to distinguish effects of agricultural management from environmentally driven variability in N_2O emissions and to provide spatially resolved estimates across heterogeneous landscapes. Consequently, they are increasingly recommended for GHG inventory development using Tier II or Tier III approaches (Buendia et al., 2019), especially in regions characterised by strong environmental gradients and rapid climatic change.

Switzerland presents a particularly relevant case for assessing agricultural N_2O emissions because it has implemented nationwide agricultural reforms aimed at reducing N losses (Decrem et al., 2007; Herzog et al., 2008; Spiess, 2011). Moreover, Switzerland has a Net-Zero target to reduce all GHG from the agricultural sector by 40% until 2050 (FOEN, 2025). At the same time, the country has experienced pronounced climate change over recent decades, with warming approximately twice the global average (MeteoSwiss, 2026). These changes in management practices and climatic

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conditions are expected to alter N availability and soil conditions, which are key controls of nitrification and denitrification processes, thereby influencing N_2O emissions (Feigenwinter et al., 2023a; Maier et al., 2022). However, the extent to which climate change and fertiliser management have affected agricultural N_2O emissions in Switzerland remains poorly quantified. In particular, long-term national-scale assessments that capture both the spatial and temporal variability of emissions across different agricultural soils are still insufficient.

In this study, we investigated the effects of fertiliser management and climate change on N_2O emissions, and present an assessment of N_2O emissions from agricultural soils across Switzerland over the past four decades using high-resolution process-based modelling. We compiled spatially explicit datasets on climate, soil properties and agricultural information, and applied the well-calibrated and validated biogeochemical model DayCent at a high spatial resolution of 1 km×1 km. Specifically, our objectives were to (i) quantify N_2O emissions from two major agricultural systems (croplands and grasslands) between 1981 and 2020, (ii) characterise their spatial and temporal variability (both inter-annual and seasonal) and analyse emission drivers, and (iii) assess the influence of fertiliser management versus climate change (temperature increase and changes in precipitation) on emissions.

2 Methods

2.1 Study region

This study focused on Swiss agricultural land, which covers approximately 1.5 million ha (BFS, 2024). Collectively, Switzerland's land use exhibits diverse agro-pastoral functions as a result of complex mountainous terrain and pedoclimatic conditions. Three primary land use types characterise Swiss agriculture: **cropland**, **managed permanent grassland** (meadow and pasture), and high alpine **summer pastures** (**SPA**) (Fig. S1 in Supplementary Materials). **Cropland** accounts for nearly 27% of Switzerland's agricultural area (BFS, 2024) and is predominantly concentrated on the Swiss Plateau, the most densely populated region of Switzerland, where moderate topography, fertile soils and temperate climate provide ideal conditions for intensive arable production. **Managed permanent grassland** occupies over 40% of the national agricultural area (BFS, 2024). It includes both lowland meadows and pastures on the plateau and extensive areas within the Pre-Alpine zones. Managed as meadows or pastures, these grasslands provide the essential resources for Switzerland's ruminant livestock sector, particularly dairy and beef production. Management practices (mowing, grazing) are closely adapted to local climatic and topographic conditions. **SPA**, covering over 30% of the total agricultural area (BFS, 2024), are situated in the mountainous regions and are utilised exclusively during the summer months (from June to August/September). These summer pastures provide high-quality forage to grazing livestock. Beyond agricultural production, SPA provide other vital ecosystem services (e.g., biodiversity conservation, soil carbon storage, cultural heritage; Schils et al., 2022) and are subject to strict environmental regulations (Meyer et al., 2025; Pauler et al., 2025).

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2.2 DayCent model

We used the biogeochemical model DayCent (DayCent17centEVI version), which simulates N and C dynamics of the soil-plant-atmosphere interface at a daily time step (Del Grosso et al., 2001). The model simulates plant growth, soil organic matter (SOM) decomposition, soil emission of trace gases, and changes in key state variables (e.g., soil temperature and soil water content) under varying climatic and land use conditions.

DayCent includes a mechanistic representation of the N cycle in terrestrial ecosystems with differentiated mineral and organic N pools, and simulates major transformation processes such as mineralisation, immobilisation, nitrification and denitrification. These processes respond to environmental factors such as temperature, soil moisture, oxygen status, soil texture, organic matter availability and soil pH (Del Grosso et al., 2000, 2001).

For this study, a key advantage of DayCent is its representation of N_2O production driven by nitrification and denitrification. This process-based structure enables simulation of N_2O emissions under changing environmental and management conditions at moderate computational cost. Previous studies have demonstrated that calibrations to site-specific soil and climate characteristics improved model performance in reproducing observed N_2O emission patterns (Del Grosso et al., 2000; Gurung et al., 2021; Laub et al., 2024; Necpalova et al., 2018). The model has been evaluated (Dos Reis Martins et al., 2022, 2024; Necpalova et al., 2018) against measurement data from Swiss croplands (Emmel et al., 2018; Hüppi et al., 2015; Krauss et al., 2017; Mayer et al., 2015) and grasslands (Ammann et al., 2007, 2009, 2020; Feigenwinter et al., 2023a). In this study, we used values of seven key N dynamic parameters that were extensively calibrated, with details presented in Dos Reis Martins et al. (2022, 2024).

2.3 Model input data

We used the same input datasets as in our companion study (Jiang et al., 2026), which we briefly described here for completeness. Model input data include daily weather data, soil properties and land use.

Daily meteorological variables including daily maximum and minimum temperature, and precipitation were obtained at 1 km×1 km resolution for the period 1981–2020 from the Federal Office of Meteorology and Climatology (MeteoSwiss) (MeteoSwiss, 2025; https://opendatadocs.meteoswiss.ch/c-climate-data/c3-ground-based-climate-data; last access: 2026.07.06). Soil properties, including soil texture (sand, silt and clay content), pH and SOM, were obtained from a national soil database recently developed by the National Competence Center for Soil ("Kompetenzzentrum Boden") (Stumpf et al., 2024). These data (originally 30 m×30 m resolution) were resampled to 1 km×1 km resolution using conservative remapping (CDO; Schulzweida, 2023). Additional properties such as soil bulk density, field capacity, wilting point and saturated hydraulic conductivity were estimated by pedotransfer functions using the built-in DayCent utility programme (Saxton et al., 1986; Saxton and Rawls, 2006).

Land use data for croplands and grasslands (i.e., managed permanent and SPA) were obtained from the Federal Statistical Office ("Bundesamt für Statistik", BFS) (BFS, 2024). Permanent grasslands in Switzerland are classified into

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meadows and pastures, with further differentiation by management intensity (intensively-managed, less intensively-managed, extensively-managed types) following national fertiliser guidelines (Sinaj et al., 2017). Switzerland was represented using 24 agri-climatic zones capturing climatic, topographic and regional differences as well as agricultural management (Wüst-Galley et al., 2020). For each zone, annual areas of different cropping systems and grasslands were provided.

2.4 Agricultural management in the simulations

Agricultural management are detailed in DayCent schedule files that represent daily sequences of common operations, including cropping systems (e.g., crop types and rotations), nutrient inputs (e.g., organic and synthetic fertilisation), cultivation, irrigation and harvest. In our simulations, we specified N inputs from both organic and synthetic fertilisers.

Organic fertiliser inputs included animal manure, compost, sewage sludge and digestates, following the categories used in the Swiss National Greenhouse Gas Inventory (NIR, 2026). As the dominant share of these organic inputs, manure (including both solid manure and slurry) quantities were estimated from livestock number, livestock-specific C and N excretion rates, and adjusted for losses in housing and storage systems (FOEN, 2026; Wüst-Galley et al., 2020). Spatial allocation of organic fertilisers to croplands and grasslands followed the approach specified in Wüst-Galley et al. (2020), accounting for (i) farm-level application preferences for manure, slurry, or poultry manure to different crop groups (Sinaj et al., 2017), and (ii) fertiliser requirements of various grassland types across elevation zones (Sinaj et al., 2017).

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. Additional management information (e.g., tillage, planting, fertilisation schedules, and harvest practices) was obtained from the Swiss guidelines "Principles for the fertilisation of agricultural crops in Switzerland" (Sinaj et al., 2017) and previous DayCent implementations for Switzerland (Lee et al., 2020a, b), e.g., a static calendar that has fixed dates for each management practice rather than dynamic dates varying by years.

For cropland simulations, we used the same crop rotations as in Jiang et al. (2026), reflecting the common practice for crop production in Switzerland. The crop rotations followed the probability scheme of Lee et al. (2020), which integrates survey data, literature, long-term experiments and agronomic principles, with details presented in Supplementary Materials Table S1. Our crop rotation scheme considers both nationwide recommendations for agricultural production and real practices sourced from farmers. This approach was used due to the lack of spatially explicit rotation data at national scale and allows consistency with reported crop distributions across Switzerland at the agri-climatic zone level. For grassland simulations, the number of mowing and grazing events and their timing were derived from grassland-use intensity maps generated using Sentinel-2 and Landsat 8 satellite data (Weber et al., 2024).

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2.5 Model simulations

The simulations were performed using the same framework as described in Jiang et al. (2026). We applied DayCent at a spatial resolution of 1 km×1 km across the entire simulated region (Switzerland), resulting in 14'926 and 36'140 grid-specific simulations for croplands and grasslands, respectively. Each simulation included a long spin-up prior to the baseline simulations, following the general approach of Lee et al. (2020). A spin-up of 1980 years was used to stabilise soil C and N pools. This was followed by transient simulations of the study period from 1981 to 2020.

Cropland simulations included 15 major crops representing more than 95% of Swiss cropland area, including grass-clover ley (i.e., temperate grassland in crop rotation), winter wheat, silage maize, winter barley, rapeseed, sugar beet, grain maize, potato, triticale, spelt, sunflower, pea, rye, soybean, and oat. Annual crop distributions were derived from the crop rotation scheme described above and were consistent with national and regional statistics across 24 agro-climatic zones (Wüst-Galley et al., 2020). As DayCent runs continuously throughout the simulated years at a daily time step, N_2O emissions during the period between harvest of one crop and planting of the next were captured, and we calculated these emissions as bare soil emissions.

Grassland simulations used mowing and grazing intensity derived from the 2020 grassland-use intensity maps (Weber et al., 2024). Fertilisation frequency and intensity were linked to management intensity and altitude (Sinaj et al., 2017). We assumed that fertilisers were applied within two weeks after a mowing event. Combining management intensity data and management practice reported by Feigenwinter et al. (2023a, b) and Hörtnagl et al. (2025), a fertilisation timing scenario was developed and applied to the entire country for meadows. For less intensely managed- and high-elevation grassland, mowing and fertiliser intensity are lower (i.e., less mowing events and lower fertiliser inputs), while the timing of fertilisation was assumed to follow the same scenario in our simulations.

For grazing, instead of using DayCent's grazing module, we simulated grazing N inputs as manure application to the field. This alternative approach was chosen to keep the deposited manure during livestock grazing consistent with the input C and N data. For SPA, grazing takes place during the summer months. We assumed a three-month grazing period (from June to end of August) and set synthetic fertilisers to zero for SPA.

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

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

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

In parallel to baseline simulations ("baseline"; Table 1) for quantifying total N_2O emission from fertilised agricultural soils, we simulated a scenario with no fertiliser inputs ("nofert"; Table 1) to quantify background N_2O emissions (F_{bg}, kg N ha^{-1} yr^{-1}; defined as N_2O emissions from soils that are not fertilised so that emissions are from SOM

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mineralisation, biological N_2 fixation (BNF) and atmospheric N deposition) and to calculate modelling-derived EF (EF_{N_2O}) using the following equation

$$EF_{N_2O} = \frac{F_{N_2O} - F_{bg}}{N_{fert}}, \quad (2)$$

where N_{fert} is the applied fertiliser rate (kg N ha^{-1} yr^{-1}) in baseline simulations. For "nofert" simulations, N inputs through synthetic and organic fertilisers were set to zero, while the other practices (e.g., planting, cultivation, harvest) specified in DayCent's schedule files were the same as the baseline simulations.

In addition, we quantified the extent to which changes in national N_2O emissions were driven by fertiliser reduction or climate change employing two model scenarios. To investigate the fertiliser reduction effect, we fixed the fertiliser application rates of individual crop types at the 1980s level ("unchanged fertiliser"; "fert1980" in Table 1) throughout the study period, while simulating emissions under time-varying meteorological inputs ("real climate", i.e., climate inputs varying with time) as used in the baseline simulations. The difference between this model scenario and the baseline simulation was attributed to changes in fertiliser inputs. 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. To investigate the climate effect, we fixed the climate representative for ~1980 ("unchanged climate"; "clim1980"; Table 1) for the entire study period, while simulating emissions under time-varying fertiliser inputs ("real fertiliser inputs", i.e., inputs varying with time) as used in the baseline simulations. For this model scenario, the meteorological input data were detrended and anchored to the climatology of 1975–1985, while the seasonal cycle and the inter-annual variability over the past 40 years were preserved. The difference in N_2O emissions compared to the baseline simulations thus resulted from the climate effect.

Table 1. Model simulations performed using DayCent, and corresponding fertiliser input and meteorological input for each scenario of simulation. [a]Fertiliser N input fixed to the 1980s level. [b]Meteorological input (temperature and precipitation) fixed to the 1980s level.

Scenarios	**Fertiliser input**	**Meteorological input (climate)**	**N_2O emissions**
baseline	1981–2020 fertiliser	1981–2020 climate	total N_2O emission from 1981–2020
nofert	None	1981–2020 climate	background N_2O emission from 1981–2020
fert1980	1980s fertiliser[a]	1981–2020 climate	N_2O emission without fertiliser change
clim1980	1981–2020 fertiliser	1980s climate[b]	N_2O emission in the absence of climate change

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2.6 Statistical analysis and sensitivity tests

We investigated the effects of environmental drivers, plant performance, and management practices on N_2O fluxes and EFs through correlation analysis and Principal Component Analysis (PCA). The statistical analysis was conducted using the 40-year average values of variables and simulated fluxes in each grid cell. The environmental drivers included mean annual temperature (MAT), mean annual precipitation (MAP), soil pH, soil clay content, soil bulk density (BD) and SOM. We used the modelled N use efficiency (NUE) that is calculated from N removed through harvests divided by total N input as an indicator for plant performance. To quantify pairwise relationships between N_2O metrics (flux and EF), environmental drivers and plant performance, both Pearson and Spearman correlation coefficients were calculated.

PCA was performed on the N_2O metrics, environmental variables and NUE. The analysis was conducted using singular value decomposition of the covariance matrix. Principal components (PCs) were ranked according to the proportion of total variance explained. The first three principal components (PC1–PC3) were retained for interpretation, as they together captured the majority (~65%) of variability in the dataset.

We also conducted sensitivity tests by selecting five key input variables (air temperature, precipitation, soil clay content, SOM and soil pH). These variables were perturbed one-at-a-time within a specified range to examine their effects on modelled N_2O emissions (see Table 2 for details). These sensitivity tests were performed on the national scale and applied the same model settings as the baseline simulations. For climate inputs, daily values were changed in these sensitivity simulations. The changes in 40-year average N_2O emissions and EFs between the baseline results and sensitivity tests were reported.

2.7 Uncertainty evaluation

Uncertainty in modelled national N_2O emissions was evaluated using a Monte Carlo ensemble approach with 200 iterations, combined with a spatially explicit implementation of the DayCent model. In this study, we focused on quantifying the uncertainty arising from N cycle parameters in DayCent (details in Table S2). These parameters have been found to profoundly influence the model performance for estimating cumulative N_2O emissions (Dos Reis Martins et al., 2022, 2024).

Uncertainty in these model parameters was characterised using probability distributions defined by default, mean and range of calibrated values taken from Dos Reis Martins et al. (2022, 2024). A total of 200 parameter sets were generated, which provided reasonable coverage of the multidimensional parameter space and reduces sampling variance. Since there were over 50’000 simulated grids, running 200 times over the full simulation domain was computationally expensive. Thus, we employed a stratified sampling using Conditioned Latin Hypercube Sampling (cLHS) to create a representative subset (n=400) of the simulated grids. The subset grids preserved spatial heterogeneity of MAT, MAP, SOM, soil pH, soil clay content, fertiliser intensity and organic fertiliser fraction. For each parameter set, the DayCent model was run for all representative grids. Model outputs were aggregated to compare with baseline results. The resulting variations expressed in 95% confidence interval (CI) were used to represent uncertainty in national emissions.

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3 Results

3.1 Simulated N_2O emissions from Swiss croplands and grasslands

Our simulations suggest that total N_2O emissions per unit area from Swiss croplands decreased from 3.8 kg N ha^{-1} yr^{-1} in the 1980s (average for 1981–1990) to 3.5 kg N ha^{-1} yr^{-1} in the 2010s (average for 2011–2020) (Fig. 1a and Table S3), while modelled background N_2O emissions (i.e., emissions without N additions from synthetic and organic fertilisers, representing SOM mineralisation, BNF of legumes and grass-clover mixture, and atmospheric deposition) declined from 1.6 kg N ha^{-1} yr^{-1} to 1.4 kg N ha^{-1} yr^{-1} (Fig. 1b and Table S3). Over the past four decades, there was a ~22% reduction in N inputs through synthetic and manure fertilisers to croplands (Fig. 1c and Table S3), while cropland area also decreased by 12% (Table S3). Contrary to the decreasing trends of emissions, modelled N_2O EF for croplands increased substantially over time (Fig. 1d and Table S3), from approximately 1.0% in the 1980s to around 1.3% in the 2010s, despite declining fertiliser inputs.

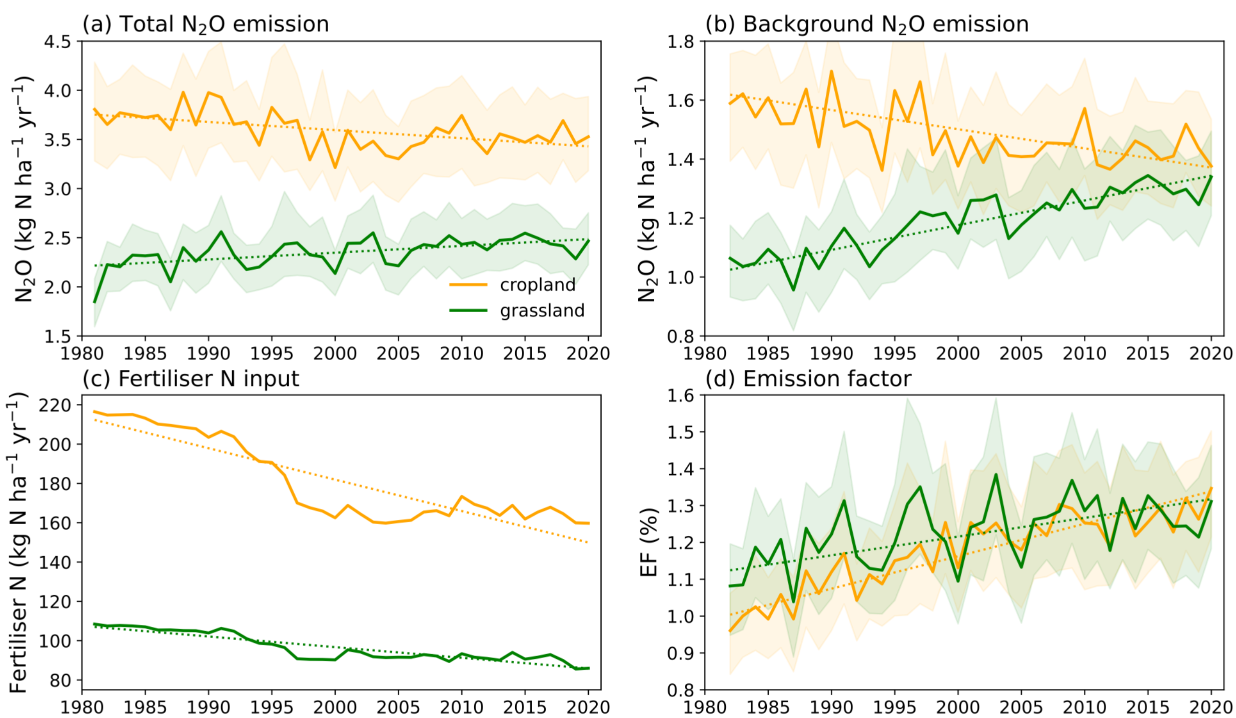

Figure 1. Timeseries results for Swiss cropland (yellow) and grassland (green) from DayCent modelling for 1981 to 2020. (a) Simulated total N_2O emissions per unit area (kt N ha^{-1} yr^{-1}). (b) Simulated background N_2O flux per unit area (kg N ha^{-1} yr^{-1}) without fertiliser inputs. (c) Fertiliser N inputs per unit area (kt N ha^{-1} yr^{-1}) to agricultural land based on national statistics. (d) Annual mean N_2O emission factors (%) derived from DayCent modelling. Grassland includes managed permanent meadows and pastures, and summer pastures. Dotted lines show statistically significant trends over the simulated 40 years determined by Mann-Kendall Trend test (with significance level *P*<0.001). Shaded areas indicate uncertainty (95% confidence interval) due to model parameters estimated from the Monte Carlo approach (Section 2.7). Note that the y-axes of each panel do not start from zero. National total results for simulated variables are shown in Fig. S2.

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Compared to croplands, N_2O emissions from Swiss grasslands (including permanent managed meadows and pastures, and SPA) exhibited a slightly increasing trend over the past 40 years. In the 1980s, simulated grassland N_2O emissions were 2.2 kg N ha^{-1} yr^{-1}. Although fertiliser inputs dropped by ~15% in the 1990s (average for 1991–2000), emissions did not show a significant reduction during this period. Instead, modelled N_2O emissions gradually increased by 9%, reaching 2.4 kt N yr^{-1} in the 2010s. The area of Swiss grasslands showed smaller changes than croplands (Table S3), with a <1% reduction in permanent grassland and a 7% reduction in SPA between the 1980s and the 2010s (Table S3). In contrast to croplands, simulated background N_2O fluxes from grasslands exhibited a long-term increasing trend (Fig. 1b). Similar to cropland, modelled EFs for grassland increased despite reductions in fertiliser inputs (Fig. 1d).

3.2 Spatial and temporal variations in modelled N_2O emissions

In the 2010s, modelled background N_2O emissions in Swiss croplands (due to SOM mineralisation, BNF and atmospheric deposition) ranged between 1.0 and 2.0 kg N ha^{-1} yr^{-1} across the Swiss Plateau (Fig. 2a), while background fluxes in grasslands were mostly below 1.0 kg N ha^{-1} yr^{-1} in SPA and many parts of the Swiss Plateau (Fig. 2b). Total emissions from both croplands and grasslands exhibited strong spatial heterogeneity (Fig. 2c, d). Emissions from croplands were largely confined to the Swiss Plateau, the primary crop-production zone, with emissions generally exceeding 3.0 kg N ha^{-1} yr^{-1}. We found that N_2O emissions during the bare soil period accounted for 24–28% of total emissions from cropland (Table S3 and Fig. S3). In accordance with the wider distribution of grasslands across Switzerland, simulated grassland N_2O emissions differed substantially in space, showing a sharp north-south gradient across the lowlands and Alpine regions. Our model results showed that grasslands had higher emissions per unit area than croplands in the northern and northwestern regions, with emissions exceeding 6.0 kg N ha^{-1} yr^{-1}. In SPA areas, N_2O fluxes remained below 1.0 kg N ha^{-1} yr^{-1}, very close to the background levels. Total N_2O emissions from Swiss grasslands were modelled as nearly double those of croplands at the national scale (Fig. S2a), reflecting the larger land use area (~70% of Swiss agricultural area is grassland). Notably, for both land use types, the highest emissions were found in the northwestern part of the country, i.e., northern part of the Jura region, with values exceeding 4.0 and 7.0 kg N ha^{-1} yr^{-1}, respectively.

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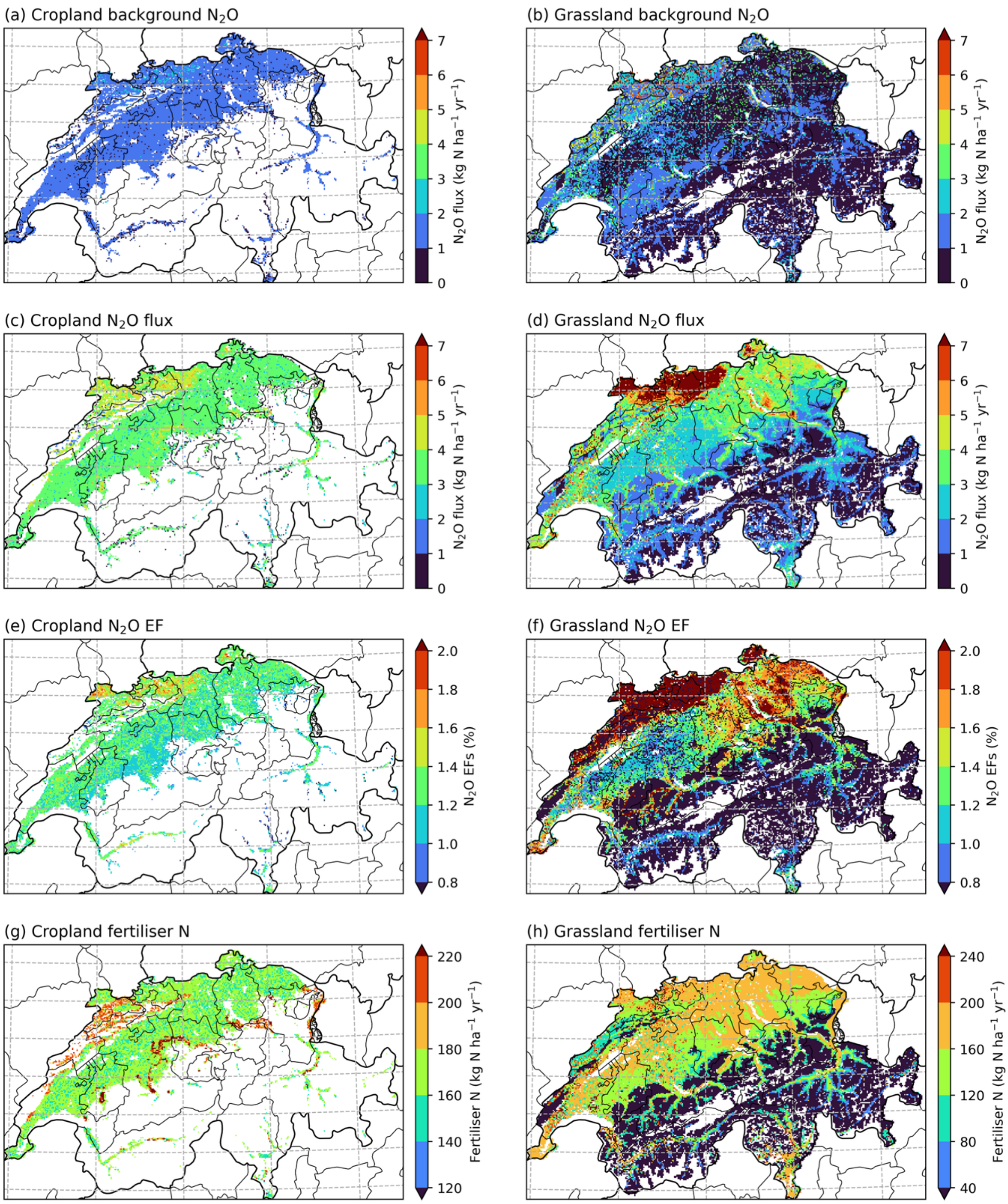

290 **Figure 2. Simulated annual mean values for (a, b) background N_2O flux (i.e., no-fertilisation, representing soil organic matter mineralisation, biological N_2 fixation and atmospheric deposition), (c, d) total N_2O flux, (e, f) model-derived N_2O emission factors, and (g, h) fertiliser N inputs (including both synthetic and organic fertilisers) for Swiss cropland and grassland in the 2010s (from**

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2011 to 2020). Grassland includes managed permanent meadows and pastures, and summer pastures. White areas indicate no N_2O emissions due to zero activity data.

The model-derived EFs showed distinct differences between the two land use types (Fig. 2e, f). Croplands EFs were more spatially uniform than those of grasslands in the lowland regions, with most of the Swiss Plateau exhibiting EFs between 1.0 and 1.4%. By comparison, grassland EFs exhibited extreme spatial variations; high EFs (>1.6%) were found in intensive grassland zones such as the eastern Swiss Plateau, whereas in the Alpine regions, EFs fell below 0.8% in less intensively managed systems (extensive pastures and SPA). Again, mirroring the spatial pattern of N_2O fluxes, the highest EFs (>2%) occurred in the northwest (Jura region), more than doubling the IPCC default value (aggregated value for synthetic and manure fertilisers).

Seasonal trends in modelled N_2O fluxes differed between croplands and grasslands (Fig. 3). Intensive spring fertilisation (between March and May, as shown in Fig. 3b) took place before the summer season when vigorous crop growth started, resulting in the largest monthly emissions (>0.5 kg N ha^{-1} $month^{-1}$) in May and June. In general, modelled cropland N_2O emissions were high from April to September (Fig. 3c). Simulated grassland emissions peaked later than croplands, with highest monthly values (~0.4 kg N ha^{-1} $month^{-1}$) from July to September, coinciding with high N inputs as well as warm and humid conditions. Moreover, grazing in SPA that largely takes place in these months caused additional emissions. Compared to spring and summer seasons, emissions in winter were lower, reflecting minimal N inputs and lower temperature. Simulated background N_2O emissions showed similar seasonality as total N_2O emissions (Fig. 3d), largely driven by SOM mineralisation (Fig. S4a). Percentage of background N_2O emission was higher in months without intense fertiliser application (i.e., December-January-February; Fig. S4b).

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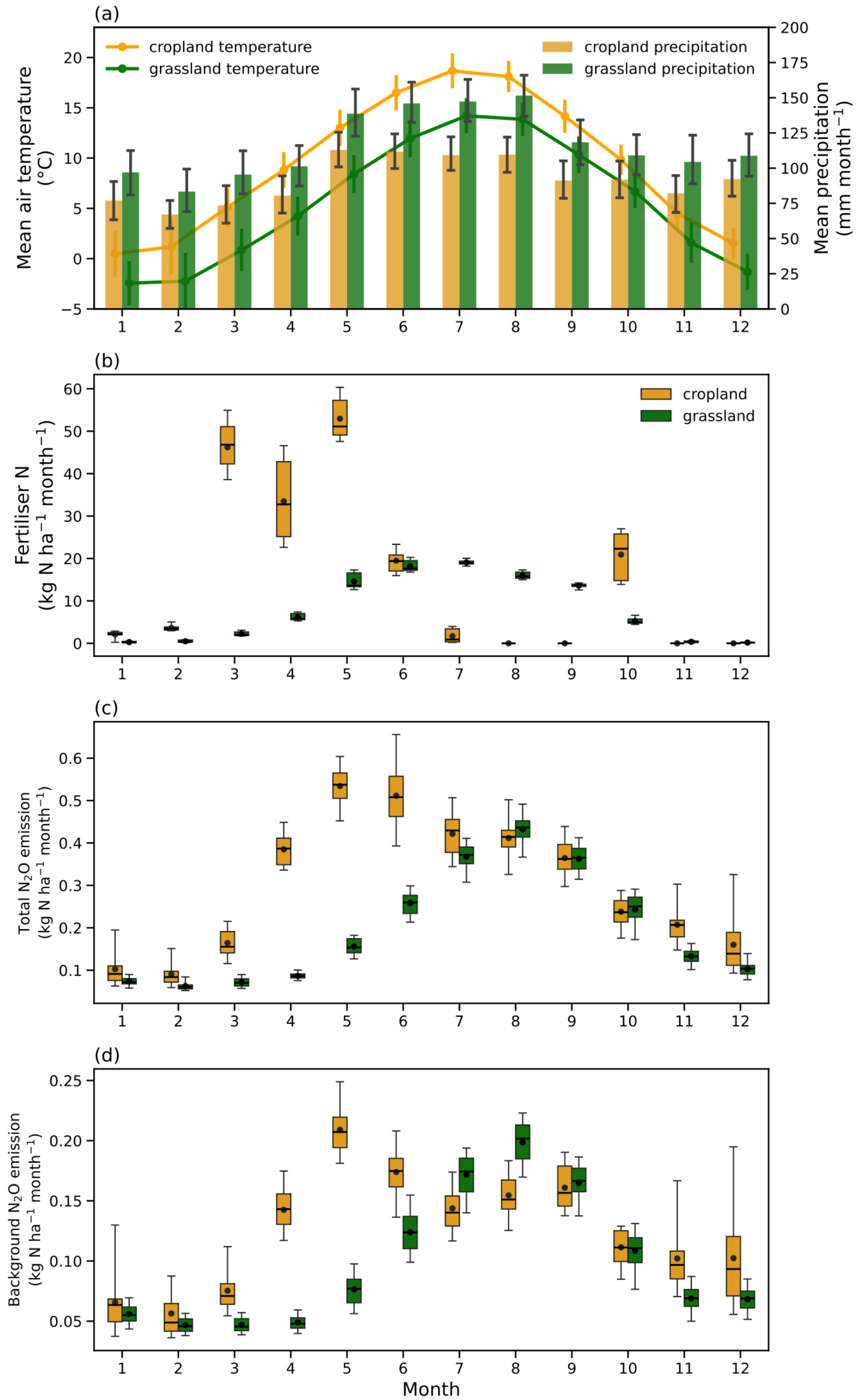

Figure 3. Monthly (a) climatic conditions, (b) fertilisation intensity, (c) modelled total N_2O emissions and (d) modelled background N_2O emissions for Swiss croplands and grasslands (including managed permanent grasslands and summer pastures). The curves and bars in panel (a) represent monthly average temperature (°C) and monthly total precipitation (mm month^{-1}). The boxplots

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show the mean (dots), median (horizontal lines), 25th to 75th percentile (boxes) and 5th to 95th percentile (whiskers) of the values from 1981 to 2020.

3.3 Factors affecting N_2O emissions from agricultural land

Carrying out correlation analyses on 40-year average values of all simulated grids, it was found that emissions (and EFs) from agricultural soils across Switzerland were positively correlated with soil clay content (Pearson's r=0.47 for croplands and 0.62 for grassland), pH (r=0.38 and 0.61, respectively) and MAT (r=0.11 and 0.58, respectively), but showed negative correlations with NUE (r= –0.54 and –0.63, respectively), MAP (r= –0.16 and –0.37, respectively) and SOM (r= –0.14 and –0.26, respectively; Figs. 4a and 4d). Increased emissions and EFs were also associated with higher soil BD in grasslands.

The PCA results corroborated the correlation analysis. N_2O fluxes and EFs clustered tightly along PC1 (Figs. 4b, 4e), indicating that they were governed by the same factors, i.e., soil characteristics (clay content and pH) and climatic conditions (MAT). High emissions were linked to high-clay soils, whereas low emissions were associated with high NUE. We found that emissions increased as SOM decreased and as soil pH increased, especially in grasslands (Fig. 4e).

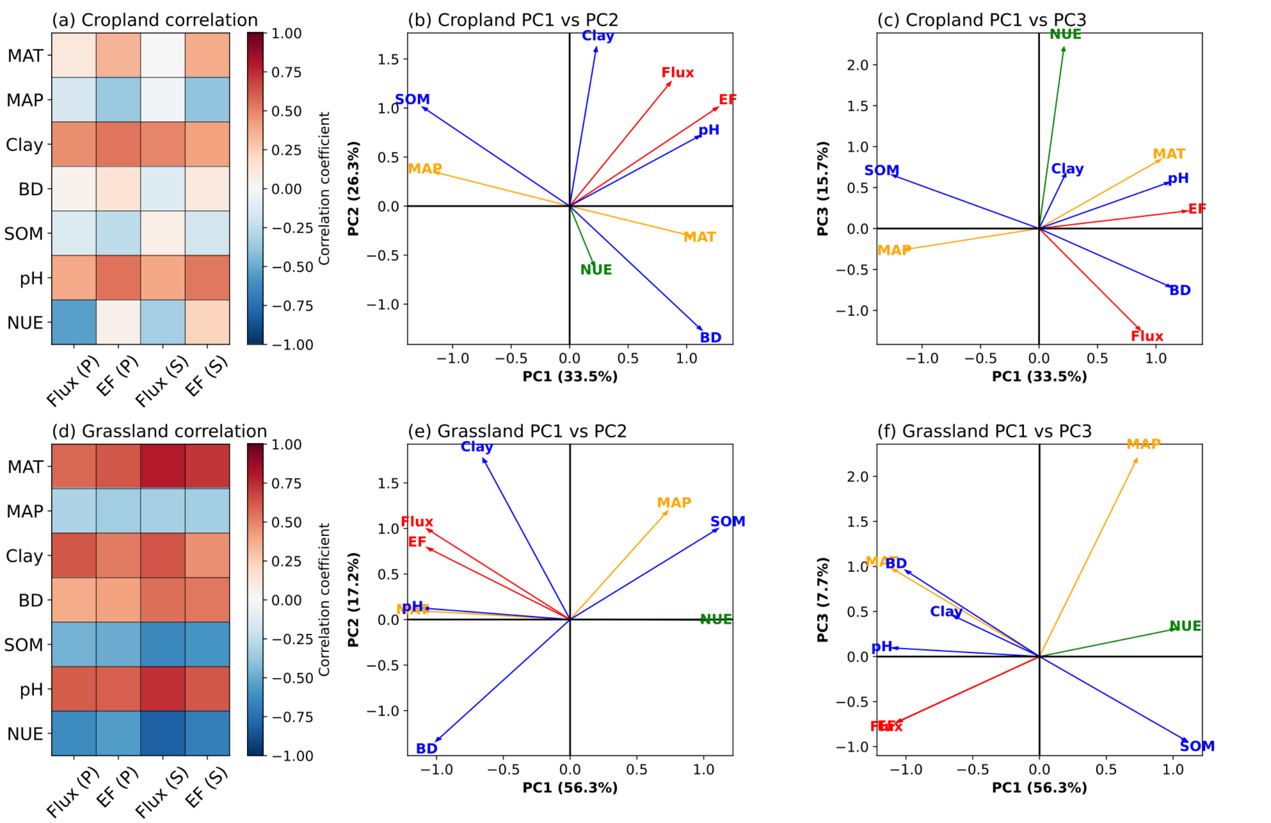

Figure 4. Effect of environmental variables (mean annual temperature–MAT, mean annual precipitation–MAP), soil properties (clay content, bulk density, soil organic matter, pH) and plant growth (N use efficiency–NUE) on modelled N_2O emissions and emission factors of Swiss cropland (a-c) and grassland (d-e). (a, d) Linear correlation matrix between analysed variables with

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modelled N_2O flux and EFs. Colours represent Pearson (P) and Spearman (S) correlation coefficients. (b, e) PCA loading plot of all variables on PC1 (cropland: 33.5%; grassland: 56.3%) and PC2 (cropland: 26.3%; grassland: 17.2%). (c, f) PCA loading plot of all variables on PC1 and PC3 (cropland: 15.7%; grassland: 7.7%). Colours of PCA loading plots indicate variable groups: red (N_2O flux and EF), orange (climate variables), blue (soil physicochemical properties) and green (plant growth).

In general, the results of the model sensitivity tests were consistent with the correlation analysis (Table 2). Air temperature, soil texture and pH had more significant and positive impacts on modelled N_2O emissions and EFs than precipitation and SOM which showed negative effects; higher simulated emissions and EFs tended to occur in hotter environments, more alkaline soils and soils with higher clay content. In contrast, wetter and more SOM-rich soils suppressed simulated N_2O emissions, although these effects were found to be limited for Swiss croplands.

Table 2. Results of sensitivity tests of environmental variables and soil properties for their effects on N_2O emission and EF in the model. Changes in total N_2O emission and EF were calculated using the national annual total values averaged over the simulated period (1981–2020), with absolute values of the baseline simulations shown in Table S3. *These changes are relative values.

Variable	Value change	ΔTotal N_2O emission %		ΔN_2O EF %	
		croplands	grasslands	croplands	grasslands
Air temperature	+2 ºC	+3.5	+10.5	+6.0	+21.1
	–2 ºC	–6.1	–10.9	–10.4	–21.8
Precipitation	+20%*	–0.7	–2.6	–1.2	–5.2
	–20%*	< +0.1	+1.8	< +0.1	+3.7
Soil clay	+20%*	+4.1	+24.9	+7.0	+49.9
	–20%*	–2.2	–14.6	–3.7	–29.2
SOM	+10%*	–0.4	–3.0	–0.7	–6.0
	–10%*	+0.5	+3.9	+0.9	+7.8
Soil pH	+0.5	+1.3	+5.8	+2.2	+11.7
	–0.5	–2.6	–10.0	–4.5	–20.1

3.4 N_2O emission changes driven by fertilisation and climate

Over the past four decades, decreased fertiliser N inputs reduced N_2O emissions, whereas emissions increased in a warmer and slightly drier climate (Fig. 5a, b). According to our model simulations (i.e., baseline simulations and scenario simulations with time-varying climate but fixed fertiliser inputs at the 1980s level, i.e., fert1980; Table 1), emissions between 2011and 2020 would have declined by 15.2% in croplands and 12.0% in grasslands because of a substantial reduction in fertiliser use, which occurred mainly in the Swiss Plateau, with nationwide decreases in emissions ranging

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between 12–20% (Fig. 5c, d). In SPA, this effect was limited because most N inputs came from grazing, which only changed to a limited extent.

In contrast, climate change significantly increased N_2O emissions, especially for grasslands. Between 1981 and 2020, the annual mean temperature across Switzerland increased by about 1.6 ºC while annual precipitation slightly decreased (Fig. S5 in Supplementary Materials) (MeteoSwiss and ETH Zurich, 2025). Based on the difference between the baseline simulations and the scenario simulations with time-varying fertiliser but fixed climate representative for the 1980s (clim1980; Table 1), modelled decadal mean N_2O emissions increased by 5.7% in croplands and 13.6% in grasslands between 2011 and 2020 due to the climatic effect (difference between "baseline" and "clim1980" simulations), with spatial increases being larger in grassland (Fig. 5f).

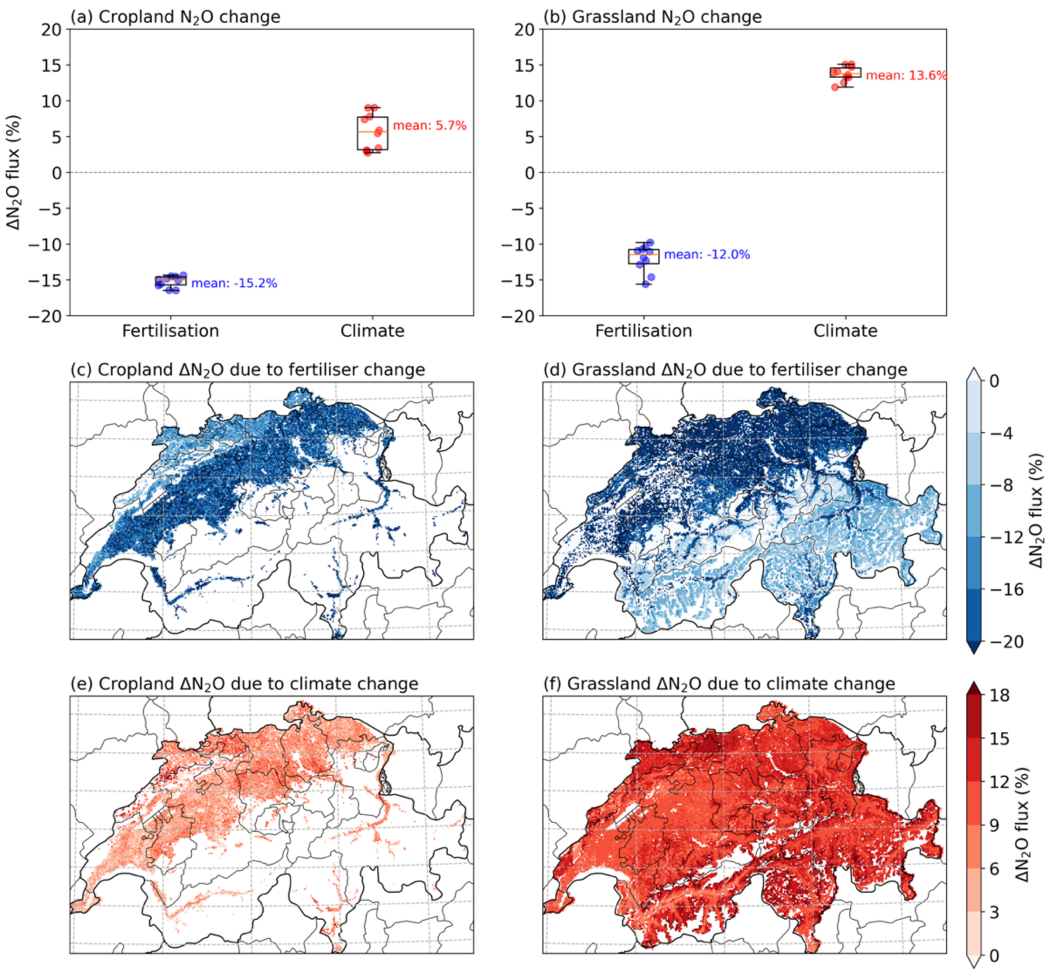

Figure 5. Impact of changing fertiliser use and climate change on modelled N_2O emissions from agricultural soils in Switzerland in the 2010s (average for 2011–2020). National average change in (a) croplands and (b) grasslands for 2011–2020. Spatial analysis for (c, e) croplands and (d, f) grasslands. Values that show changes in N_2O emissions due to fertiliser use changes are calculated from

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the difference between the "baseline" and "fert1980" simulations (time-varying climate and fixed fertiliser inputs at the 1980s level). Values that show changes in N_2O emissions due to climate change are calculated from the difference between the "baseline" and "clim1980" simulations (time-varying fertiliser inputs but fixed climate representative (temperature and precipitation) for the 1980s).

4 Discussion

In this study, we applied the biogeochemical model DayCent to present a process-based estimate of N_2O emissions from agricultural soils across Switzerland over the past four decades. We observe, as expected, that modelled agricultural N_2O emissions are highly dynamic, exhibiting strong spatial-temporal variations driven by interactions among environmental factors, soil conditions and local management practices. This variability is also reflected in the simulated EFs, highlighting that N_2O emission cannot be adequately represented by a single constant EF across diverse environmental conditions for different agricultural systems. Furthermore, our scenario analyses disentangled the relative contributions of climate variability and agricultural management to long-term changes in N_2O emissions. Before discussing these findings in detail, we first evaluate uncertainty and limitations of the modelling framework to provide context for interpreting the results.

4.1 Modelling uncertainty and limitations

For both agricultural systems, total N_2O emissions were predominantly produced through nitrification based on our simulations using DayCent, which accounted for 93% of cropland emissions and 66% grassland emissions (data not shown), whereas measurement studies using isotope techniques demonstrated that denitrification is the more important process (Ibraim et al., 2020; Rainford et al., 2026; Turco et al., 2026; Wolf et al., 2015). This discrepancy indicates that the model likely overestimates nitrification-driven N_2O emissions, which has also been reported in previous research (Fuchs et al., 2019; Zimmermann et al., 2018). Moreover, DayCent does not include a sophisticated module for ammonia volatilisation, resulting in higher prediction of soil ammonium pools and thus greater production of nitrate through nitrification. Additionally, the pedotransfer functions we used may not adequately represent soil hydraulic properties. As soil moisture is one of the dominant controls on nitrification and denitrification, biases in simulated water dynamics may lead to overestimation of N_2O emissions from nitrification when soils drain too fast. In contrast, we found that at the national scale, elevated N_2O emissions were associated with clay-rich soils (Fig. 4 and Table 2), i.e., high emissions in the Jura regions with high clay content (Fig. S8a in Supplementary Materials). This can be attributed to the high water retention of clays, which creates anaerobic conditions needed for denitrification (Charles et al., 2017; Lesschen et al., 2011; Zhang et al., 2024). Although the modelled N_2O production pathways are uncertain, the cumulative N_2O emissions are considered robust as the DayCent model has been extensively calibrated to reproduce the total amount of N_2O (e.g., Dos Reis Martins et al. (2022): $r^2 = 0.63$ between observed and modelled cropland N_2O emissions across four Swiss and two French sites; and Dos Reis Martins et al. (2024): $r^2 = 0.65$ between observed and modelled grassland N_2O emissions across two Swiss and two German sites). Nevertheless, in future studies, long-term measurements of N_2O fluxes with isotope analyses differentiating N_2O production pathways are useful for constraining model parameters and improving the representation of relevant processes.

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For example, Rainford et al. (2026) showed that integrating isotope measurements into the model calibration substantially improved estimates of N_2O production pathways, i.e., nitrification vs. denitrification. These observations, together with improved soil, crop and management datasets, will further enhance the reliability of such assessments in future research.

Nevertheless, despite the above-outlined limitations, the use of process-based models provides advantages compared with simpler EF approaches by explicitly representing the interactions between climate, soil and management for national scale N_2O emission estimates.

4.2 N_2O emissions from Swiss agriculture

Using DayCent biogeochemical modelling, we estimated that agricultural N_2O emissions in Switzerland have decreased by about 5%, from 4.0 kt N yr^{-1} in the 1980s (average for 1981–1990) to 3.8 kt N yr^{-1} in the 2010s (average for 2011–2020), with croplands contributing about 40% and grasslands about 60% to total emissions, respectively. Between 1990 and 2020, the National Greenhouse Gas Inventory (NIR) reported a ~18% reduction in N_2O emissions from agricultural soils (FOEN, 2026), while DayCent simulations suggested a ~9% decreasing of N_2O emissions for this period; thus a same order of mangitude change. However, our N_2O emission estimates are ~40% higher than the NIR (2.7 kt N yr^{-1} averaged between 1990 and 2020; the sources of NIR N_2O included for comparison are presented in Table S5; FOEN, 2026), and modelled EFs are 10–30% larger than the default IPCC EF. These differences are presumably associated with the larger estimated background N_2O fluxes and the climate impacts reflected in our simulations. Since the NIR uses a fixed EF of 1% for most of agricultural activities (i.e., various N inputs to fields such as fertiliser application and livestock grazing), the ~18% reduction in N_2O emissions reported in NIR largely reflected the corresponding changes in N inputs.

Our modelling results suggested that the national total N_2O emissions from croplands declined by 18% between 1981–1990 and the 2011–2020, whereas grassland emissions increased by 2%. These simulated long-term changes can be attributed to three different factors: land use change, fertiliser use reduction and climate change. Between the 1980s and the 2010s, croplands shrank by 12%, reflecting gradual urbanisation, while permanent grassland areas remained roughly stable (–1%; BFS, 2024). Fertiliser application decreased by ~25% over the studied period (Figs. S2c). These reductions resulted from a series of agri-environmental policy reforms in the 1990s, including a direct payment scheme and Proof of Ecological Performance (PEP) (Decrem et al., 2007; Herzog et al., 2008; Spiess, 2011). The implementation of these schemes, in line with decreased livestock number (due to improved productivity, e.g., milk yield), led to a decline in synthetic fertiliser consumption and less manure application (Fig. S6). Note that reducing fertiliser use alone would have led to a nonlinear reduction in N_2O emissions in croplands (–15.2%) and in grasslands (–12.0%) based on our model scenarios between 2011 and 2020. Two further aspects, however, had additional and profound impacts on the N_2O flux. On the one hand, climate change offset reductions driven by decreased fertiliser rates through warming-induced N_2O emissions, especially in grasslands, based on our model scenarios (Fig. 5). More specifically, continuous warming and slightly drier conditions over the past 40 years in the country (Fig. S5) were recorded, discussed in more detail in the next section. On the other hand, simulated background N_2O fluxes (per unit area) showed contrasting trends between croplands and grasslands over the

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studied period (Fig. 1b). These differences were closely linked to changes in SOM mineralisation, which decreased in croplands while increased in grasslands, and showed a strong positive correlation with background N_2O fluxes for both agroecosystem types (Fig. S7a). The decline in cropland SOM has been reported by both field measurements and nationwide monitoring. For example, Emmel et al. (2018) found that a Swiss cropland field lost more than 16 t C ha^{-1} between 2004 and 2016. At the national scale, Wollmann et al. (2025) reported that mean topsoil (0-20 cm) total organic carbon (TOC) in Swiss croplands declined from 54 to 46 t TOC ha^{-1} between 1985–1989 and 2015–2019. In contrast, topsoil TOC in grassland is 1.4–1.6 times higher than in croplands and remained stable at approximately 76 t TOC ha^{-1} (Wollmann et al., 2025). In addition to changes in SOM mineralisation, BNF became an increasingly important N input in unfertilised grasslands, potentially contributing to an increase in modelled background emissions under warming conditions.

4.3 Factors affecting modelled N_2O emissions

We found that plant performance played a crucial role in regulating N_2O emissions, with simulated N_2O emissions and EFs exhibiting strong negative correlations with NUE (Fig. 4). This finding is consistent with existing studies. Using gross primary productivity (Turco et al., 2026) and vegetation height (Maier et al., 2022; Feigenwinter et al., 2023a) as proxies for plant N uptake, all studies identified vegetation performance as an important driver of cropland and grassland N_2O emissions, with enhanced plant growth suppressing N_2O losses. From a N budget perspective, reduced plant N uptake (e.g., due to environmental stress, improper management, and mismatch between plant N demand and supply) leads to an accumulation of soil mineral N (e.g., ammonium and nitrate); this excess mineral N becomes available for microbial processes and can be readily lost as N_2O under favourable environmental conditions (Omonode et al., 2017). Conversely, healthy and actively growing plants take up more mineral N and outcompete soil microorganisms for available mineral N, thereby reducing microbial pathways that produce N_2O (Maier et al., 2022; Feigenwinter et al., 2023a; Turco et al., 2026).

Our results also indicated that soil pH is a critical factor governing simulated N_2O fluxes and EFs. For Switzerland, modelled N_2O was generally higher in more alkaline soils in both croplands and grasslands. Nitrification in the model is enhanced at high soil pH, which leads to nitrite accumulation and oxygen depletion, stimulating N_2O production (Li et al., 2023). Since nitrification was likely overestimated in our simulations, the soil pH effects may not be properly represented. Nevertheless, high pH values have also been shown to increase SOM pools through Ca-mediated soil stabilisation (Rowley et al., 2018), which in turn could provide substrates for nitrification and N_2O production. On the other hand, previous studies suggested that N_2O production is often suppressed when soil pH is high (Wang et al., 2018). For example, liming as an effective agronomical practice to alleviate soil acidification has been shown to reduce N_2O emissions (Hénault et al., 2019; Shaaban et al., 2020). Microbial studies demonstrated that the enzyme N_2O reductase is inhibited at low pH, leading to incomplete denitrification and higher N_2O emissions (Bergaust et al., 2010; Krause et al., 2017; Liu et al., 2014). Soil pH also influences the abundance and activities of microbial communities, making the relationship between soil pH and N_2O flux complex and usually nonlinear. A recent global synthesis showed that N_2O emissions peak at intermediate pH levels (5.6–6.3) (Qiu et al., 2024). Under suboptimal conditions (very acidic or alkaline soils), N_2O emissions tend to decrease

(Cheng et al., 2021; Qiu et al., 2024). Thus, currently, our understanding and parametrisation of process-models for N_2O production are still limited.

Other soil properties, such as SOM, showed weak negative correlations with simulated total N_2O emissions and EFs across Switzerland (r= –0.14 and –0.48 in cropland and grassland, respectively). In DayCent, SOM is partitioned into three pools: active, slow and passive. Both labile and stable SOM fractions can influence N_2O fluxes (De Figueiredo et al., 2018). Higher labile C can stimulate N_2O production by providing more substrates (Del Grosso et al., 2000; Guenet et al., 2021), whereas SOM accumulated in more stable fractions is physically protected and therefore less accessible to microbes in the short term, reducing N_2O production (Sato et al., 2019). In the model, SOM can influence N_2O emissions through two distinct mechanisms: first, greater labile C enhanced mineralisation and increased mineral N supply, stimulating N_2O production from nitrification (Table S4 and Fig. S7); and second, higher labile C can modify soil physical and biochemical conditions, promoting more complete reduction of N_2O to N_2 during denitrification (as shown in Table S4) and thereby lowering total emissions (Lazcano et al., 2021). Based on sensitivity tests in croplands, where more than 90% of simulated N_2O emissions were produced from nitrification, these opposing effects largely offset each other, leading to only minor changes in total N_2O emissions. In contrast, in grasslands, where more than 30% of emissions originated from denitrification, the enhanced reduction of N_2O to N_2 dominated, resulting in lower simulated total N_2O emissions with increasing SOM.

4.4 N_2O emissions under a changing climate

Environmental factors, particularly temperature and moisture, strongly influence N_2O emissions (Butterbach-Bahl et al., 2013; Decock et al., 2015; Flechard et al., 2007; Skiba and Smith, 2000). Global warming is expected to increase N_2O emissions by accelerating microbial activities that enhance nitrification and denitrification. Our sensitivity tests showed that temperature was a dominant environmental driver of N_2O production (Table 2). Our results indicate that N_2O emissions would have increased by 5.7% in croplands and 13.6% in grasslands due to warming and changes in precipitation patterns between 2011 and 2020 (Fig. 5a, b). These increases in N_2O emissions, in turn, intensify warming and create a positive feedback loop to climate change (Harris et al., 2022; Li et al., 2020; Smith, 1997; Xu-Ri et al., 2012), with significant implications for future climate mitigation and agricultural management. Given the high global warming potential of N_2O, a more sustainable development scenario would reinforce emission mitigation, whereas a poor scenario could lead to amplified warming. However, agricultural N_r species may have a net cooling effect on the climate globally (excluding the effect of CO_2 related to fertiliser manufacturing and transport; Gong et al., 2024), because the warming related to agricultural N_2O emissions might be potentially outweighed by N_r-enhanced terrestrial carbon sequestration (i.e., N deposition to forests) and aerosol cooling related to agricultural NH_3 (Gong et al., 2024). Therefore, management strategies that aim to reduce N loss should address multiple N_r gases (i.e., long-lived vs. short-lived climate forcers) and eventual changes in soil C stocks simultaneously to avoid trade-offs that could result in a net climate penalty.

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Sensitivity tests showed that changes in precipitation had a less significant influence on N_2O than temperature (Table 2). This is partly because we only modified the absolute amount of precipitation while precipitation patterns were unchanged in the sensitivity tests. As a result, there was a limited reduction in N_2O flux under wetter conditions (or increased flux under drier conditions) at the national scale (Table 2, and Fig. 4), presumably because of enhanced reduction to N_2 in denitrification, as reflected by higher N_2:dnit-N_2O ratio and increased total N_2 emissions (Table S4). Admittedly, changes in precipitation patterns or variability can equally important impacts on N_2O emissions as the amount of rainfall. Furthermore, the interactions between temperature and soil moisture further complicate N_2O dynamics. Thus, as extremes (heatwaves, droughts or compound events) are expected to become more frequent under climate change (Calvin et al., 2023), N_2O emissions are likely to experience substantial shifts.

Our simulations suggest that N_2O fluxes from grasslands (both per unit and national total) were more strongly affected by climate warming than those from croplands (Fig. 5). Modelled EFs increased in both systems over the past four decades, indicating higher fertiliser-induced N_2O emissions (Fig. 2d). In grasslands, warming stimulated SOM mineralisation and elevated background N_2O emissions, resulting in substantial increases in total N_2O emissions. In contrast, croplands likely experienced declines in SOM pools, reflected by lower simulated gross mineralisation rate and negative simulated soil N balances, as reported by Jiang et al. (2026). Consequently, background N_2O fluxes decreased, partially offsetting increases in fertiliser-induced emissions. As a result, total N_2O emissions from croplands showed smaller overall responses to warming than those from grasslands.

4.5 Mitigation of N_2O emissions

According to our simulations, reducing fertiliser rates is an effective measure for N_2O mitigation, providing evidence that supports the implementation of nationwide agri-environmental policies. Field experiments have demonstrated reduced N_2O emissions from unfertilised grassland with higher fraction of cultivated legumes compared to slurry-fertilised grassland (Feigenwinter et al., 2023a; Fuchs et al., 2018), with no substantial decrease in yield but potentially improved yield quality. However, this long-term field experiment also demonstrated a relevant, often neglected trade-off: reduced N_2O emissions came at the cost of a substantial loss in soil C sequestration (Feigenwinter et al., 2023b).

As highlighted by both, this modelling study and recent field-based investigations, improving plant performance represents a promising strategy for reducing N_2O losses from agricultural soils (Maier et al., 2022; Omonode et al., 2017; Turco et al., 2026; Feigenwinter et al. 2023a). A key objective is to improve the synchrony between fertiliser N supply and plant N demand through optimisation of the type, amount, timing and place of fertiliser application, known as the "4R" principle (Johnston and Bruulsema, 2014; Snyder, 2017). Equally important is the promotion of rapid and sustained plant growth (Turco et al., 2026), which enhances plant N uptake and shortens bare soil period when a substantial portion of N_2O emissions can occur (Maier et al., 2025; Verhoeven et al., 2017).

Thus, although it has been extensively researched, mitigation of agricultural N_2O emissions still remains challenging (Cui et al., 2024; Decock et al., 2015; Nyameasem et al., 2026). Three main aspects need to be addressed. First,

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as shown and discussed in this study, climate change might increase N_2O emissions and render mitigation measures less effective. We showed modelling results that benefits of reducing fertiliser use can be partly or entirely offset by the warming effect, underscoring that future mitigation strategies need to be more ambitious within the context of climate change. Existing experimental and modelling studies demonstrated inconsistent effectiveness of mitigation measures at different places. This implies that generalized scenarios for N_2O reduction might be insufficient given the varying pedoclimatic conditions, management practices, and highly dynamic nature of N_2O fluxes. Therefore, site-specific mitigation strategies developed from monitoring, process-based modelling and field experiments should be considered. Third, N losses through N_2O emissions represent only a small but climate-relevant fraction of total N inputs to the agricultural system, while other N losses (e.g., leaching and volatilization) are usually more substantial, albeit not directly climate-relevant. A crucial question is how different forms of N losses can be tackled simultaneously without comprising yield or increasing other C or N losses. Successful strategies should minimise potential trade-offs (i.e., pollution swapping, yield decline, loss of C sequestration) and pursue synergies across productivity, environmental quality, soil health and climate benefits. This requires a better understanding of the coupling between the climate system and the N cycle, as well as an integrated approach to N management in the future.

5 Conclusion

Process-based models provide a useful alternative to EF-based approaches by explicitly representing the effects of environmental factors and management practices on N_2O emissions. In this study, we conducted high-resolution simulations using the biogeochemical model DayCent to quantify N_2O emissions from Swiss croplands and grasslands over the past 40 years. We estimated that total N_2O emissions from Swiss agricultural land decreased by 5% between 1981–1990 and 2011–2020, a smaller reduction than suggested by NIR. Our modelling results indicate that reductions in N fertiliser use driven by nationwide policy intervention have effectively mitigated N_2O emissions, consistent with inventory trends. However, this mitigation was partly offset by climate change, specifically warming, which increased fertiliser-induced N_2O emissions, as reflected by increased modelling-derived EFs in both croplands and grasslands. These findings highlight a trade-off between mitigation efforts and environmental-driven feedback. While management changes have reduced emissions, ongoing warming can partly cancel out these benefits, particularly in countries experiencing intense warming like Switzerland. Our results therefore suggest long-term integrated measures such as optimising fertiliser application and improving plant performance are needed to effectively mitigate N_2O emissions from agricultural soils in a changing climate.

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Code and data availability

Modelling results of the nitrogen budgets presented in this study are in netCDF format and are deposited at https://doi.org/10.3929/ethz-c-000802619. Code of the DayCent model is publicly available at https://www.soilcarbonsolutionscenter.com/daycent. For specific versions, please contact the developers directly.

Author contributions

J.J. and J.S. conceptualised the study. J.J. designed and performed the modelling simulations, and analysed the data. A.S. processed and prepared climate input. M.N. and M.L. assisted with software and modelling. I.F. and N.B. provided eddy-covariance flux measurements and site management data. L.H.E.W. and J.S. supervised the project and acquired funding. J.J. wrote the original draft of paper. All authors contributed to interpretation of results, intensive discussions and critical revision of the paper.

Competing interests

The authors declare no competing interests.

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