Supplementary Materials for "Warming-induced agricultural nitrous oxide emissions can offset mitigation benefits of fertiliser management"

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Table S1. Probability used for generating crop rotation for DayCent modelling (Lee et al., 2020a, 2020b). Values are probability of crops that will be planted (the 1st row) following the current crop (or crop sequence) (the 1st column). BR-sugar beet, BW-winter barley, CO-grain maize, CS-silage maize, GC-grass-clover mixture, OA-oat, PO-potato, PW-pea, RP-rapeseed, RY-rye, SB-soybean, SP-spelt, SU-sunflower, TR-triticale, WW-winter wheat. [a]Two years of grass-clover mixture in a row. [b]Three years of grass-clover mixture in a row. [c]Two years of grass-clover mixture followed by winter wheat.

	BR	BW	CO	CS	GC	OA	PO	PW	RP	RY	SB	SP	SU	TR	WW
BR	0.08	0.00	0.17	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.50
BW	0.00	0.00	0.33	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.80
CS	0.06	0.00	0.00	0.06	0.00	0.06	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.80
GC	0.00	0.00	0.00	0.00	1.00[a]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OA	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00
PO	0.00	0.30	0.08	0.08	0.00	0.00	0.08	0.15	0.07	0.00	0.00	0.00	0.00	0.01	0.23
PW	0.00	0.50	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25
RP	0.33	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34
RY	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SB	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.50
SP	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SU	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
TR	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WW	0.22	0.04	0.15	0.11	0.04	0.00	0.15	0.07	0.07	0.00	0.11	0.00	0.04	0.00	0.00
GCGC	0.00	0.00	0.00	0.50[b]	0.50[c]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GCGCGC	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table S2. N cycle parameters in DayCent used in this study. 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.

Parameter	Description	Unit	Default	Calibrated mean*	95% CI
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]

Table S3. Summary of land use change, fertiliser (synthetic and organic) N inputs (national statistics), background N_2O (modelled), total N_2O emissions (modelled), N_2O EFs (modelled) and bare soil N_2O (modelled) from cropland and grassland for the 1980s and the 2010s. *Grassland includes permanent grassland and summer pastures.

Land use	Area (kha)	Fertiliser N (kg N ha^{-1} yr^{-1})	Background N_2O (kg N ha^{-1} yr^{-1})	Total N_2O (kg N ha^{-1} yr^{-1})	EF (%)	Bare soil N_2O[a] (kg N ha^{-1} yr^{-1})
Cropland						
1980s	435	211	1.6	3.8	1.0	0.9
2010s	384	165	1.4	3.5	1.3	1.0
Grassland*						
1980s	1058	106	1.0	2.2	1.1	—
2010s	1020	90	1.3	2.4	1.3	—
Permanent grassland						
1980s	603	179	1.1	3.2	1.2	—
2010s	598	142	1.5	3.4	1.4	—
Summer pasture (SPA)						
1980s	455	10*	0.9	0.9	0.0	—
2010s	422	17*	1.0	1.0	0.0	—

Table S4. Results of sensitivity tests of precipitation and soil properties for their effects on N_2O production pathway and N_2 emissions 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	Δnit-N_2O %		ΔN_2:dnit-N_2O %		ΔN_2 %	
		croplands	grasslands	croplands	grasslands	croplands	grasslands
Precipitation	+20%*	–0.9	+0.9	+12.7	+17.6	+24.7	+12.6
	–20%*	+1.4	–0.3	–13.2	–16.3	–27.5	–14.2
Soil clay	+20%*	–3.7	–20.9	–24.9	–34.3	+12.7	+14.6
	–20%*	+1.8	+18.5	+19.2	+63.3	–8.7	–9.4
SOM	+10%*	+0.4	+3.0	+6.2	+10.2	+0.3	+0.7
	–10%*	–0.5	–3.6	–6.9	–10.5	–0.2	–0.6
Soil pH	+0.5	+0.1	+1.4	0.0	+6.9	+0.3	+9.9
	–0.5	–0.2	–2.5	0.0	–14.3	–0.5	–19.3

Table S5. Source category of N_2O emissions from agricultural soils used in the National Greenhouse Gas Inventory (NIR) for model comparison. *N_2O emissions induced from atmospheric deposition to agricultural soils were recalculated using a default EF of 1% and DayCent simulated N deposition to represent NIR values, after consulting with NIR scientists.

For comparison	**Specification in NIR**
Sources included	Inorganic N fertilisers
	Organic fertilisers
	Urine and dung deposited by grazing animals
	Crop residues
	Mineralisation/immobilisation associated with loss/gain of soil organic matter
	Atmospheric deposition*
Sources excluded	Cultivation of organic soils
	N from fertilizers and other agricultural inputs that is lost through leaching and run-off
	Other (not specified)

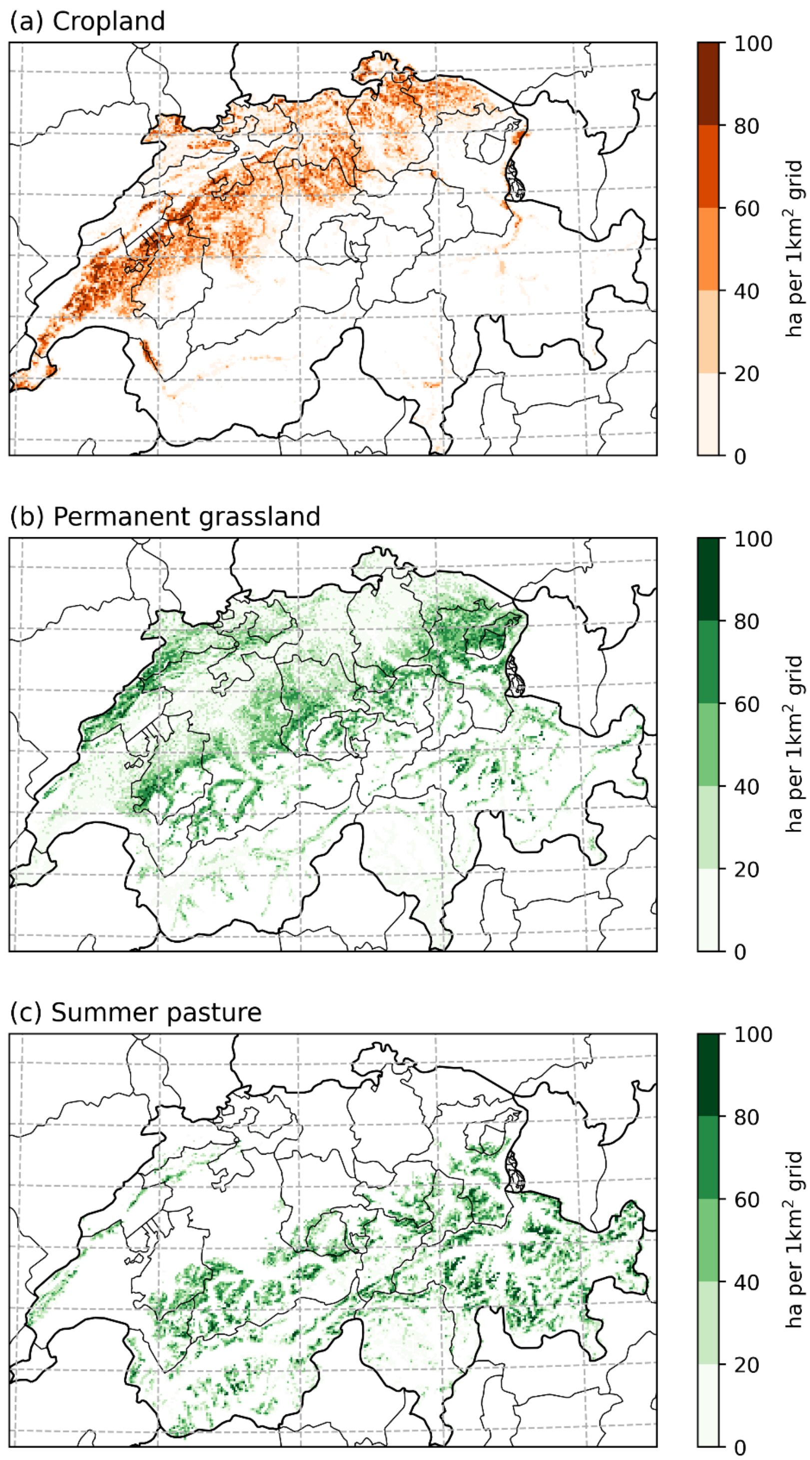

Figure S1. Geographical distribution of (a) cropland (including temporary leys in rotation, i.e. grass-clover mixture), (b) managed permanent grassland (meadow and pasture) and (c) summer pasture in Switzerland. Areas of each land use type in 1 km×1 km grids are shown in the maps. Original data were obtained from Swiss Federal Statistical Office (BFS, 2024).

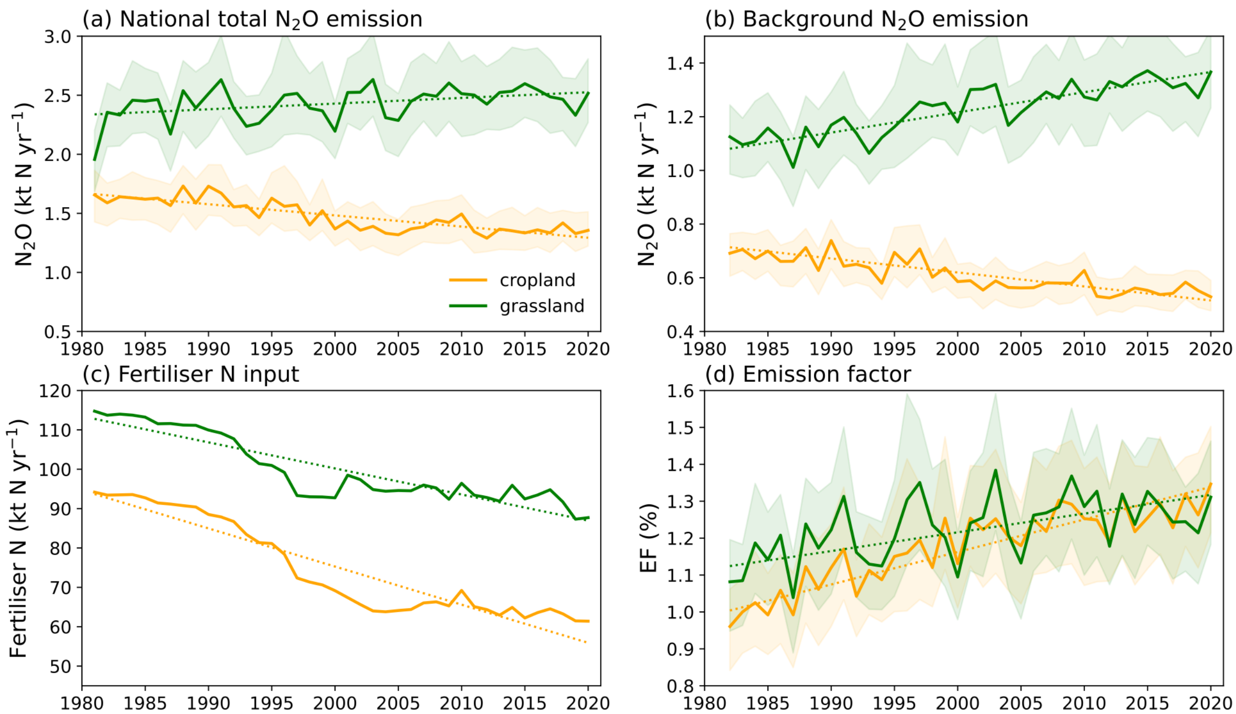

Figure S2. Timeseries results for Swiss cropland (yellow) and grassland (green) from DayCent modelling for 1981 to 2020. (a) Simulated national total N_2O emissions (kt N yr^{-1}). (b) Simulated national background N_2O flux (kg N yr^{-1}) without fertiliser inputs. (c) Fertiliser N inputs (kt N yr^{-1}) 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.

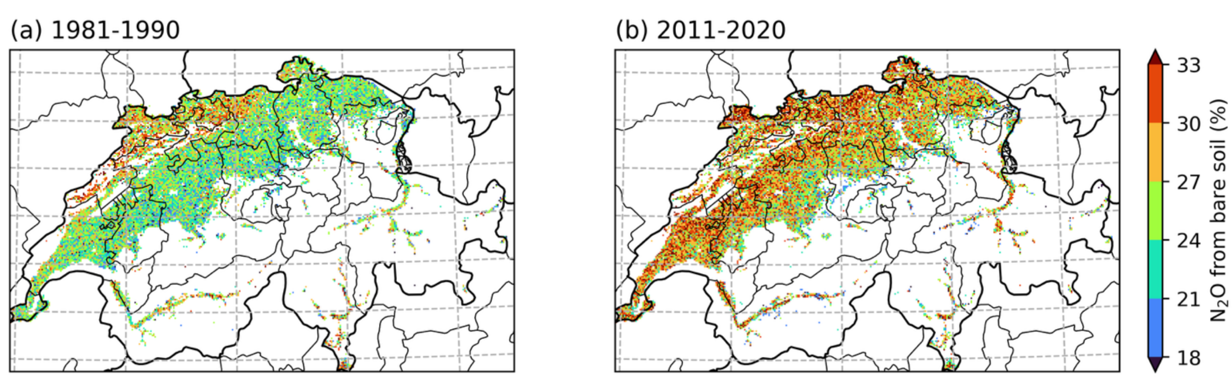

Figure S3. Percentage of (modelled) total cropland N_2O emissions that were released during bare soil period in (a) the 1980s and (b) the 2010s.

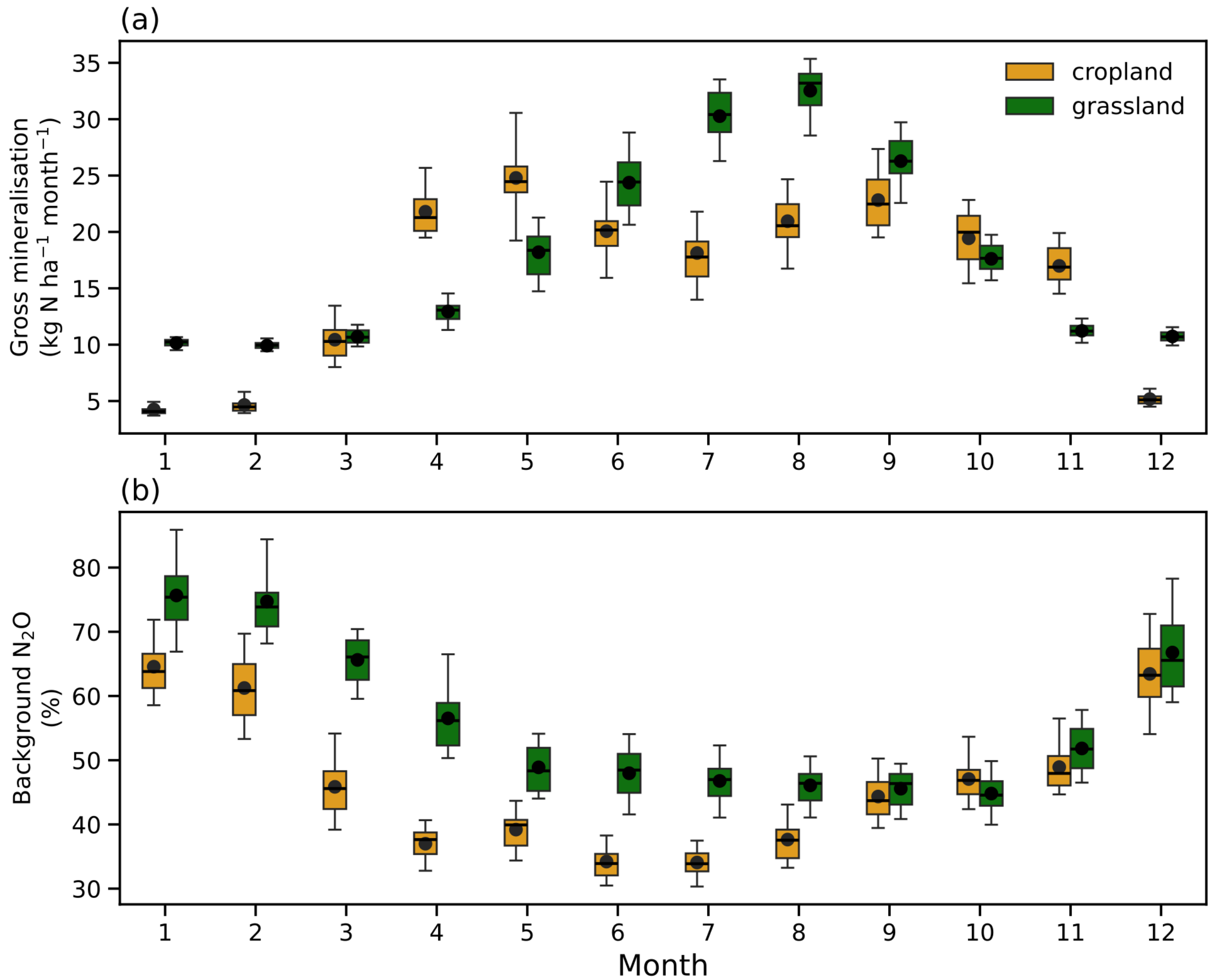

Figure S4. (a) Modelled monthly gross mineralization rate (kg N ha^{-1} month^{-1}) for Swiss croplands and grasslands (including managed permanent grasslands and summer pastures). (b) Monthly average background N_2O emissions as percentages of total N_2O emissions (100% indicates that total N_2O emissions are entirely from background N_2O emissions). The boxplots 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.

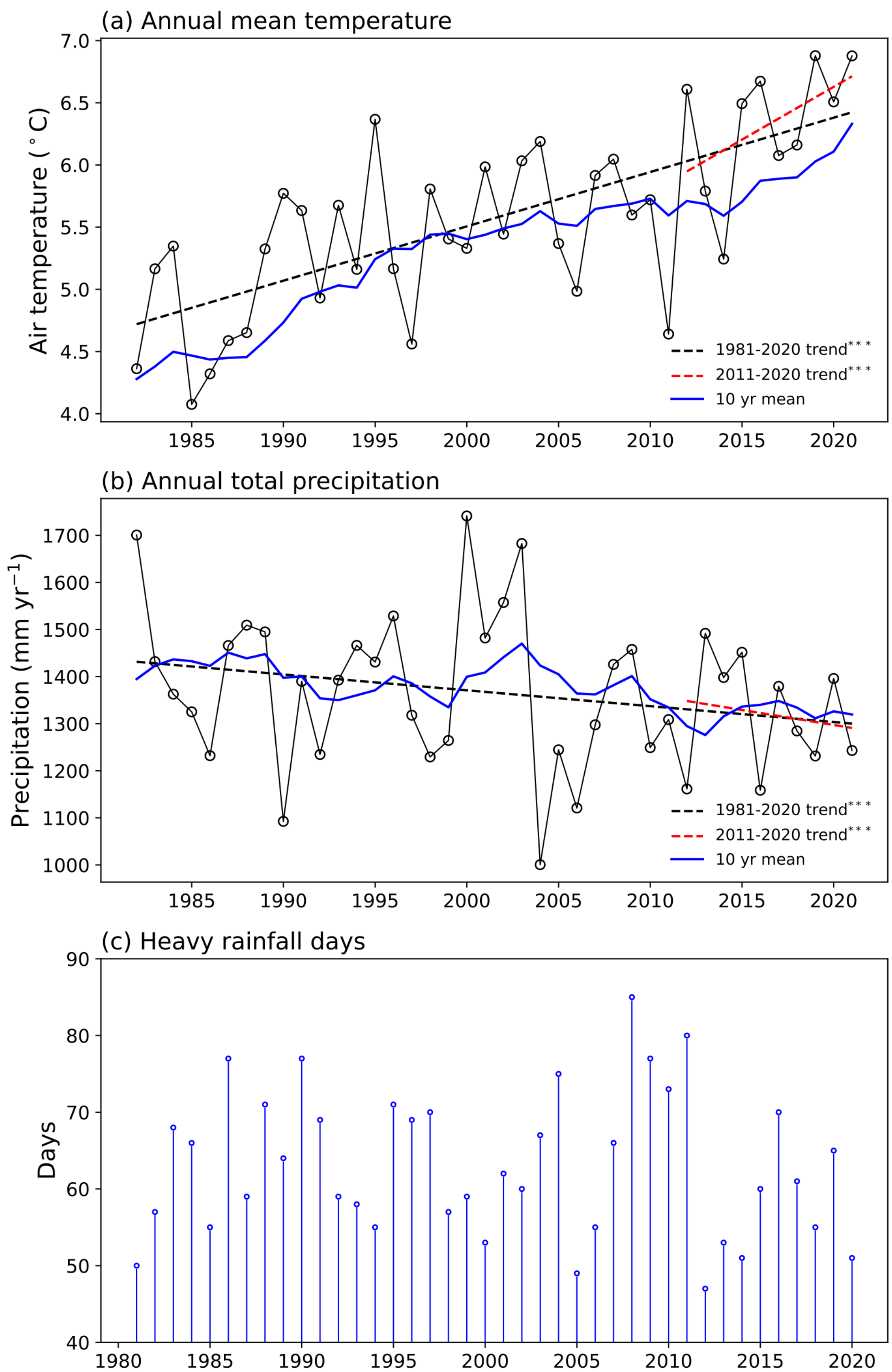

Figure S5. Observations of (a) annual mean temperature, (b) annual total precipitation, and (c) heavy rainfall (>7.5mm/d) days in Switzerland for the period 1981–2020. Dashed lines show significant trends determined by Mann-Kendall Trend test, with significance level $^{***}P$<0.001. Data are from MeteoSwiss, 2026.

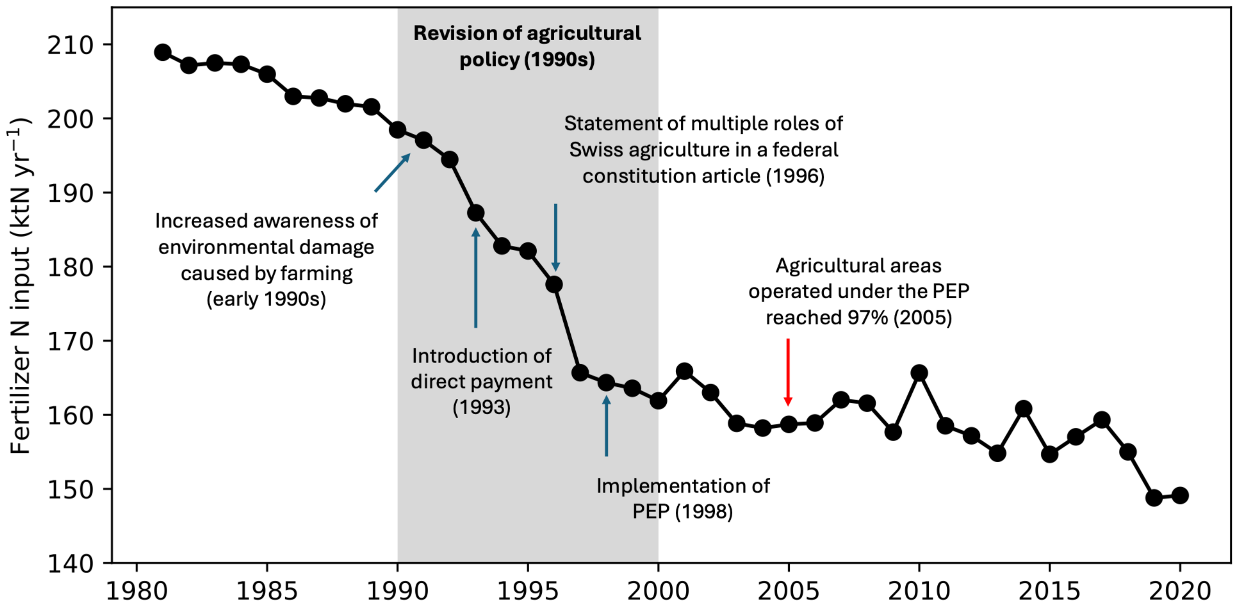

Figure S6. Nitrogen inputs from fertilizers to agricultural land in Switzerland. Fertilizers include livestock manure and synthetic fertilizers. Values from compiled datasets (see Methods). Shaded grey area represents the period in the 1990s when national policies and measures were implemented in the agricultural sector, prior to changing the Federal Constitution. Important events are shown along the timeseries of fertilizer nitrogen inputs. Values in parenthesis are corresponding years. Note that the y-axis starts from 140 kt N yr^{-1}. PEP is Proof of Ecological Performance. Figure is taken from Jiang et al. (2026).

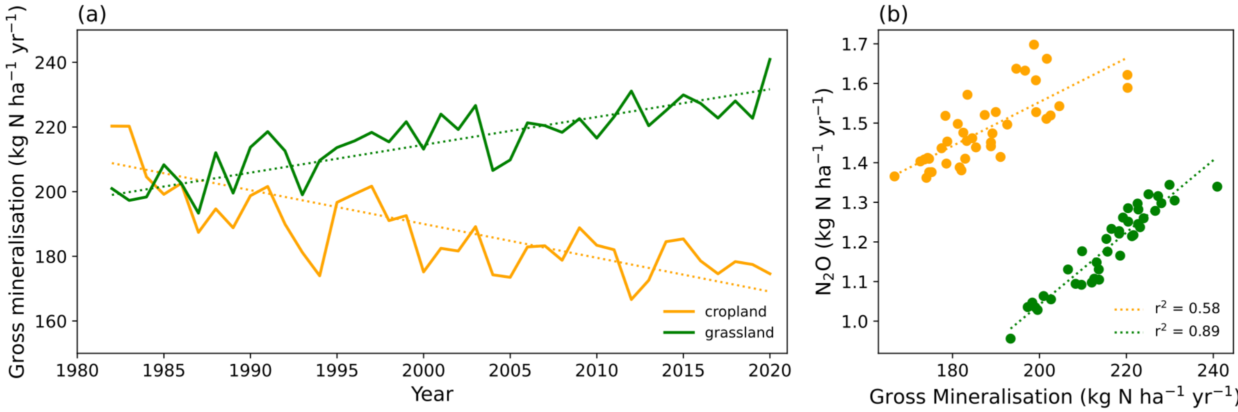

Figure S7. (a) Timeseries of simulated gross mineralisation rate (kg N ha^{-1} yr^{-1}) in Swiss cropland (yellow) and grassland (green) from DayCent modelling for 1981 to 2020. (b) Correlation between (modelled) annual gross mineralisation rate (kg N ha^{-1} yr^{-1}) and (modelled) annual background N_2O emissions (kg N ha^{-1} yr^{-1}). Dotted lines show significant trends or relationships determined by Mann-Kendall Trend test with significance level $P<0.001$.

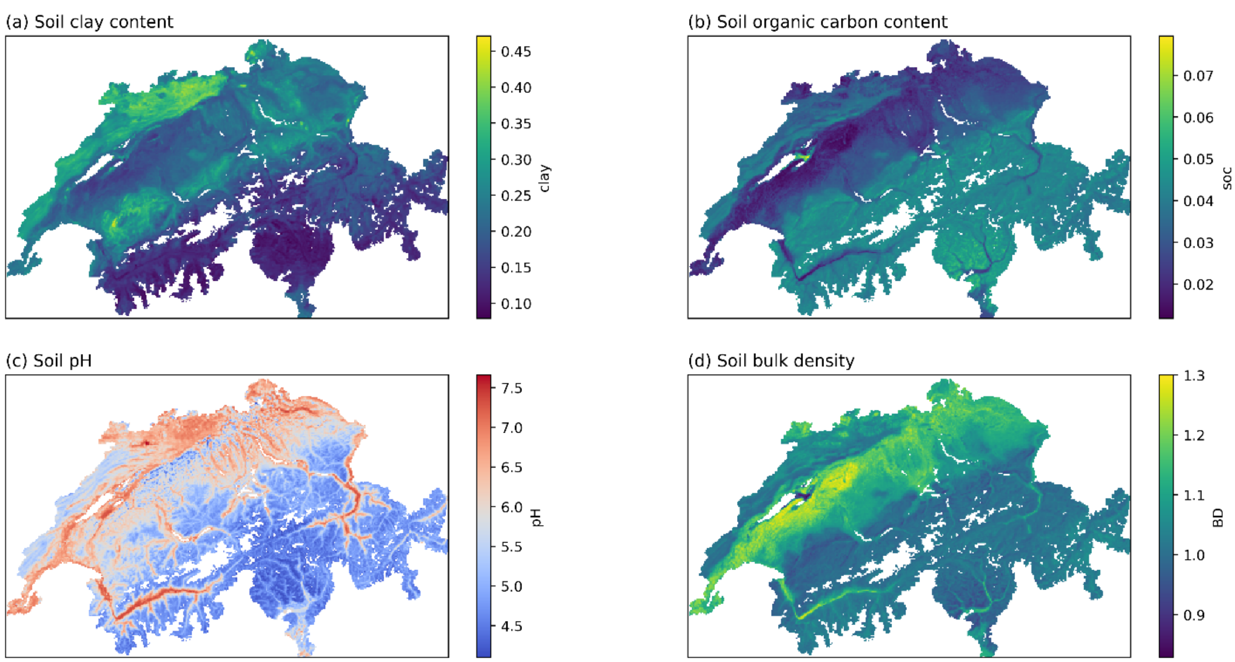

Figure S8. Properties of topsoil (0-30 cm) in Switzerland. (a) Map of soil clay content (fraction). (b) Map of soil organic carbon content (fraction). (c) Map of soil pH. (d) Map of soil bulk density (g cm^{-3}).