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Balancing nitrogen use efficiency, losses and soil nitrogen depletion to evaluate national scale agri-environmental performance over 40 years

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Supplementary Materials

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-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 roll. [b]Three years of grass-clover mixture in a roll. [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. 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]

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

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

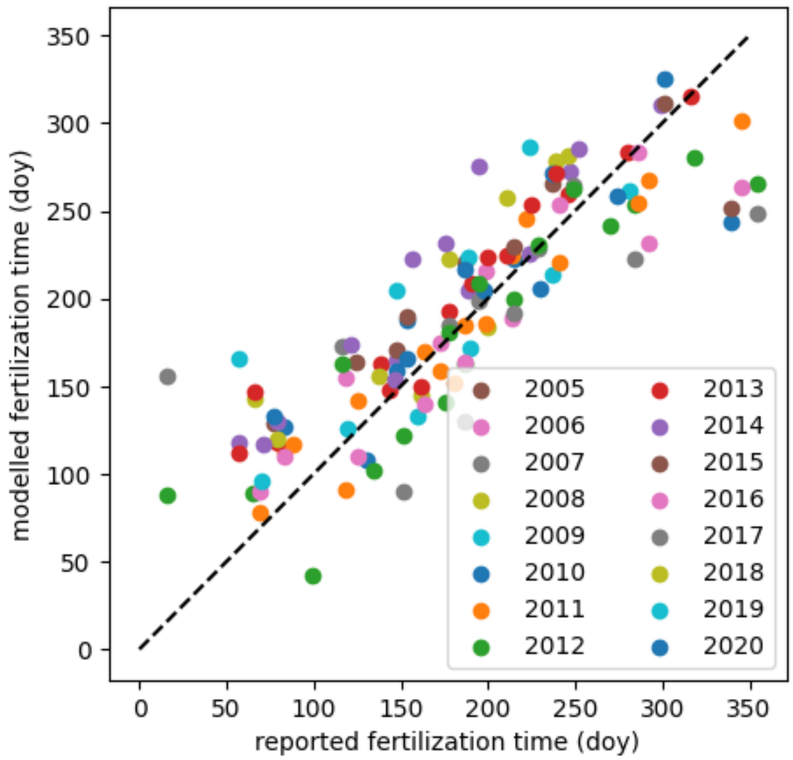

Figure S1. Reported and modelled timing (day of the year) of fertilizer application of an intensively-managed grassland in Chamau, Switzerland between 2005 and 2020 (Feigenwinter et al., 2023a, 2023b).

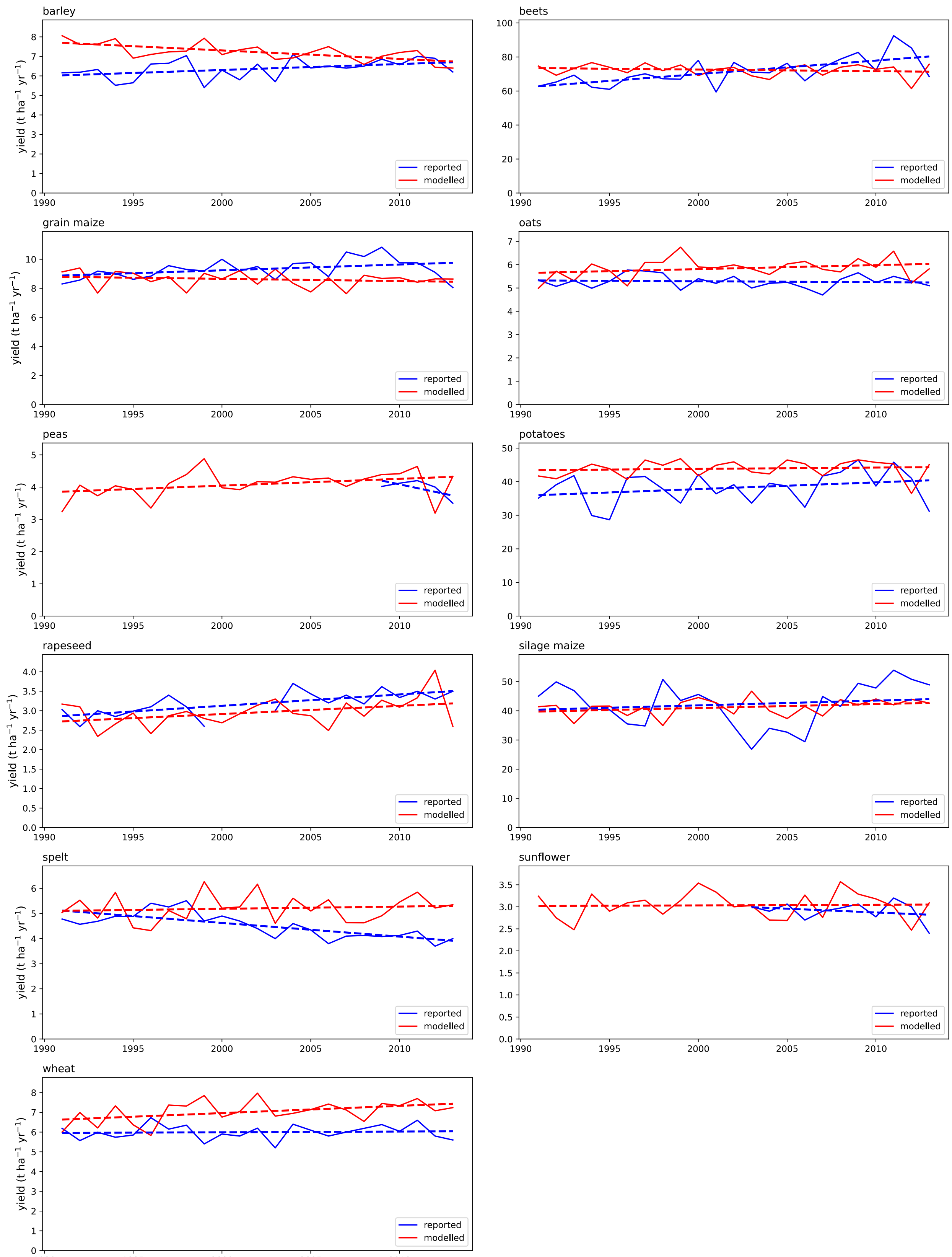

Figure S2. Reported and modelled yields for 11 crops from 1991 to 2013 in Switzerland. All yields are national mean expressed on a wet matter basis at harvest. The dashed black lines indicate fitted linear changes between 1991 and 2013.

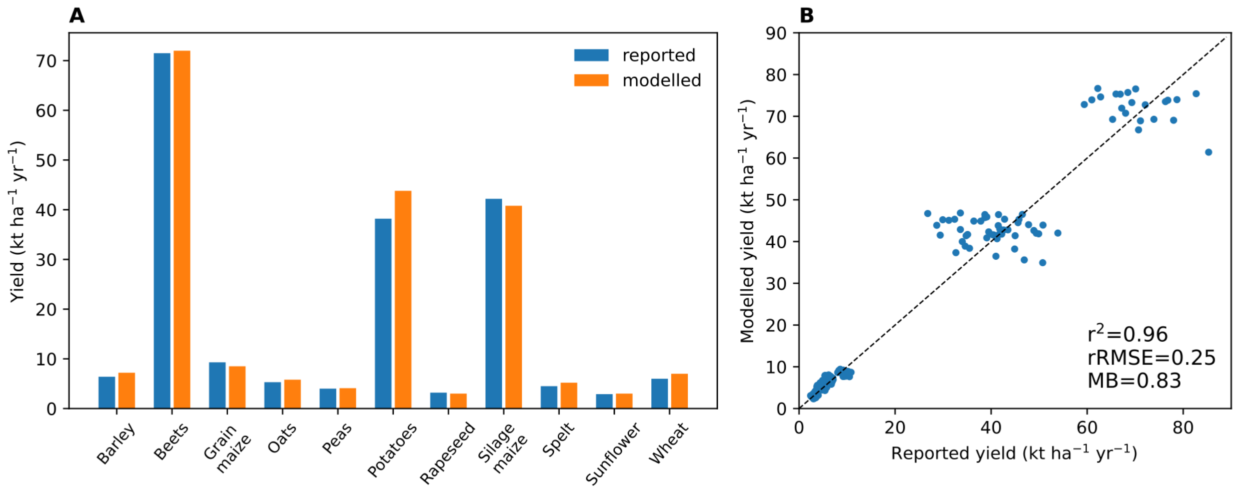

Figure S3. Comparisons between modelled and reported yields for 11 crops from 1991 to 2013 in Switzerland. All yields are national mean expressed on a wet matter basis at harvest.

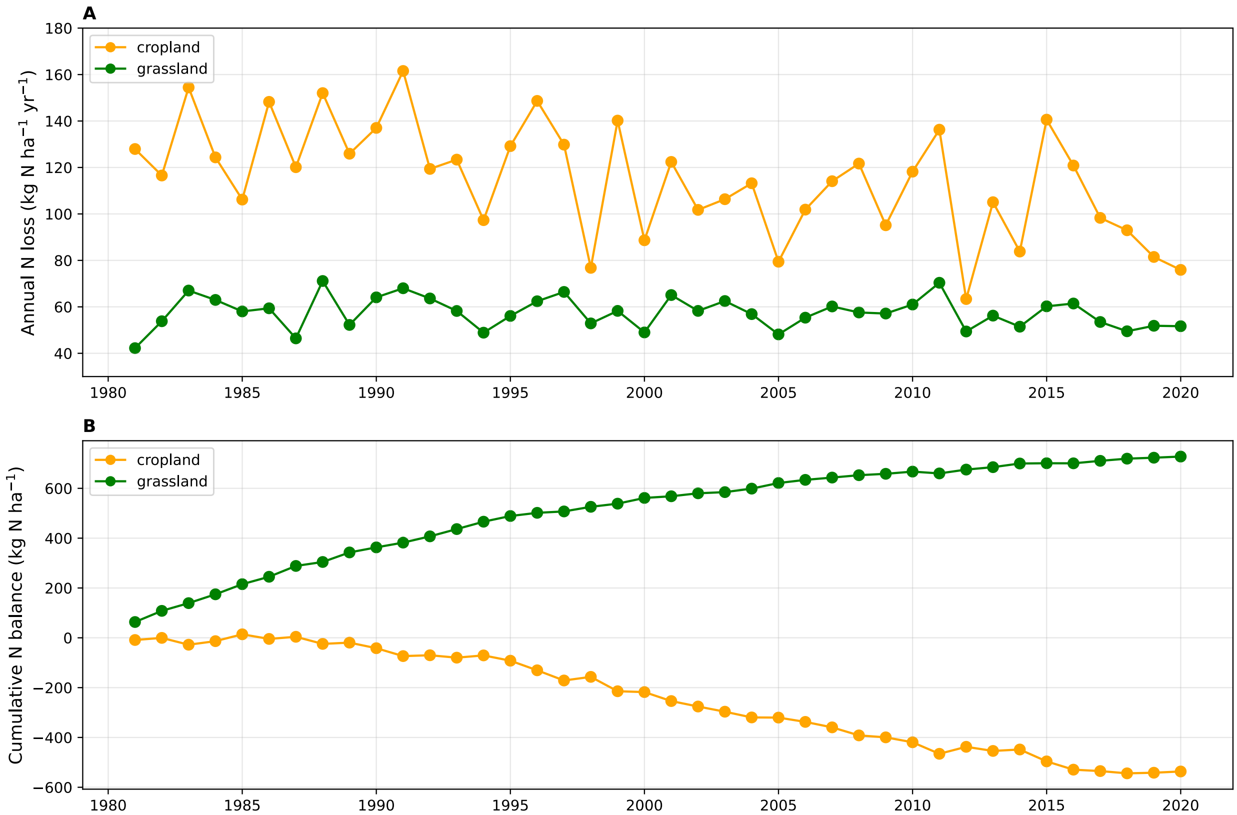

Figure S4. Annual mean N losses and soil N change in Swiss agroecosystems from 1981-2020. (A) Annual mean N losses, including gaseous emissions and leaching. Note that y-axis starts from 40 kg N ha^{-1} yr^{-1}. **(B)** Cumulative changes of soil N balance. Positive values indicate N accumulation, and negative values indicate N depletion.

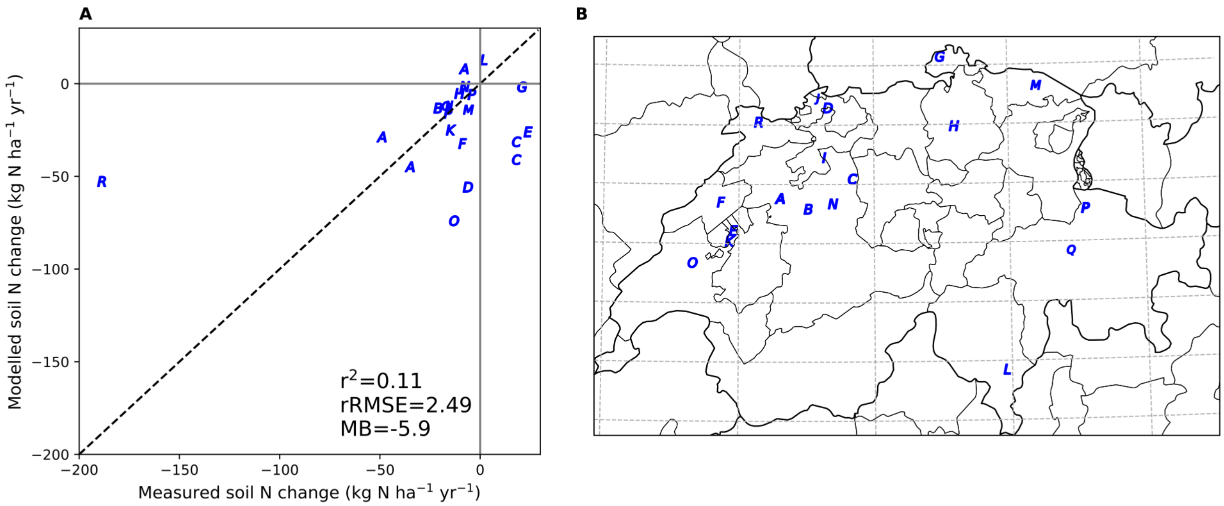

Figure S5. (A) Comparisons between modelled and measured soil N change (kg N ha^{-1} yr^{-1}) in croplands. **(B)** Locations of measuring sites. Measurements are from NABO long-term soil monitoring data. Multiple occurrences of the same symbol in panel a represent soil N changes in different time periods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

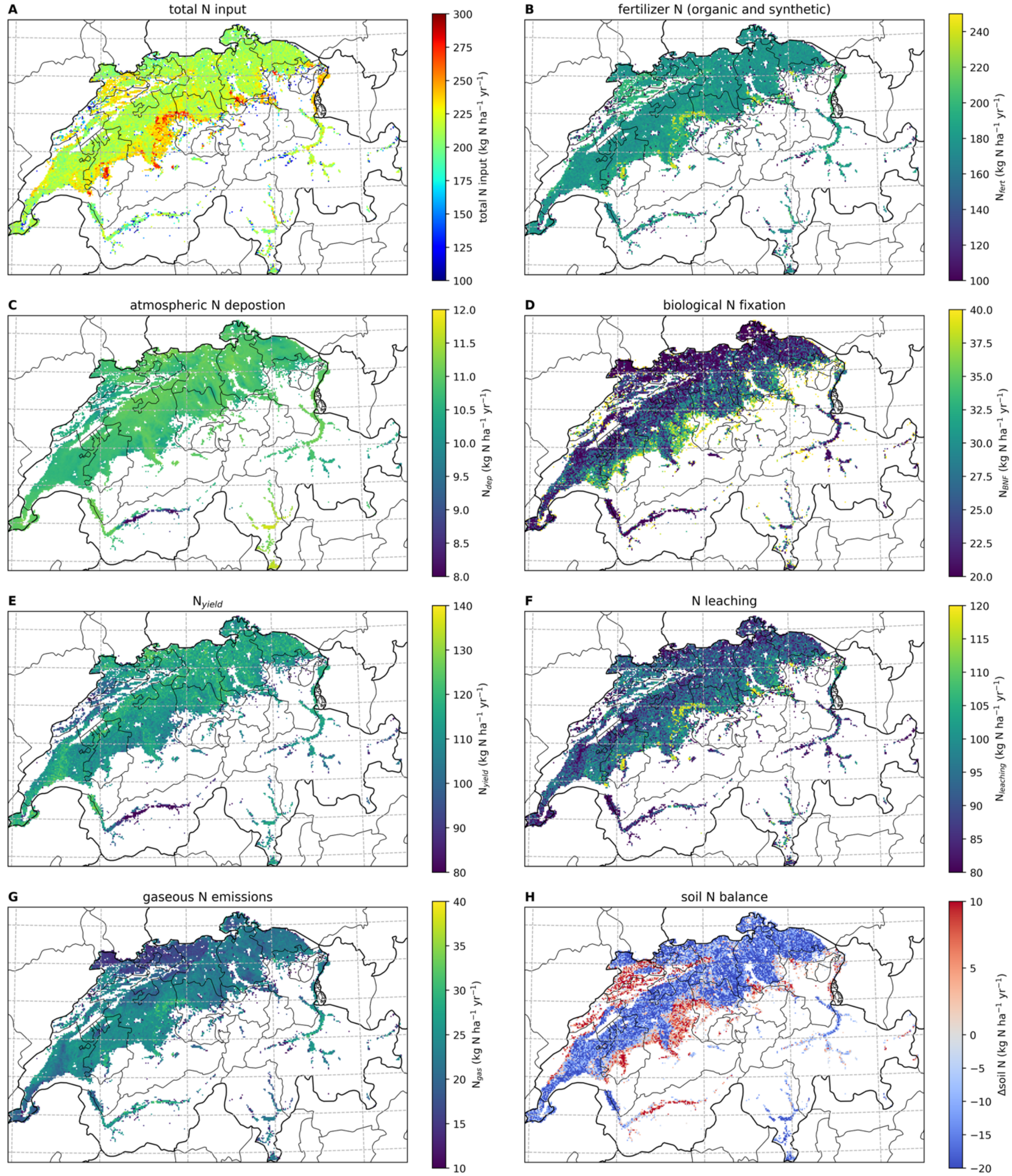

Figure S6. Spatial maps of N budgets and soil N balance of Swiss croplands over 1981-2020. (A) total N input **(B)** fertilizer N including manure and synthetic fertilizers **(C)** atmospheric N deposition **(D)** BNF **(E)** NUE **(F)** N leaching **(G)** gaseous emissions **(H)** soil N balance. All variables have the unit kg N ha^{-1} yr^{-1} (note the difference in scales). See Fig. 4 in main text for maps shown budgets expressed in percentage.

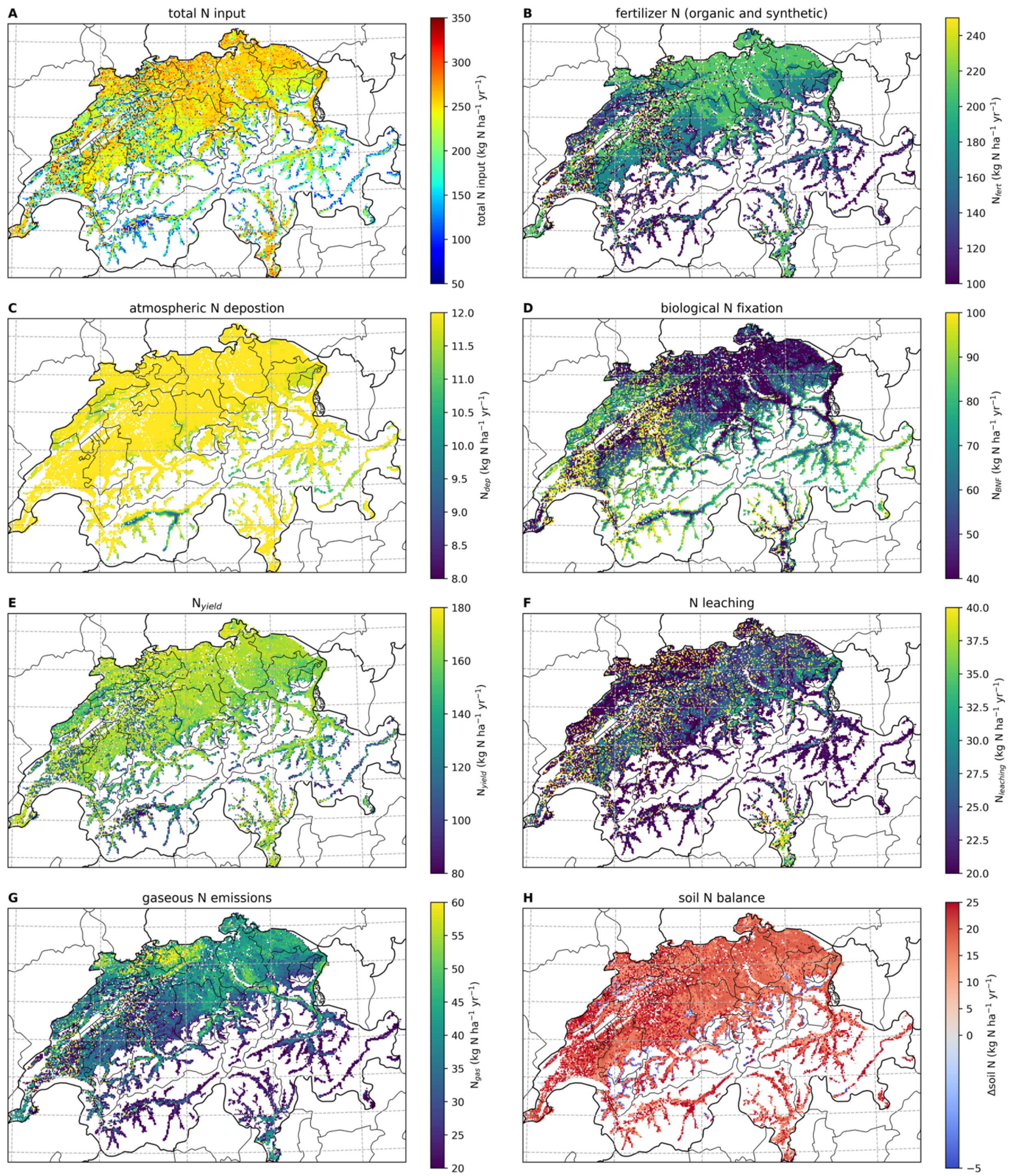

Figure S7. Spatial maps of N budgets and soil N balance of Swiss grasslands over 1981-2020. (A) total N input **(B)** fertilizer N including manure and synthetic fertilizers **(C)** atmospheric N deposition **(D)** BNF **(E)** NUE **(F)** N leaching **(G)** gaseous emissions **(H)** soil N balance. All variables have the unit kg N ha^{-1} yr^{-1} (note the difference in scales). See Fig. 5 in main text for maps shown budgets expressed in percentage. Grasslands refer to managed meadows only, while managed pastures and summer pastures for grazing are not included.

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