Supporting Information for

Impacts of fertilization on grassland productivity and water quality across the European Alps under current and warming climate: insights from a mechanistic model

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Introduction

The supporting information includes additional results supporting the analysis of the main manuscript (Figure S1- S7 and Table S2-S3) and the list of the model parameters for each study site (Table S1)

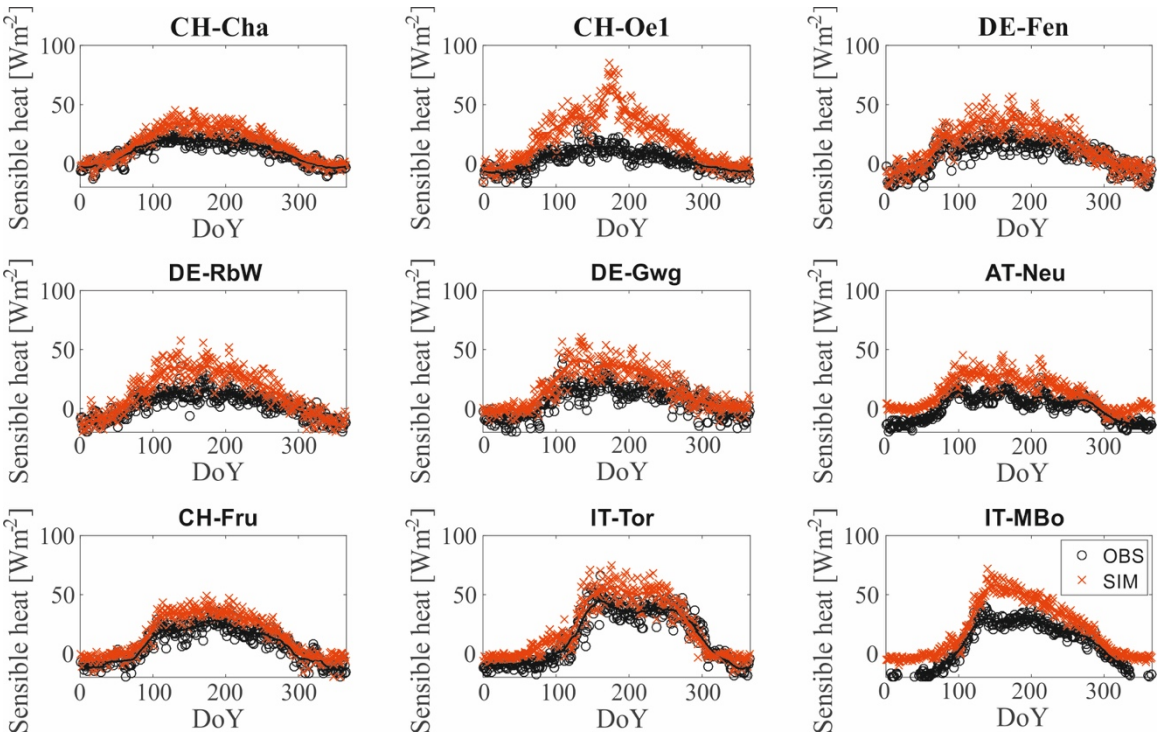

Figure S1. Observed versus simulated seasonal sensible heat (H). We compare the observed (black circles) and simulated (red crosses) seasonal pattern of H computing the average value for every day of the year (DoY) considering all the years for which observations are available. We also apply a moving average with a centered window of 30 days (continuous lines).

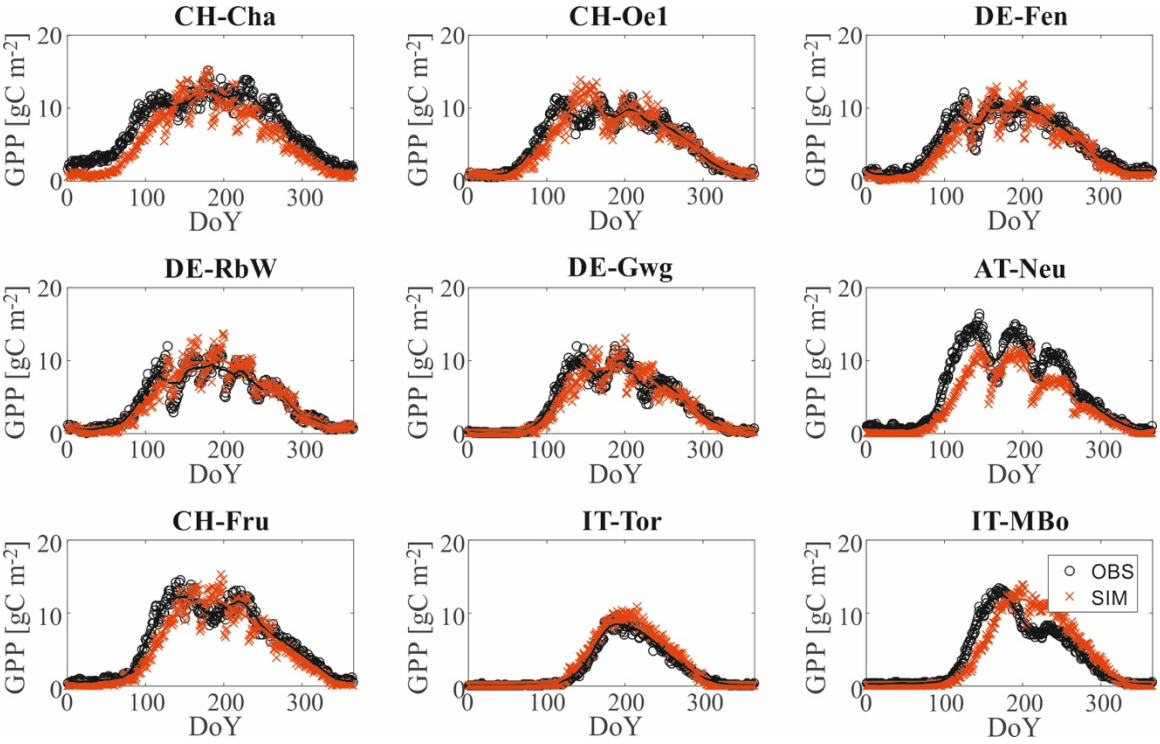

Figure S2. Observed versus simulated seasonal Gross Primary Production (GPP). We compare the observed (black circles) and simulated (red crosses) seasonal pattern of GPP computing the average value for every day of the year (DoY) considering all the years for which observations are available. We also apply a moving average with a centered window of 30 days (continuous lines).

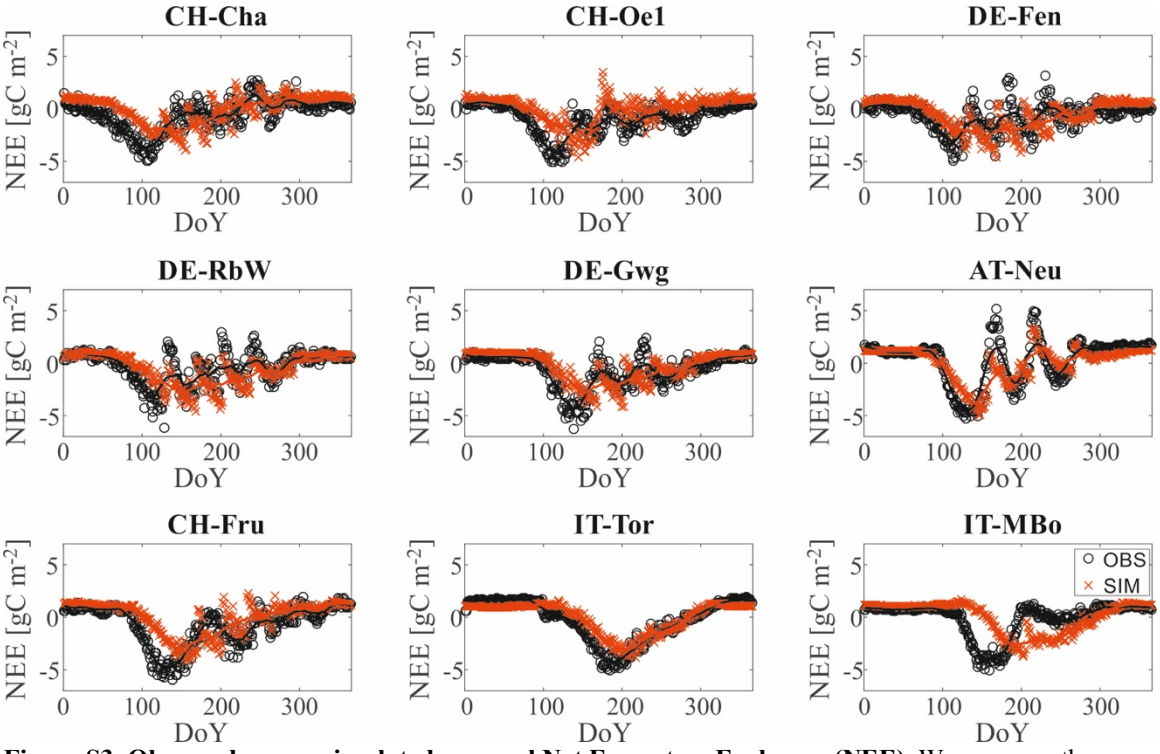

Figure S3. Observed versus simulated seasonal Net Ecosystem Exchange (NEE). We compare the observed (black circles) and simulated (red crosses) seasonal pattern of NEE computing the average value for every day of the year (DoY) considering all the years for which observations are available. We also apply a moving average with a centered window of 30 days (continuous lines).

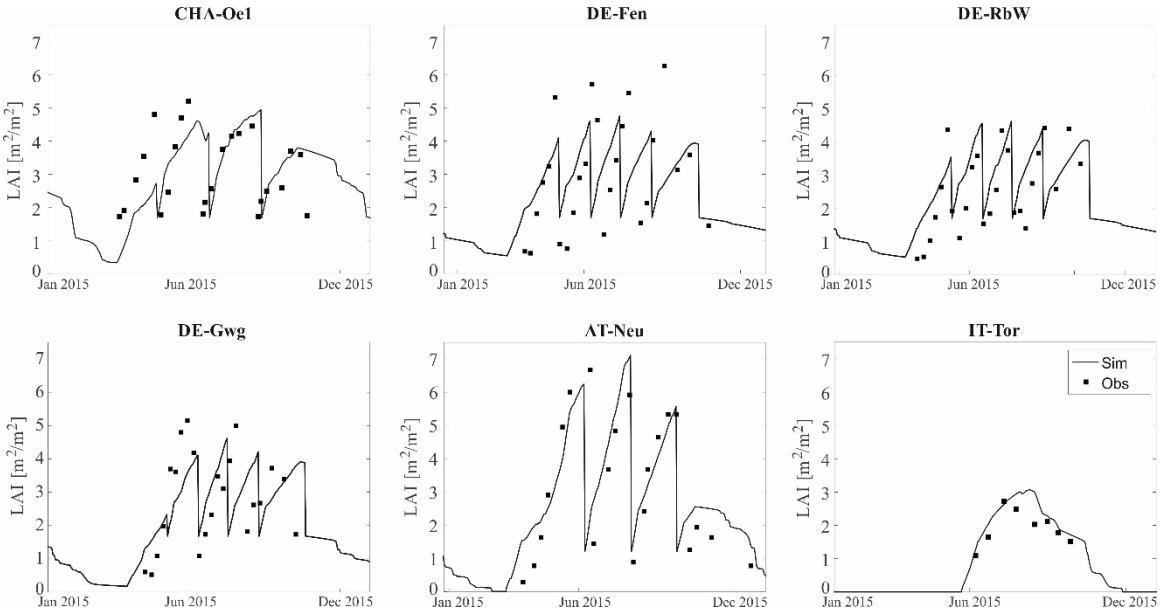

Figure S4. Zoom on the yearly pattern of observed vs. simulates Leaf Area Index (LAI) in CH-Cha, DE-Fen, DE-RbW, DE-Gwg, AT-Neu, and IT-Tor. Simulations (black line) are compare with observations (black dots). LAI data for CHA-Oe1 are retrieved from Chang et al., 2013. Observations for DE-Fen, DE-RbW and DE-Gwg are retrieved from the ScaleX campaign 2015 (Wolf et al. 2017; Zeeman et al. 2019). LAI data for AT-Neu were digitalized from Wohlfahrt et al., 2008 and LAI data in IT-Tor were provided by the Environmental Protection Agency of Aosta Valley (Filippa et al., 2015).

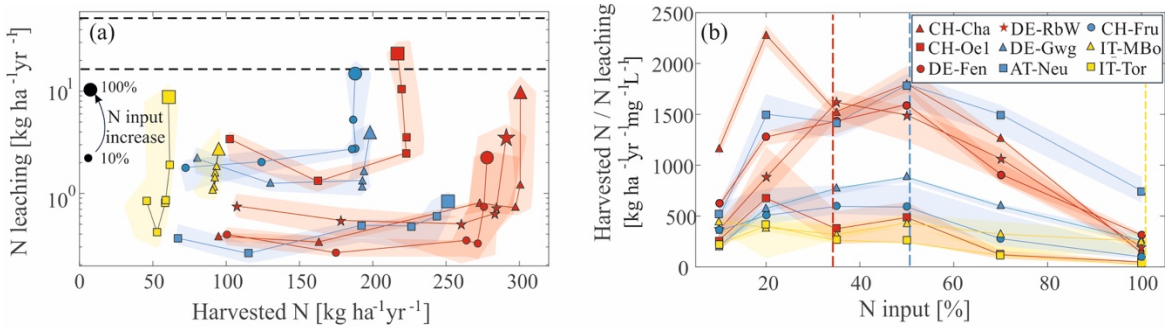

Figure S5. Results of the modified climate experiments. (a) Harvested N vs N leaching in each site. Moving counterclockwise follows the increase in N input. As a reference the biggest marker indicates N input of 100%. The dotted lines represent the estimate of maximum NO_3^- losses assumed by EU regulations or nearby countries. They correspond to the values 17 and 51 kgN ha^{-1} yr^{-1}, i.e., 10% and 30% of the maximum allowed input 170 kgN ha^{-1} yr^{-1}. (b) N fertilization efficiency index computed as the ratio between the harvested N and N concentration in groundwater recharge as a function of nitrogen input. In all the subplots the colors represent the elevation class, i.e., pre-Alpine (red), Alpine (blue) and high-Alpine (yellow) sites. The colored area around the markers and lines represent the 25th and 75th percentile of the interannual variability of the simulated variables, while the colored lines connecting data points represent the median values. The vertical dashed bars represent the limit of 170 kgN ha^{-1} yr^{-1} imposed by the EU Nitrate Directive in each of the three classes.

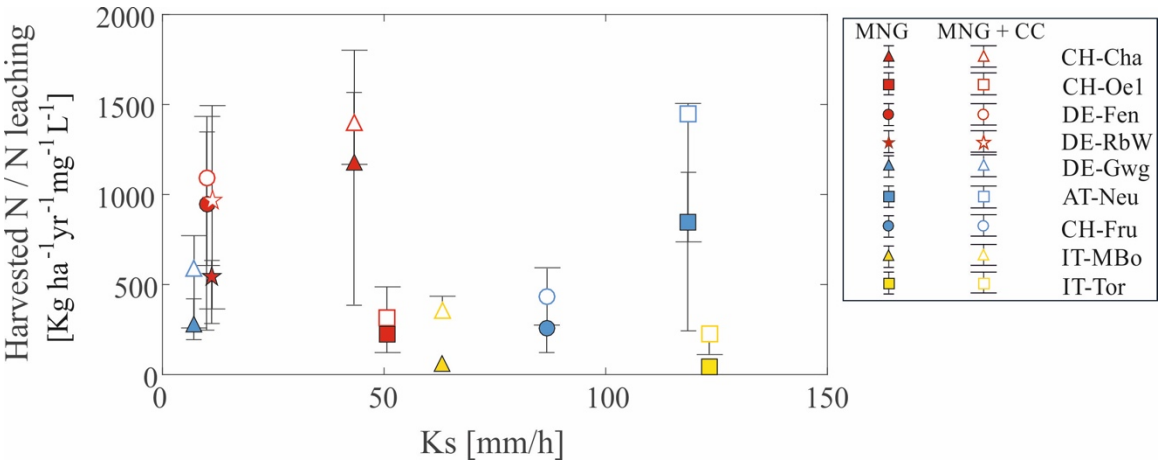

Figure S6. Ratio between harvested N and N leaching concentration as a function of soil saturated hydraulic conductivity (Ks). The whiskers span the 25th and 75th percentile of the interannual variability. Full markers refer to management scenarios (MNG), while empty markers refer to management + climate change (MNG + CC) scenarios.

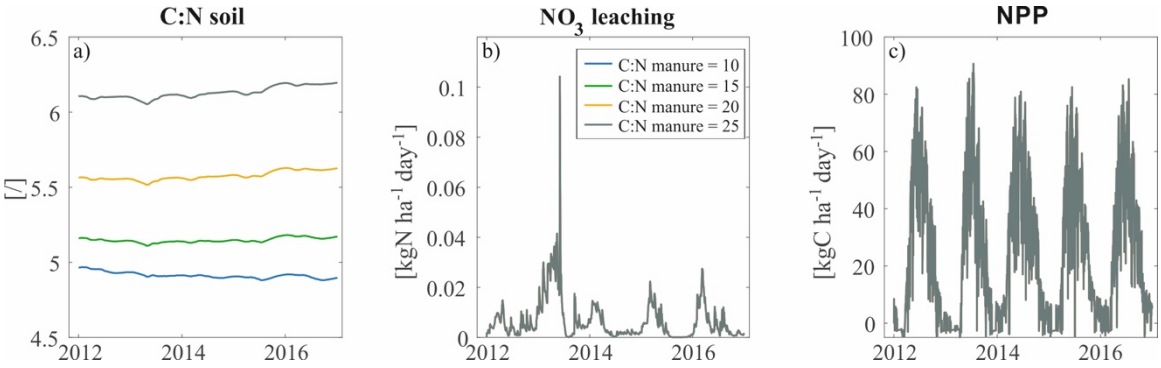

Figure S7. Results of experiments performed in DE-RbW adding manure to the system with different C:N values. (a) C:N of soil, (b) N leaching and (c) grass NPP patterns resulting from simulations characterized by addiction of manure with increasing C:N values. Simulations are run with C:N=10 (blue), C:N = 15 (green), C:N=20 (yellow) and C:N=25 (grey). All the lines almost perfectly overlaps in subplot (b) and (c)

Table S1. Model parametrization in each site.

Table S2. Mean bias error (MBR), Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) of the simulated latent heat, sensible heat, net radiation, and GPP compared to observations from flux towers. The values of the goodness of fit indexes is reported for each station.

	Latent heat			Sensible heat			Net radiation			GPP		
	MBE (Wm^{-2})	MAE (Wm^{-2})	RMSE (Wm^{-2})	MBE (Wm^{-2})	MAE (Wm^{-2})	RMSE (Wm^{-2})	MBE (Wm^{-2})	MAE (Wm^{-2})	RMSE (Wm^{-2})	MBE (gCm^{-2} day^{-1})	MAE (gCm^{-2} day^{-1})	RMSE (gCm^{-2} day^{-1})
CH-Cha	-8.53	21.0	35.2	6.29	14.90	25	-0.08	14.3	26.27	-1.30	2.7	4.90

CH-Oe1	-2.54	19.7	34.0	18.25	24.22	43	11.52	16.34	28.09	-0.21	2.28	4.73
DE-Fen	5.17	26.0	41.2	12.19	22.70	33	8.27	23.4	34.50	-0.50	1.9	3.78
DE-RbW	22.53	27.6	45.9	11.80	21.77	34	-18.75	53.61	88.19	0.01	1.69	3.49
DE-Gwg	1.90	25.8	49.0	16.04	25.36	41	11.66	24.56	38.58	-0.29	1.52	3.28
AT-Neu	3.54	16.1	34.3	12.20	20.51	34	5.50	29.05	41.63	-1.72	2.29	4.55
CH-Fru	-7.94	19.5	32.8	7.49	17.77	28	-0.63	15.41	31.69	-0.49	1.75	3.51
IT-MBo	-5.39	14.5	27.6	10.07	18.25	37	13.44	26.07	46.74	-0.20	1.14	2.50
IT-Tor	-1.99	15.2	26.3	15.95	24.55	35	8.04	24.07	43.58	-0.03	1.87	3.88

Table S3. Soil C:N ratio resulting from the long-term spin-up process vs observed soil C:N across the different sites.

	SOIL C:N		
	Spin-up	**Observations**	**Reference**
CH-Cha	8.46 ± 0.04	9.4 ± 0.1	Roth, 2006
CH-Oe1	5.85 ± 0.04	9.3	Amman et al., 2009
DE-Fen	5.29 ± 0.04	8.8 ± 0.1	Fu et al., 2017
DE-RbW	5.00 ± 0.03	8.9 ± 0.1	Fu et al., 2017
DE-Gwg	6.19 ± 0.06	8.8 ±0.1	Fu et al., 2017
AT-Neu	7.07 ± 0.03	9.5	Kitz et al., 2019
CH-Fru	8.86 ± 0.06	12.4	Roth, 2006
IT-MBo	6.48 ± 0.04	11.45	Peichl et al., 2013
IT-Tor	6.15 ± 0.06	12.73	Peichl et al., 2013

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