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Drivers of soil organic carbon from temperate to alpine forests: a model-based analysis of the Swiss forest soil inventory with Yasso20

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Supplementary material

Table S1 (a) Principal component analysis (PCA) of n = 468 sites (excluding waterlogged soils) for the three principal components (PC) with eigenvalues >1, with highest loadings (> 0.4) for each principal component marked in **bold**, and (b) PCA-based analysis of total SOC stocks and Yasso20 deviations (i.e. simulated minus measured values of total SOC stocks), tested with linear mixed-effect models with region as random intercept.

(a) Principal component analysis (PCA)

	PC1	PC2	PC3
Eigenvalue	3.5	2.4	1.5
Variability (%)	34.6	23.7	15.2
Cumulative (%)	34.6	58.3	73.6
Loadings			
pH	**0.48**	-0.12	0.05
Clay	0.33	0.06	**0.44**
Fe	**-0.40**	-0.04	0.36
Al	**-0.43**	0.07	0.35
Ca	**0.47**	-0.11	0.21
MAT	0.07	**0.58**	-0.09
MAP	-0.02	0.12	**0.63**
NPP	0.05	**0.58**	0.13
Broadleaf%	0.22	**0.44**	-0.06
Slope	0.20	-0.29	0.28

(b) Statistical model including the three PCs

	Total SOC stocks All sites (n = 468)				Yasso20 deviations All sites (n = 468)			
	Estimate	SE	t	*P*	Estimate	SE	t	*P*
(Intercept)	13.5	1.0	13.1	**<0.001**	-0.1	1.3	0.0	0.96
PC1	-0.9	0.3	-3.3	**<0.001**	0.7	0.3	2.6	**0.010**
PC2	-0.7	0.4	-1.9	0.06	0.6	0.4	1.5	0.14
PC3	2.8	0.3	9.3	**<0.001**	-2.4	0.3	-7.6	**<0.001**
DF	460				460			
marginal R^2	0.21				0.14			
conditional R^2	0.33				0.31			
RMSE	5.3				5.5			

Model estimates, standard errors (SE), t statistic and *P*-values are reported ($P < 0.05$ highlighted in **bold**).
DF is the degrees of freedom. Marginal R^2 considers the variance of the fixed effects, while conditional R^2 both the fixed and random effects calculated using the R package *performance* (Lüdecke et al., 2021).
RMSE is the root mean squared error.

Table S2. Additional analysis of drivers of total SOC stocks considering factor interactions. Effects of soil properties in the upper 30 cm mineral soil (i.e. pH, clay content, exchangeable contents of Fe and Ca), MAT (mean annual temperature), MAP (mean annual precipitation), NPP (net primary production) percentage of broadleaves and slope**,** including the interactions, on total SOC stocks (kg C m^{-2}). Linear mixed-effect models with region as random intercept were developed separately for (i) all sites excluding waterlogged soils, and (ii) sites with pH ≤ 5. Only two-way interactions that decreased the Bayesian Information Criterion (BIC) were included in the final statistical model. For sites with pH > 5, no model was developed since interactions did not decrease the BIC.

	All sites (n = 468)					pH ≤ 5 (n = 287)			
	Estimate	SE	t	*P*		Estimate	SE	t	*P*
(Intercept)	9.01	1.23	7.3	**<0.001**	(Intercept)	12.45	0.91	13.7	**<0.001**
pH	-2.64	0.68	-3.9	**<0.001**	pH	-0.45	1.26	-0.4	0.72
log(Clay)	-0.82	0.58	-1.4	0.16	log(Clay)	-1.48	0.78	-1.9	0.06
sqrt(Fe)	4.49	0.71	6.4	**<0.001**	sqrt(Fe)	4.93	0.94	5.2	**<0.001**
log(Ca)	2.59	0.41	6.4	**<0.001**	log(Ca)	-0.23	0.29	-0.8	0.43
MAT	0.02	0.20	0.1	0.93	MAT	-0.39	0.27	-1.4	0.15
MAP	0.70	0.11	6.4	**<0.001**	MAP	0.92	0.14	6.6	**<0.001**
NPP	-1.40	4.13	-0.3	0.73	NPP	2.12	4.98	0.4	0.67
Broadleaf%	-0.02	0.01	-2.2	**0.027**	Broadleaf%	-0.01	0.01	-0.8	0.45
sqrt(Slope)	-0.41	0.10	-4.1	**<0.001**	sqrt(Slope)	-0.46	0.13	-3.5	**<0.001**
log(Clay)*MAP	-0.57	0.13	-4.3	**<0.001**	log(Clay)*MAP	-0.75	0.18	-4.1	**<0.001**
pH*log(Ca)	1.80	0.26	7.0	**<0.001**	#	#	#	#	#
#	#	#	#	#	pH*sqrt(Fe)	-6.44	1.55	-4.15	**<0.001**
DF	452					271			
marginal R^2	0.38					0.53			
conditional R^2	0.50					0.60			
RMSE (kg C m^{-2})	4.6					4.4			

Model estimates, standard errors (SE), t statistic and *P*-values are reported ($P < 0.05$ highlighted in **bold**).
Measurement units of independent variables are reported in Table 1. For result interpretation, MAP is here reported in 100 mm unit.
DF is the degrees of freedom. Marginal R^2 includes the variance of the fixed effects, while conditional R^2 both the fixed and random effects calculated with the R package *performance* (Lüdecke et al., 2021).
RMSE is the root mean squared error.
The symbol "#" indicates that an interaction was excluded from the model since it did not decrease the BIC.

Table S3. Additional analysis of drivers of Yasso20 deviations considering factor interactions. Effects of soil properties in the upper 30 cm mineral soil (i.e. pH, clay content, exchangeable contents of Fe and Ca), MAT (mean annual temperature), MAP (mean annual precipitation), percentage of broadleaves and slope, including the interactions, on Yasso20 deviations (i.e. simulated minus measured values of total SOC stocks) in kg C m^{-2}. Linear mixed-effect models with region as random intercept were developed separately for (i) all sites excluding waterlogged soils, (ii) sites with pH ≤ 5, and (iii) sites with pH > 5. Only two-way interactions that decreased the Bayesian Information Criterion (BIC) were included in the final statistical model.

	All sites (n = 468)					pH ≤ 5 (n = 287)					pH > 5 (n = 181)			
	Estimate	SE	t	*P*		Estimate	SE	t	*P*		Estimate	SE	t	*P*
(Intercept)	3.99	1.56	2.6	**0.011**	(Intercept)	0.92	1.08	0.9	0.40	(Intercept)	-0.74	2.67	-0.3	0.78
pH	2.27	0.70	3.2	**0.001**	pH	0.20	1.29	0.2	0.88	pH	-1.32	0.72	-1.8	0.07
log(Clay)	1.14	0.60	1.9	0.06	log(Clay)	1.74	0.80	2.2	**0.030**	Clay	-0.03	0.04	-0.7	0.49
sqrt(Fe)	-4.74	0.73	-6.5	**<0.001**	sqrt(Fe)	-5.30	0.96	-5.5	**<0.001**	sqrt(Fe)	-6.30	3.59	-1.8	0.08
log(Ca)	-2.58	0.42	-6.2	**<0.001**	log(Ca)	-0.02	0.29	-0.1	0.95	Ca	-0.02	0.00	-4.7	**<0.001**
MAT	-0.48	0.17	-2.7	**0.007**	MAT	-0.18	0.25	-0.7	0.47	MAT	-0.58	0.25	-2.4	**0.020**
MAP	-0.61	0.11	-5.5	**<0.001**	MAP	-0.88	0.14	-6.2	**<0.001**	MAP	-0.36	0.17	-2.1	**0.037**
Broadleaf%	0.02	0.01	2.6	**0.011**	Broadleaf%	0.01	0.01	1.0	0.34	Broadleaf%	0.03	0.01	2.8	**0.006**
sqrt(Slope)	0.42	0.10	4.1	**<0.001**	sqrt(Slope)	0.46	0.14	3.4	**<0.001**	Slope	0.04	0.02	2.9	**0.004**
log(Clay)*MAP	0.51	0.14	3.7	**<0.001**	log(Clay)*MAP	0.70	0.19	3.8	**<0.001**	#	#	#	#	#
pH*log(Ca)	-1.64	0.26	-6.2	**<0.001**	#	#	#	#	#	pH*log(Ca)	-0.01	0.00	-2.9	**0.004**
#	#	#	#	#	pH*sqrt(Fe)	5.48	1.58	3.5	**<0.001**	#	#	#	#	#
DF	453					272					167			
marginal R^2	0.31					0.48					0.20			
conditional R^2	0.51					0.58					0.69			
RMSE (kg C m^{-2})	4.7					4.5					4.5			

Model estimates, standard errors (SE), t statistic and *P*-values are reported ($P < 0.05$ highlighted in **bold**).
Measurement units of independent variables are reported in Table 1. For result interpretation, MAP is here reported in 100 mm unit.
DF is the degrees of freedom. Marginal R^2 includes the variance of the fixed effects, while conditional R^2 both the fixed and random effects calculated with the R package *performance* (Lüdecke et al., 2021).
RMSE is the root mean squared error.
The symbol "#" indicates that an interaction was excluded from the model since it did not decrease the BIC.

Table S4. Additional analysis of drivers of total SOC stocks and Yasso20 deviations for sites (i) excluding Southern Alps, and (ii) including waterlogged soils. Effects of soil properties in the upper 30 cm mineral soil (i.e. pH, clay content, exchangeable contents of Fe and Ca), MAT (mean annual temperature), MAP (mean annual precipitation), NPP (net primary production), percentage of broadleaves and slope on (a) total SOC stocks, and (b) Yasso20 deviations (i.e. simulated minus measured values of total SOC stocks) in kg C m^{-2}. Linear mixed-effect models with region as random intercept were developed separately for (i) sites excluding Southern Alps and waterlogged soils (n = 437), and (ii) all sites including waterlogged soils (n = 556).

(a) Total SOC stocks

	Sites excluding Southern Alps (n = 437)					Sites including waterlogged (n = 556)			
	Estimate	SE	t	*P*		Estimate	SE	t	*P*
(Intercept)	12.65	0.77	16.5	**<0.001**	(Intercept)	14.07	0.99	14.2	**<0.001**
pH	1.67	0.30	5.5	**<0.001**	pH	1.74	0.35	5.0	**<0.001**
log(Clay)	0.39	0.60	0.7	0.51	log(Clay)	0.36	0.66	0.5	0.59
sqrt(Fe)	5.98	0.70	8.6	**<0.001**	sqrt(Fe)	6.94	0.77	9.0	**<0.001**
log(Ca)	0.11	0.24	0.4	0.65	log(Ca)	0.57	0.28	2.0	**0.042**
MAT	0.19	0.21	0.9	0.36	MAT	-0.09	0.24	-0.3	0.73
MAP	0.69	0.12	6.0	**<0.001**	MAP	0.86	0.13	6.7	**<0.001**
NPP	-0.95	4.56	-0.2	0.83	NPP	-3.47	4.95	-0.7	0.48
Broadleaf%	-0.03	0.01	-3.6	**<0.001**	Broadleaf%	-0.03	0.01	-2.9	**0.005**
sqrt(Slope)	-0.32	0.10	-3.2	**0.002**	sqrt(Slope)	-0.50	0.12	-4.3	**<0.001**
DF	424					542			
marginal R^2	0.33					0.30			
conditional R^2	0.38					0.37			
RMSE (kg C m^{-2})	4.6					6.1			

Model estimates, standard errors (SE), t statistic and *P*-values are reported ($P < 0.05$ highlighted in **bold**).
Measurement units of independent variables are reported in Table 1. For result interpretation, MAP is here reported in 100 mm unit.
DF is the degrees of freedom. Marginal R^2 includes the variance of the fixed effects, while conditional R^2 both the fixed and random effects calculated with the R package *performance* (Lüdecke et al., 2021).
RMSE is the root mean squared error.

(b) Yasso20 deviations

	Sites excluding Southern Alps (n = 437)					Sites including waterlogged (n = 556)			
	Estimate	SE	t	*P*		Estimate	SE	t	*P*
(Intercept)	0.97	1.05	0.9	0.36	(Intercept)	-0.67	1.28	-0.5	0.60
pH	-1.65	0.31	-5.3	**<0.001**	pH	-1.69	0.35	-4.8	**<0.001**
log(Clay)	0.02	0.61	0.0	0.97	log(Clay)	0.02	0.67	0.0	0.98
sqrt(Fe)	-6.10	0.71	-8.6	**<0.001**	sqrt(Fe)	-6.98	0.79	-8.9	**<0.001**
log(Ca)	-0.29	0.24	-1.2	0.24	log(Ca)	-0.76	0.28	-2.7	**0.007**
MAT	-0.71	0.18	-3.9	**<0.001**	MAT	-0.29	0.21	-1.4	0.16
MAP	-0.66	0.12	-5.7	**<0.001**	MAP	-0.78	0.13	-6.0	**<0.001**
Broadleaf%	0.03	0.01	3.7	**<0.001**	Broadleaf%	0.03	0.01	3.1	**0.002**
sqrt(Slope)	0.33	0.11	3.1	**0.002**	sqrt(Slope)	0.50	0.12	4.2	**<0.001**
DF	425					543			
marginal R^2	0.30					0.25			
conditional R^2	0.41					0.37			
RMSE (kg C m^{-2})	4.7					6.2			

Model estimates, standard errors (SE), t statistic and *P*-values are reported ($P < 0.05$ highlighted in **bold**).
Measurement units of independent variables are reported in Table 1. For result interpretation, MAP is here reported in 100 mm unit.
DF is the degrees of freedom. Marginal R^2 includes the variance of the fixed effects, while conditional R^2 both the fixed and random effects calculated with the R package *performance* (Lüdecke et al., 2021).
RMSE is the root mean squared error.

Table S5. Additional analysis of drivers of total SOC stocks by biogeographic regions. Effects of soil properties in the upper 30 cm mineral soil (i.e. pH, clay content, exchangeable contents of Fe and Ca), MAT (mean annual temperature), MAP (mean annual precipitation), NPP (net primary production), percentage of broadleaves and slope on total SOC stocks in kg C m^{-2}. Linear models were developed separately for each region excluding waterlogged soils (total n = 468).

	Jura (n = 54)				Plateau (n = 164)				Pre-Alps (n = 138)				Alps (n = 81)				Southern Alps (n = 31)		
	Estimate	P	% R^2		Estimate	P	% R^2		Estimate	P	% R^2		Estimate	P	% R^2		Estimate	P	% R^2
(Intercept)	13.56	**<0.001**	-	(Intercept)	10.21	**<0.001**	-	(Intercept)	13.61	**<0.001**	-	(Intercept)	13.01	**<0.001**	-	(Intercept)	19.49	**<0.001**	-
pH	0.58	0.59	20	pH	1.29	**0.001**	8	pH	2.47	**<0.001**	10	pH	0.99	0.25	4	pH	4.93	0.12	8
Clay	0.01	0.85	8	log(Clay)	2.02	**0.022**	12	Clay	0.05	0.27	2	log(Clay)	-0.70	0.70	2	log(Clay)	-3.96	0.24	2
sqrt(Fe)	2.25	0.41	6	sqrt(Fe)	5.47	**<0.001**	33	sqrt(Fe)	5.78	**<0.001**	30	sqrt(Fe)	6.03	**0.004**	31	sqrt(Fe)	11.77	**0.005**	46
Ca	0.02	**0.021**	44	log(Ca)	-0.11	0.72	3	log(Ca)	-0.51	0.20	6	log(Ca)	0.73	0.37	3	log(Ca)	1.55	0.41	3
MAT	0.03	0.97	5	MAT	0.15	0.81	3	MAT	0.38	0.41	6	MAT	0.68	0.17	14	MAT	-2.17	0.08	19
MAP	0.12	0.76	2	MAP	1.02	**<0.001**	25	MAP	0.77	**<0.001**	12	MAP	0.71	0.06	20	MAP	0.75	0.51	2
NPP	-5.85	0.70	1	NPP	4.57	0.48	1	NPP	-2.49	0.78	2	NPP	0.98	0.95	9	NPP	25.85	0.21	8
Broadleaf%	-0.04	0.09	10	Broadleaf%	0.00	0.72	6	Broadleaf%	-0.06	**<0.001**	30	Broadleaf%	-0.04	0.33	3	Broadleaf%	0.07	0.37	10
Slope	-0.04	0.18	5	sqrt(Slope)	-0.43	**<0.001**	9	Slope	-0.01	0.58	1	Slope	-0.05	0.08	13	Slope	-0.09	0.26	3
DF	44				154				128				71				21		
adj R^2	0.23				0.37				0.42				0.20				0.34		
RMSE (kg C m^{-2})	3.7				3.4				4.5				5.9				6.3		

Model estimates and P-values are reported ($P < 0.05$ highlighted in **bold**). The relative contribution of each variable to the model variance (% R^2) was calculated with the R package *relaimpo* with metrics normalized to sum to 100% (Groemping and Matthias, 2018).
Measurement units of independent variables are reported in Table 1. For result interpretation, MAP is here reported in 100 mm unit.
DF is the degrees of freedom. Adj R^2 is the adjusted R^2.
RMSE is the root mean squared error.

Table S6. Drivers of organic layer SOC stocks. Effects of pH in the upper 30 cm mineral soil, MAT (mean annual temperature), MAP (mean annual precipitation), NPP (net primary production), percentage of broadleaves and slope on organic layer SOC stocks (transformed with natural logarithm to meet model assumptions) in kg C m^{-2}. Linear mixed-effect model with region as random intercept was developed for all sites excluding waterlogged soils. Among soil properties, only pH was included as predictor since organic layer SOC stocks are generally not stabilized in the long-term against microbial decomposition by organo-mineral associations (Prietzel et al., 2020).

	All sites (n = 468)			
	Estimate	SE	t	*P*
(Intercept)	0.19	0.10	1.9	0.06
pH	-0.34	0.04	-9.6	**<0.001**
MAT	-0.02	0.04	-0.6	0.58
MAP	0.00	0.02	0.0	0.98
NPP	-0.79	0.86	-0.9	0.36
Broadleaf%	-0.01	0.00	-5.4	**<0.001**
sqrt(Slope)	0.00	0.02	-0.2	0.82
DF	457			
marginal R^2	0.31			
conditional R^2	0.34			
RMSE (kg C m^{-2})	1.0			

Model estimates, standard errors (SE), t statistic and *P*-values are reported ($P < 0.05$ highlighted in **bold**).
Measurement units of independent variables are reported in Table 1. For result interpretation, MAP is here reported in 100 mm unit.
DF is the degrees of freedom. Marginal R^2 includes the variance of the fixed effects, while conditional R^2 both the fixed and random effects calculated with the R package *performance* (Lüdecke et al., 2021).
RMSE is the root mean squared error.

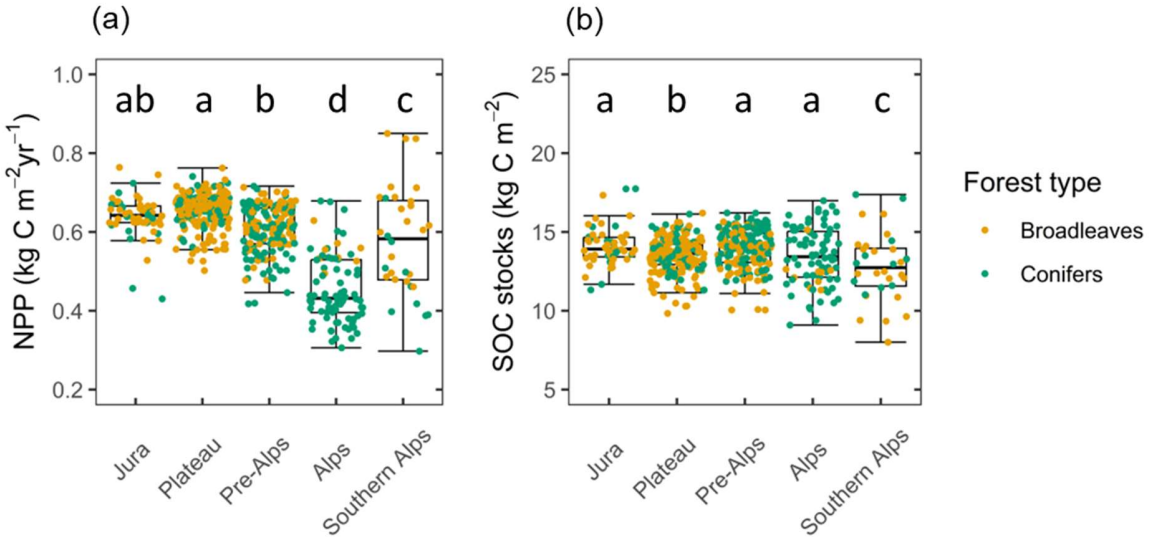

Fig. S1. Net primary production (NPP) (a), and Yasso20-simulated SOC stocks (b) across Swiss forest regions, excluding waterlogged soils. Total *n* sites = 468. Letters indicate significantly different means across regions, based on ANOVA followed by Tukey's test with $P < 0.05$.

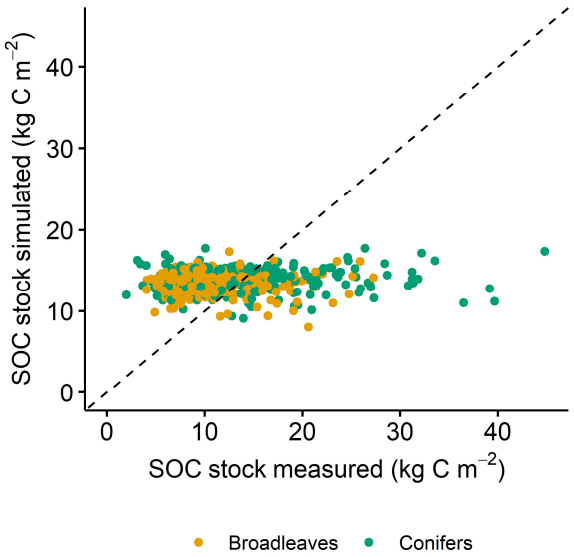

Fig. S2. Comparison between Yasso20-simulated and measured SOC stocks by forest types, with 1:1 dotted line. The measured SOC stocks are the sum of SOC stocks in organic layers and mineral soils to 100 cm depth (total *n* sites = 468, excluding waterlogged soils). The simulated SOC stocks at each site are based on the mean of 500 replicate simulations representing model parameters uncertainty.

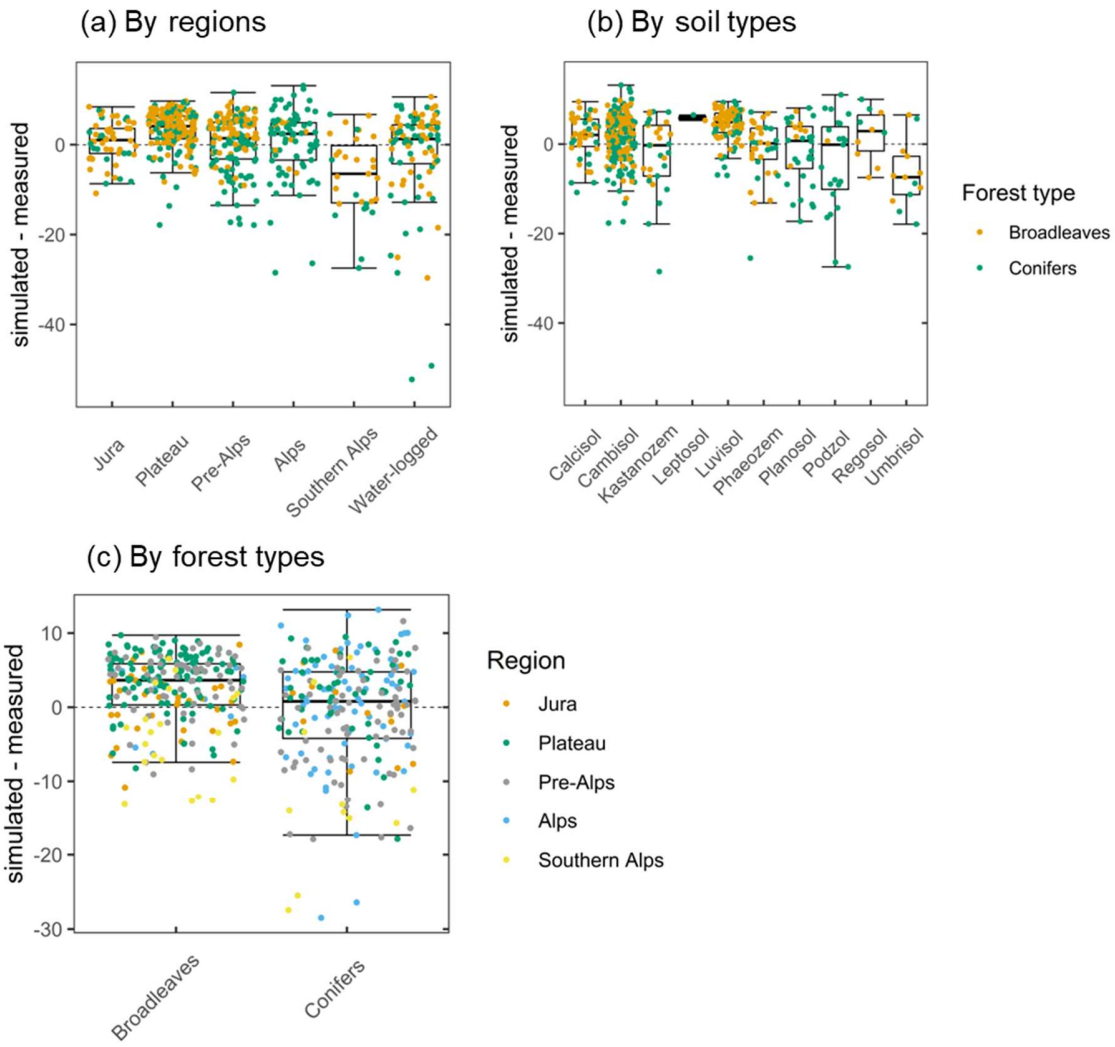

Fig. S3. Yasso20 deviations (i.e. simulated minus measured SOC stocks) in kg C m^{-2} by: (a) biogeographic regions of Switzerland with waterlogged soils shown separately, (b) soil types, and (c) forest types, with (b) and (c) excluding water-logged soils. The box represents the median (50^{th} percentile), 25^{th} and 75^{th} percentile of the data. The whiskers represent 1.5 times the inter-quartile range and points more than 1.5 times the interquartile range are plotted individually. Total *n* sites = 556, while excluding waterlogged soils *n* = 468. The dashed line indicates the zero line for deviations.

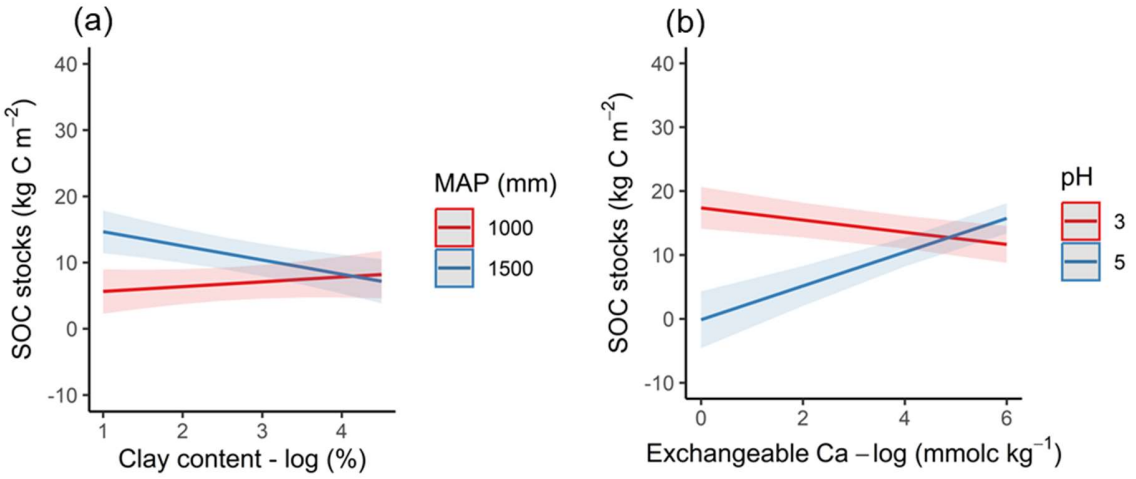

Fig. S4. Interactive effect of (a) mean annual precipitation (MAP) with log-transformed (i.e. natural logarithmic scale) clay content, and (b) of pH with log-transformed exchangeable Ca on total SOC stocks. The full statistical models including interactions are shown in Table S2. Interactions are visualized using the R package *sjPlot*, version 2.8.16 (Lüdecke, 2024).

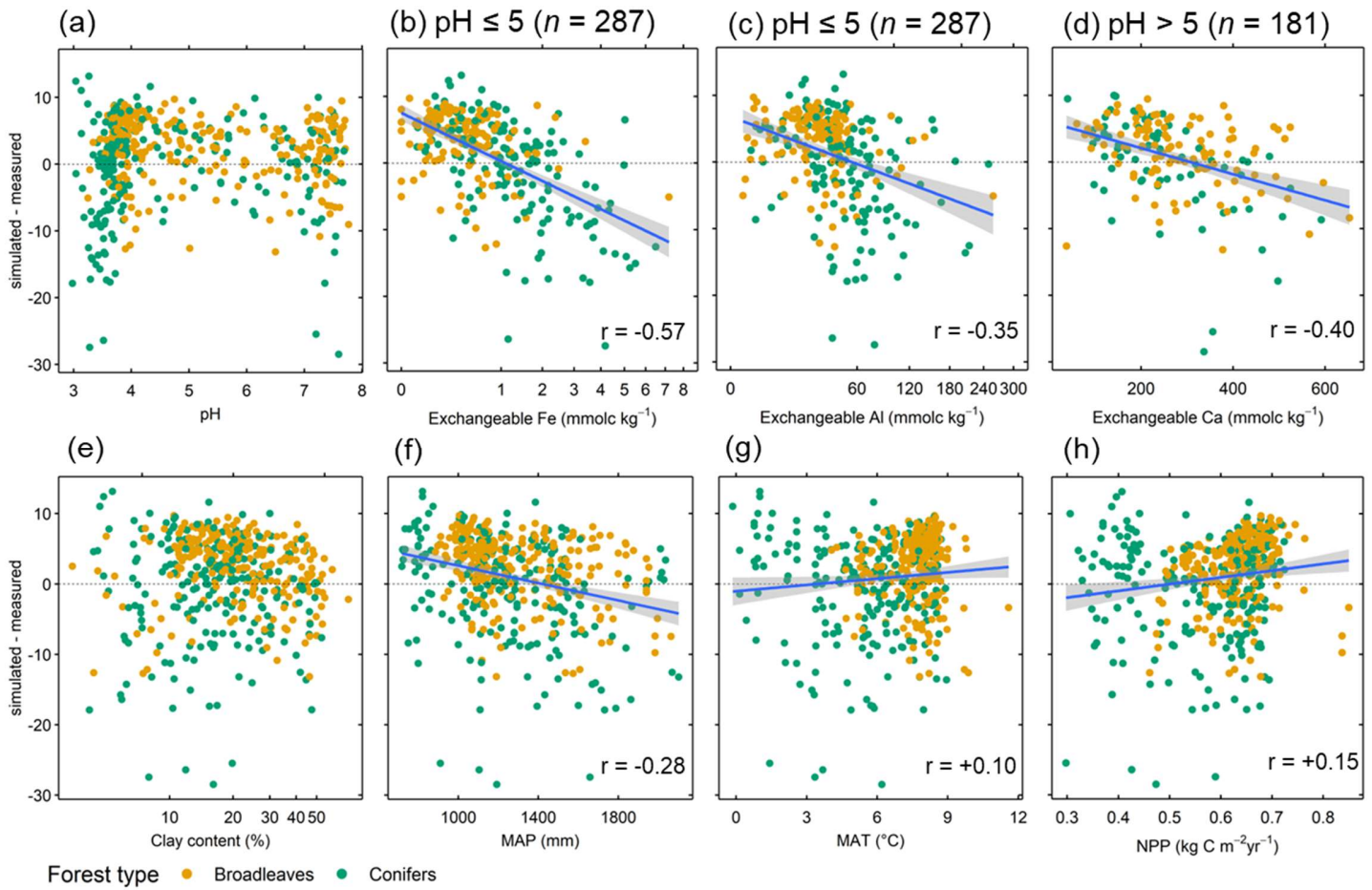

Fig. S5. Correlations between Yasso20 deviations (i.e. simulated minus measured total SOC stocks, in kg C m^{-2}), selected soil properties (exchangeable Fe and Al shown on a square-root scale axis, clay on a natural-logarithm scale axis) and site variables (MAP = mean annual precipitation; MAT = mean annual temperature; NPP = net primary production). Total *n* sites = 468 (waterlogged soils excluded). Plotted lines show significant linear correlations ($P < 0.05$) with 95% confidence intervals in grey and the Pearson correlation coefficient (r).

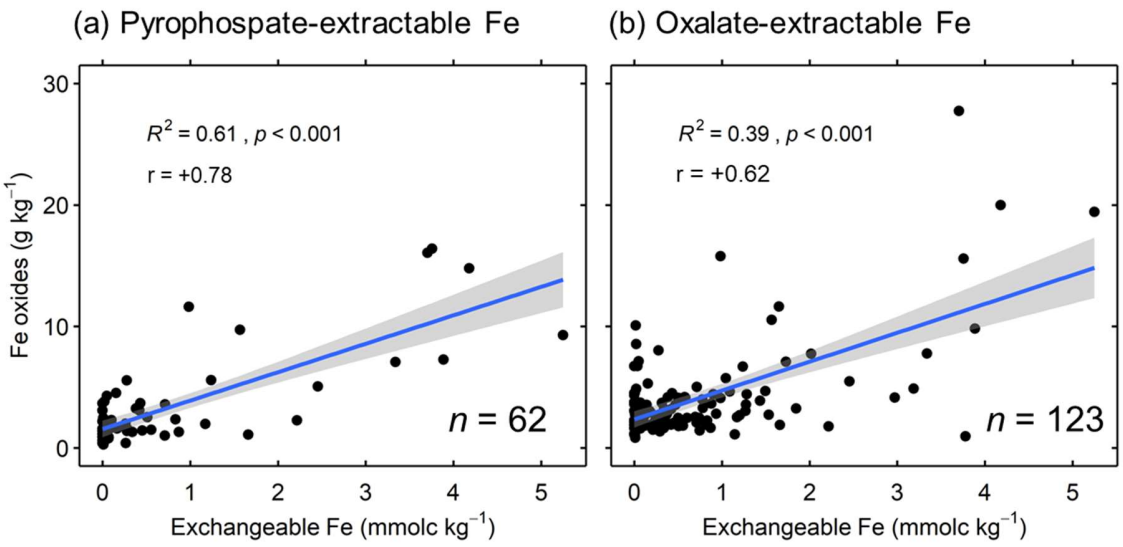

Fig. S6. Relationship between content of exchangeable Fe extracted with NH_4Cl and pedogenic oxides in surface mineral soils (0-30 cm depth). Pyrophospate-extractable Fe (organically bound Fe-oxides) in (a) and oxalate-extractable Fe (poorly crystalline Fe-oxides) in (b) were extracted according to Schwertmann et al. (1987). Plotted lines show significant linear correlations only when significant ($P < 0.05$) with 95% confidence intervals in grey. R^2 values are coefficient of determination, and r is the Pearson correlation coefficient.

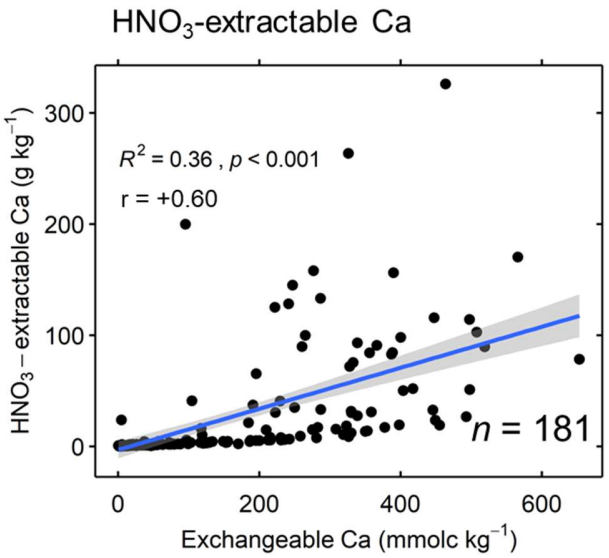

Fig. S7. Relationship between content of exchangeable Ca extracted with NH_4Cl and HNO_3-extractable Ca in surface mineral soils, 0-30 cm depth (n = 181 plots). Plotted lines show significant linear correlations only when significant ($P < 0.05$) with 95% confidence intervals in grey. R^2 values are coefficient of determination, and r is the Pearson correlation coefficient.

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