



1 **Is the content and potential preservation of soil organic**
2 **carbon reflected by cation exchange capacity? A case study**
3 **in Swiss forest soils**

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13

14 **Abstract**

15 The content of organic carbon (C) in soils is not stable, but depends on a number of
16 environmental variables and biogeochemical processes that actively regulate its balance. An
17 improved identification of the environmental variables that can be used as predictors of soil
18 organic C (SOC) content is needed to reduce uncertainties of how the soil C reservoir will
19 respond to environmental change. Although several simulations rely on the amount of clay to
20 reproduce changes in the balance of SOC, recent efforts have suggested that other soil
21 physicochemical properties may serve as better predictors. Here we tested whether the effective
22 cation exchange capacity (CEC eff.), may be a more suitable predictor of the content and
23 potential preservation of SOC as compared to the mere quantification of clay-size particles. We
24 further assessed how various climatic, vegetation and edaphic variables explain the variance of
25 SOC content across different soil depths and soil pH classes. A set of more than 1000 forest



26 sites across Switzerland, spanning a unique gradient of mean annual precipitation (636-2484
27 mm), altitude (277-2207 m a.s.l), pH (2.8-8.1) and representing different geologies and soil
28 orders was used as a case study for this linear model analysis. Our results showed that CEC eff.
29 has the largest explanatory potential of SOC content (35 % of response variance in the complete
30 mineral soil profile) as compared to the amount of clay (which only explained 7 % of the
31 response variance in the complete mineral soil profile) and other environmental variables. CEC
32 eff. is strongly linked to SOC especially in the top mineral soil (0-30 cm depth) with the larger
33 presence of organic matter. At deeper soil depths most of the variance in SOC is instead
34 explained by climate, which in Switzerland is related to a greater weathering activity and
35 translocation of organic C through leaching with increasing mean annual precipitation. We
36 further observed soil pH to have a complex influence on SOC content, with CEC eff. being a
37 dominant variable controlling SOC content at pH >4.5 in the upper mineral soil and pH >6 in
38 the subsoil. Since CEC eff. is an edaphic property which is intimately associated to both the
39 conditions that shaped the soil and the current edaphic physicochemical conditions, these
40 findings indicate that considering CEC eff. as an integrative proxy for the potential preservation
41 of SOC and its alteration could improve future predictions of how the soil C reservoir will feed
42 back to environmental change.

43

44 **1 Introduction**

45 Large uncertainties in our understanding and predictions of how the terrestrial carbon (C) cycle
46 interacts with alterations in the environment exist about the effects on the content of soil organic
47 C (SOC) and its stabilization or destabilization (Jobbágy and Jackson, 2000; Friedlingstein et
48 al., 2014; Jackson et al., 2017; Todd-Brown et al., 2013). To assess the impacts not only of the
49 occurring but also of the forecasted global changes, it is desirable to identify environmental
50 predictors of SOC dynamics (Bailey et al., 2018; Rasmussen et al., 2018; Harden et al., 2018),
51 that match the recent shifts in paradigm of SOC (de)stabilization (Lehmann and Kleber, 2015;



52 Schmidt et al., 2011). Measuring and predicting the content and potential preservation of SOC
53 is elaborate due to the large spatial and temporal scales that are needed to detect changes
54 (Harden et al., 2018; van der Voort et al., 2016). However, the exchange of knowledge between
55 empirical research and simulation models offers great promise to facilitate innovations in C
56 management and programs to reach climate-change mitigation goals, e.g. the ‘4 per mille Soils
57 for Food Security and Climate’ international research program (Minasny et al., 2017).

58 Advances in soil science have demonstrated that the content and preservation of SOC is
59 not controlled by the chemical composition of organic matter alone but is rather predominantly
60 driven by environmental and biological variables (Schmidt et al., 2011; Marschner et al., 2008;
61 Kleber and Johnson, 2010). In this context, the effects of climatic, biotic, and geogenic controls
62 of SOC dynamics have been extensively studied for different spatial and temporal scales
63 (Davidson and Janssens, 2006; Hicks Pries et al., 2017; Jobbágy and Jackson, 2000; Falloon et
64 al., 2011; Liang et al., 2017; Doetterl et al., 2015). Climatic variables generally appear to exert
65 a major control of SOC dynamics and consequently a significant feedback of the terrestrial-C
66 cycle to climate change is expected (Carvalhais et al., 2014; Chen et al., 2013). Biotic activity
67 (plant and microbial) and soil physicochemical variables are additionally contributing to
68 explain the large uncertainties covering the fate of SOC (Doetterl et al., 2015; Schmidt et al.,
69 2011; Rasmussen et al., 2018; Torn et al., 1997).

70 Despite this improved understanding, model frameworks aimed at assessing how SOC
71 responds to environmental change still necessitate the use of proxy variables that represent soil
72 characteristics that cannot be measured (correlative proxies), or that aggregate information
73 about multiple soil characteristics (integrative proxies) (Bailey et al., 2018). To improve
74 projections of the largest actively cycling terrestrial C reservoir to environmental change, recent
75 efforts have hence been focusing on identifying new sets of variables that can be used to
76 determine the content of SOC. For instance, although several biogeochemical models rely on
77 the amount of clay to simulate mineral protection of SOC (Coleman and Jenkinson, 1996;



78 Wieder et al., 2015), Rasmussen et al. (2018) recently suggested that other soil physicochemical
79 properties, such as exchangeable Ca or Fe, and Al oxyhydroxides, can be used as better
80 predictors depending on the local soil pH. Soil pH reflects the chemical state of soil systems,
81 e.g. protonation, controlled by geological and mineralogical properties, and dictates some of
82 the main driving processes of SOC (de)stabilization (Deng and Dixon, 2002; Oades, 1988).
83 Such processes include organo-mineral complexation, solubility and organism activity, which
84 vary with depth across soil profiles (as reviewed by Sollins et al., 1996; Six et al., 2004;
85 Trumbore, 2009).

86 The amount of clay, that is the soil mineral fraction $<2 \mu\text{m}$ in size, influences the content
87 of SOC by promoting the adsorption of organic molecules to its surfaces primarily by the
88 interaction with pedogenic oxides and the aggregation within clay structures (Lützow et al.,
89 2006; Oades, 1988; Eusterhues et al., 2003). Through its control on soil hydrology, oxygen
90 availability as well as soil microbial community, the amount of clay can further indirectly alter
91 SOC preservation (Andrews et al., 2011; Fierer and Schimel, 2002). Due to these properties,
92 the amount of clay is often used as a proxy for sorption on mineral surfaces and aggregation of
93 SOC, especially by more generalized larger scale models (Bailey et al., 2018). Several recent
94 studies, however, did not find the amount of clay to be a predominant physicochemical predictor
95 of SOC content and preservation (e.g. Schrumpf et al., 2013; Rasmussen et al., 2018; Doetterl
96 et al., 2015). A reason for this is likely that the amount of clay merely represents a size class of
97 soil particles rather an equivalent indication of available surface area or aggregate formation. It
98 follows that other soil properties that represent an indication of available soil surfaces may be
99 more appropriate to estimate SOC than clay.

100 An example of a soil property representing an indication of available soil surfaces is the
101 effective cation exchange capacity (CEC eff.). CEC eff. is an edaphic property reflecting
102 geology, mineralogical composition, organic matter and the pH that shapes the soil and its
103 current physicochemical conditions. The CEC eff. of a soil represents the total amount of



104 exchangeable cations such as Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Mn^{2+} , Al^{3+} , Fe^{2+} , H^+ that can be retained
105 through electrostatic adsorption on soil particle surfaces. Soil particles exhibit negative and
106 positive charges that can adsorb oppositely charged ions from the soil solution. In most soils,
107 CEC eff. increases with soil pH. At low pH, it is mainly the permanent charges of the 2:1 type
108 clays that adsorb exchangeable cations, while at higher pH values the negative charges on some
109 1:1-type clays, allophane, Fe- and Al- oxides, and soil organic matter increase, thereby
110 increasing CEC eff. (Weil and Brady, 2016). There are several reasons why CEC eff. may be a
111 better integrative proxy for the content and potential preservation of SOC than others.
112 Quantifying the amount of clay is time-consuming. Determining clay mineralogy is expensive
113 and requires specialized equipment, and quantification can be challenging. The key variables
114 for soil organic matter protection are short range order minerals, Al- and Fe- oxyhydroxides,
115 and Al-, Fe- organo-metal complexes (Rasmussen et al., 2018), which cannot be thoroughly
116 identified and quantified for large sample sets with analytical techniques available today. Soil
117 surface area that has been calculated by using gas adsorption as a proxy for the protective
118 potential of soil and sediment, cannot be measured routinely on large sample sets. On the other
119 hand, CEC eff. is measured routinely to assess soil fertility for agricultural and forest use.

120 Here we ask the question whether CEC eff. can serve as a new integrative proxy of SOC
121 content and its potential preservation, integrating effects of soil surfaces of different clay types,
122 short-range order mineral phases and organic matter at the actual soil pH. Moreover, we are
123 interested in understanding how the variance of SOC content is explained by various
124 environmental variables across different soil depths and soil pH classes. We test this by using
125 a set of more than 1000 forest soil profiles across Switzerland spanning a strong gradient of
126 climate, altitude, geology, soil pH and soil orders (Gosheva et al., 2017).

127

128 **2 Materials and Methods**

129 **2.1 Study area and dataset**



130 The study area covers the complete country of Switzerland (~ 45-47° N, 6-10° E), situated in
131 the centre of Europe. Switzerland offers a wide and intricate range of geology and topography
132 which vary abruptly often within short distances, leading to very diverse soil orders (Walthert
133 et al., 2013; Gosheva et al., 2017). About 30 % of the country (~ 12.000 km²) is covered by
134 forest, and half of this area is located above 1000 m a.s.l. Forest management is mainly practiced
135 at low elevations, where no large-scale clear-cutting is applied and natural regeneration is often
136 fostered by silvicultural management (Brassel and Brändli, 1999). Forest soil fertilization and
137 liming was always forbidden in Switzerland.

138 The dataset analyzed in this study originates from a database of the Swiss Federal
139 Institute for Forest, Snow and Landscape Research (WSL) containing data on 1204 forest sites
140 across Switzerland (for more details see Walthert et al., 2013; and Walthert and Meier, 2017).
141 More than 80% of these sites have been covered for at least 150 years with forests (Gosheva et
142 al., 2017).

143 The variables which we evaluated included SOC content (g kg⁻¹) and other soil
144 physicochemical properties (pH in CaCl₂, CEC eff. (mmolc kg⁻¹) and soil texture) as well as
145 climatic, topographic and vegetation data. In this study we report weighted means of SOC
146 content over fixed depths rather than SOC stocks. This is because SOC content represents a
147 direct measure of SOC after a single correction for the amount of fine earth in pedogenic
148 horizons, while SOC stock estimates required multiple imponderable corrections (Gosheva et
149 al., 2017).

150

151 **2.2 Soil chemical and physical properties**

152 In each forest site a soil profile was sampled by pedogenetic horizons down to a profile depth
153 of 120 cm if possible, otherwise down to parent rock, with six samples per pit on average. Soil
154 samples were dried at 40-60° C and sieved at 2 mm for chemical analyses. SOC content was
155 measured in milled subsamples by dry combustion using a C/N analyser (NC 2500, Carlo Erba



156 Instruments, Italy). Inorganic C was removed in samples with a pH above 6.0 by fumigating
157 with HCl vapour prior to analysis (Walthert et al., 2010). Soil pH was measured
158 potentiometrically in 0.01 M CaCl₂ with a soil - extract ratio of 1:2 after 30 min of equilibration.
159 Exchangeable cations were extracted in an unbuffered solution of 1 M NH₄Cl for 1 h on an end-
160 over-end shaker using a soil - extract ratio of 1:10. The elemental concentrations were
161 subsequently measured with an ICP-AES (Optima 3000, Perkin–Elmer). For soil samples with
162 a pH (CaCl₂) <6.5 concentrations of exchangeable protons were calculated as the difference
163 between the total and the Al-induced exchangeable acidity with the KCl method (Thomas,
164 1982). For soil samples with a higher pH, concentrations of exchangeable protons were
165 assumed to be negligible. The effective cation exchange capacity (CEC eff.) was finally
166 calculated by summing the charge equivalents of exchangeable Na, K, Mg, Ca, Mn, Al, Fe and
167 H. Grain size distribution was measured with the sedimentation method according to Gee and
168 Bauder (1986) for 750 soil profiles. For the remaining soil profiles, we used the field estimates
169 based on ten texture classes from Walthert et al. (2004). We focused on the following soil-depth
170 intervals: 0-30 cm of the mineral soil profile (topsoil), 30-120 cm of the mineral soil profile
171 (subsoil) and for a comprehensive interpretation of the data we also considered the complete
172 mineral soil profile at 0-120 cm. We calculated the mean average content of all the above
173 mentioned soil properties for 0-30 cm, 30-120 cm and 0-120 cm by weighting the averages of
174 the content with the amount of fine earth determined in the pedogenetic horizons of those fixed
175 depth increments, as described in Walthert et al. (2013). Soil type was classified according to
176 the World Reference Base from 2007 (IWG, 2007).

177

178 **2.3 Climatic, topographic and vegetation data**

179 The soil data of each forest site was paired with climatic and vegetation data. Climatic data was
180 based on the Swiss meteorological network (MeteoSwiss), combined with suitable interpolation
181 algorithms (Walthert et al., 2013). Specifically, mean annual precipitation (MAP) and mean



182 annual temperature (MAT) were provided by Meteotest (<https://meteotest.ch/en/>) for the period
183 1981-2010 (for details see Remund et al., 2014). The altitude of the forest sites was extracted
184 from a 25 m digital elevation model (DEM) of the Federal Geo-Information centre swisstopo.
185 For each forest site, the local Leaf Area Index (LAI) a common measure of canopy foliage
186 acting as a control over primary production (Asner et al., 2003), was further estimated according
187 to Schleppei et al. (2011) based on data from a vegetation survey using the Braun-Blanquet cover
188 abundance scale (Braun-Blanquet, 1964; Mueller-Dombois and Ellenberg, 1974).

189

190 **2.4 Statistical analysis**

191 To identify which environmental variable of interest had the greatest prediction power on SOC
192 content in the complete mineral soil profiles (0-120 cm), topsoils (0-30 cm) and subsoils (30-
193 120 cm), we applied linear model analysis. CEC eff., percentage of clay, LAI, MAT and, MAP
194 were treated as explanatory variables while SOC content was treated as main response variable.
195 To meet the normality assumptions of the applied statistical tests and standardize the variation
196 among variables, we transformed the continuous variables to normal distributions applying log-
197 transformations when required, and subsequently standardized them to a mean of 0 and standard
198 deviation of 1. The linear models were checked for multicollinearity using the variance inflation
199 factor (VIF). The value of VIF >4 was set as a threshold for evidence of multicollinearity. We
200 checked the model assumptions using the diagnostic plot functions in R (Crawley, 2012), and
201 the normality of the residuals was tested using histograms. The explanatory power of the
202 variables included in the linear models was computed as the standardized regression coefficient.
203 The more positive or negative the coefficient is, the higher is its relative power in predicting
204 the response variable SOC. We then partitioned the contribution of each of the explanatory
205 variables to the explained variance in SOC employing hierarchical variance partitioning. For
206 this, we used the 'lmg' metric in the R package 'relaimpo' (Groemping and Matthias, 2006),
207 which decomposes R squares into non-negative contributions that automatically sum to the total



208 R squared of the linear model and takes care of the dependence on orderings by averaging over
209 orderings (Grömping, 2006). The contribution of the environmental variables in explaining the
210 variance of SOC was additionally normalized to sum to 100 %, i.e. in place of the total R
211 squared (Groemping and Matthias, 2006). We further performed a linear model analysis of the
212 relative importance of climatic, vegetation and edaphic variables to predict SOC across pH
213 classes at 0-120 cm, 0-30 and 30-120 cm soil depth. Specifically, soil-pH data was grouped into
214 nine consecutive pH ranges: (pH: <4, 4-4.5, 4.5-5, 5-5.5, 5.5-6, 6-6.5, 6.5-7, 7-7.5, >7.5 see
215 Table 1 for the complete pH ranges at the three different depths). The relation between SOC
216 content and all explanatory variables, parsed among different soil depths and pH classes, was
217 also tested using Spearman's correlation coefficient. Significance was evaluated based on
218 Bonferroni's corrected p-values to account for Type I errors. For each statistical test $P < 0.05$
219 was considered to be statistically significant. All analyses were performed with the R statistical
220 software version 3.5.0 (R Core Team, 2018), and the packages 'vegan', 'MASS', 'dplyr',
221 'plyr', 'car', 'quantPsyc', 'caret', 'relaimpo', 'Psych'.

222

223 **3 Results**

224 **3.1 Environmental characteristics of the forest sites**

225 The Swiss forest sites where the soils were sampled are distributed between 277 and 2207 m
226 a.s.l. They are characterized by a mean annual precipitation (MAP) ranging between 636 and
227 2484 mm, and mean annual temperatures (MAT) ranging between 0.1 and 12.0 ° C. MAT and
228 altitude are strongly negatively correlated ($r = -0.97$). The predominant soil types are classified
229 as Cambisols ($n = 365$), Luvisols ($n = 127$) and Gleysols ($n = 89$). About half of the sites are
230 covered by broadleaf tree species while the rest are coniferous forests (Gosheva et al., 2017),
231 with LAI values varying between 2 to 7.2. pH values range from 2.8 to 8.1 and the percentage
232 of clay varies between 0.8 and 75.6 % (for details about specific ranges in topsoils and in the
233 subsoils see Table 1). The parent material of the north of Switzerland is dominated by a



234 calcareous bedrock and sediments, from which alkaline soils have developed. The most acidic
235 soils are instead found in the Southern Alps and parts of the Swiss plateau, in the center of
236 Switzerland (Figure S2). The content of SOC varies between 6 and 376.8 g kg⁻¹ in topsoils
237 (upper 0-30 cm of the mineral soil) and between 0 (lower than detection limit) and 229 g kg⁻¹
238 in subsoils (30-120 cm depth). CEC eff. ranges between 20.4 and 1046.4 mmolc kg⁻¹ in topsoils
239 and between 6.2 and 727.9 mmolc kg⁻¹ in subsoils.

240

241 **3.2 Predictors of soil organic carbon (complete pH range)**

242 All of the explanatory variables except MAT in the topsoil have a significant effect on SOC
243 content when considering the complete pH range (Table 2). The standardized regression
244 coefficients indicate that throughout Switzerland the SOC content increases with increasing
245 CEC eff. and MAP, while decreases with greater MAT, LAI and percentage of clay. The signs
246 of these relations are overall coherent with the sign of significant Pearson's correlations
247 coefficients, with the exception of the correlation between SOC and CEC eff. in the pH range
248 4.5-5 in the subsoil (Fig. 1). The assessment of the relative contribution of the explanatory
249 variables to the explained variance in SOC shows that within the complete mineral soil profile
250 CEC eff. explains most of the response variance in SOC content (35 %), followed by MAP (26
251 %), and smaller significant contributions of explained variance by LAI and MAT (Table 2).
252 Within the topsoil CEC eff. also has the overall strongest influence on SOC accounting for 60
253 % of its variance (Table 2). In subsoils, climatic variables (MAP and MAT) are instead the
254 predominant variables controlling the variance in SOC content (31 and 28 % respectively)
255 (Table 2).

256

257 **3.3 Soil organic carbon across pH classes**

258 SOC content is greater in more alkaline soils with pH >5.5 (Fig. S1). The relative contribution
259 of the explanatory variables to the explained variance in SOC is dependent upon pH (Fig. 1,



260 Fig. 2). For lower pH classes, MAP explains the largest portion of the response variance of
261 SOC content, while CEC eff. explains the greatest portion of variance in more alkaline soils
262 Fig. 3 presents the normalized contribution of MAP, MAT, LAI, percent clay and CEC eff. in
263 explaining the variance of SOC content. The total amount of variance explained (R squared) by
264 each independent linear model across pH classes ranges between 0.76 (0-30cm depth, pH 6-
265 6.5) and 0.11 (30-120 cm depth, pH 5.5-6) (Fig. 4). On average, each pH class contains 125 ± 94
266 (mean \pm SD) forest sites that we could analyze with independent linear models (Fig. 4). The
267 total amount of variance explained by the linear model runs is independent from the number of
268 forest sites included in the models.

269

270 4 Discussion

271

272 4.1 Can the effective cation exchange capacity be used as a proxy for soil 273 organic carbon content?

274 Our linear model analysis indicates that throughout 1204 Swiss forest sites, encompassing a
275 pronounced gradient of climate, geology, soil pH and soil orders, CEC eff. has the largest
276 explanatory potential of SOC content (35 % of response variance in the complete mineral soil
277 profile) as compared to other environmental variables (Table 2). Since CEC eff. is an edaphic
278 property which is intimately associated to both the conditions that shaped the soil and the
279 current physicochemical conditions in the soil, the significant link between CEC eff. and SOC
280 hints towards a potential of this edaphic property to be used as an integrative proxy of the
281 present and future content of SOC. In our evaluation we included a range of climatic, vegetation
282 and edaphic properties, as these variables are commonly regarded as primary controls of SOC
283 (Torn et al., 2009). However, we cannot rule out that our analysis could be biased by the lack
284 of available information on the activity by soil organisms (microbial communities and soil
285 macro- and meso- fauna) (Jackson et al., 2017). The weak relationship between the vegetation



286 property we adopted as an indication of plant primary production (the LAI) and SOC content
287 strongly suggests that the quantity of litter inputs is less important for SOC than
288 physicochemical properties. This is in agreement with mechanistic studies employing isotopic
289 tracers, as well as spectroscopic and molecular techniques (Hagedorn et al., 2003; Marschner
290 et al., 2008; Schmidt et al., 2011). The weak relationship may however also result from the lack
291 of information on the growth of belowground plant biomass as well as on differing
292 decomposition rates of above and belowground plant debris before incorporation into the soil
293 (Hobbie et al., 2010). Nevertheless, the results of our analysis clearly demonstrate that CEC eff.
294 explains a larger portion of the variance in SOC content than the percentage of clay - on which
295 many biogeochemical models rely as a proxy of SOC. Such pattern might be partly related to
296 the contribution of variably charged functional groups of organic matter to CEC eff. but it also
297 corroborates the emerging conceptual understanding that other soil physicochemical properties
298 predict the content and potential persistence of SOC better than the amount of clay (e.g.
299 Rasmussen et al., 2018).

300

301 **4.2 How is the variance of soil organic carbon content explained by** 302 **environmental variables at different soil depths?**

303 In agreement with vast ranging observations showing that SOC content decreases with soil
304 depth (e.g. Jobbágy and Jackson, 2000; Rumpel and Kögel-Knabner, 2011), we observed a
305 higher SOC content in the upper 30 cm of the mineral soil as compared to that found at lower
306 depths (Table 2). This pattern is commonly related to a decline in the inputs of plant-derived
307 organic matter with depth because litterfall from leaves, needles and twigs occurs on the soil
308 surface, and this material is only partially translocated to the subsoil in dissolved form or via
309 bioturbation. Moreover, plant root densities are commonly smaller in subsoils than in topsoils
310 (Jackson et al., 1997). Microbial communities involved in the breakdown of organic matter also
311 vary across depth profiles (e. g. Lindahl et al., 2007). Our linear model analysis demonstrates



312 that CEC eff. is the strongest predictor of SOC in topsoils (explaining 60 % of the total variance
313 in SOC content) while climatic variables (MAT and MAP) are stronger predictors of SOC in
314 subsoils (Table 2). The primary influence of CEC eff. on SOC content in topsoils as compared
315 to deeper soil depths can be attributed to the overall larger presence of organic matter that
316 contributes markedly to a higher number of available negative charges in soils to which cations
317 can bind. The dominant control of climate on the content of SOC in subsoils is instead
318 connected to a significant transport of fresh C to deeper soil depths through leaching of
319 dissolved organic matter (Kaiser and Guggenberger, 2000), which increases with increasing
320 precipitation and a greater accumulation of organic horizons, especially under cool and humid
321 climatic conditions (Gosheva et al., 2017). Analyses of the content of SOC in the soil solution
322 and in the organic debris residing inside and outside aggregates and bound to minerals would
323 be necessary to test these mechanisms across complete soil profiles in Swiss forest sites.

324

325 **4.3 How does soil pH influence the variance of soil organic carbon content** 326 **explained by different environmental variables?**

327 Overall, we observed a significant and complex influence of soil pH on the content of SOC
328 confirming results from previous studies (Rasmussen et al., 2018; Newcomb et al., 2017). Our
329 study provided a unique soil pH gradient (spanning from 2.8 to 8.1, Fig. S2) which largely
330 resulted from the complex topography and orogeny of the territory of Switzerland
331 encompassing various types of parent material, made up of sedimentary, crystalline or
332 metamorphic rocks with highly variable mineralogical compositions (Gosheva et al., 2017). We
333 found that SOC content is higher in more alkaline soils with pH >5.5 (Fig. S1). However, it has
334 to be noted that SOC stocks in Swiss forests are generally not higher in calcareous than acidic
335 soils (Gosheva et al., 2017), indicating that acidic soils e.g. in the South of Switzerland (Fig.
336 S2), have a lower SOC content but are generally deeper. Moreover, our analysis revealed that
337 the relative control of climatic, vegetation and edaphic variables on SOC evolves as a function



338 of soil pH. MAP explained most of the variance in SOC content at low pH (pH <5.5), while
339 CEC eff. was the dominant variable at higher pH values (pH >4.5 in topsoils and pH >6 in
340 subsoils) (Fig. 2).

341 The strong influence of MAP on SOC that we observed at low pH is likely primarily
342 related to the reaction of organic ligands with aluminium cations (Al^{3+}) that often occurs in
343 many soils of regions with a high MAP and thus high water availabilities (Chadwick and
344 Chorover, 2001; Torn et al., 1997; Blaser et al., 1997; Blaser and Sposito, 1987; Eckmeier et
345 al., 2010). Firstly, in acid soils the presence of Al^{3+} cations is commonly associated to the
346 production of organo-metal complexes during the process of weathering. Secondly, a strong
347 chelation of Al^{3+} by organic acids in Swiss forest soils characterized by a high MAP and acid
348 soils, is pointed out by the high levels of exchangeable aluminium (Al^{3+}) found at low pH
349 classes (Fig. S1), and by the observation of the highest MAP regimes in regions with the most
350 acidic soils (Fig. S2, S3). These patterns corroborate previous results showing that the relatively
351 humid climate of the Southern Alps promotes both the formation of pedogenic oxides and the
352 leaching of dissolved organic C from the organic layer to the mineral soil, where organic matter
353 i.e. tannins and other polyphenols forms organo-metal complexes (Eckmeier et al., 2010). The
354 peak in the explanatory power of MAP on the content of SOC at pH 4.5-5 (Fig. 3) is probably
355 related to the greater occurrence of Luvisols and Podzols in this pH range (Fig. S4). These soil
356 orders are characterized by translocation of clay and organic matter.

357 The dominant contribution of CEC eff. in explaining the variance of SOC in higher pH
358 classes can be explained by the established knowledge that the amount of available negative
359 charges to which cations can be bound on organic matter - together as on allophane and some
360 1:1-type clays - increase with rising pH (Weil and Brady, 2016). In particular, the deprotonation
361 of carboxyl and hydroxyl groups present in organic matter has often been observed to contribute
362 markedly to the greater number of available negative charges in soils, and more so at higher pH
363 values (Krishnaswamy and Richter, 2002; Tate and Theng, 1980; Sullivan et al., 2006).



364 Furthermore at pH levels higher than 6 the charges of 2:1-type clays have been observed to
365 increase due to a deprotonation of exposed hydroxyl functional groups (Tournassat et al., 2016).

366

367 **5 Conclusions**

368 In conclusion, our study of Swiss forest soils provides a first indication that CEC eff. could be
369 used as an integrative proxy of SOC content and its potential preservation. Determining whether
370 CEC eff. is an effective proxy for the content of SOC also in non-forested ecosystems and in
371 other geographical locations would be a further step forward to test its broad applicability in
372 Earth System models. This information could be compiled starting from available soil profile
373 samples, soil surveys and monitoring programs at the country, continental or climatic zone level
374 (e.g. <http://icp-forests.net/>, <http://ncsslabdatamart.sc.egov.usda.gov/>). Some global gridded
375 data about CEC. eff has also already been derived (Hengl et al., 2017) by the international soil
376 reference and information center ISRIC. We observed that CEC eff and SOC are closely linked
377 especially in the top mineral soil (0-30 cm depth) as compared to deeper depths. This is due to
378 the overall larger presence of organic matter contributing to a higher number of available
379 negative charges in topsoils. In subsoils most of the variance in SOC is instead explained by
380 climate, which in our study is potentially related to increasing weathering and transport of fresh
381 C to greater soil depths through leaching of dissolved organic matter with increasing MAP. Soil
382 pH strongly affects the explanatory power of CEC eff. on the content of SOC in Swiss forest
383 soils, with CEC eff. being the dominant variable at pH >4.5 in topsoils and pH >6 in subsoils.
384 Since 73% of the land surface is covered by soils with pH >5.5 (area calculated according to
385 the global pH dataset IGBP-DIS (1998)) the consideration of CEC eff. as an integrative proxy
386 for the potential alterations of SOC content could strengthen our ability to predict future
387 changes in the belowground C reservoir.

388



389 **Author contributions**

390 MWIS, SZ, FH conceived the idea of this analysis, SZ and LW provided and quality checked
391 the data, EFS developed the ideas for this manuscript and considering the preliminary analyses
392 by VW defined the final statistical approach. EFS prepared and wrote the manuscript with
393 contributions from all co-authors.

394

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405

406 **Competing interests**

407 The authors declare no competing interests.

408

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**Figures:**

Fig. 1: Pearson's correlations between the content of SOC and explanatory variables for (a) complete mineral soil profiles (0-120 cm depth), (b) topsoils (0-30 cm depth), (c) subsoils (30-120 cm depth). MAP, mean annual precipitation (mm), MAT, mean annual temperature (°C), LAI, leaf area index, clay, percentage of clay (%), CEC, effective cation exchange capacity (mmolc kg⁻¹). Those correlations with $P > 0.05$ are considered not significant (NS) based on Bonferroni's correction.

Fig. 2: Amount of explained variance by climatic, vegetation and edaphic variables in predicting the content of SOC (g kg⁻¹) across pH classes for (a) complete mineral soil profiles (0-120 cm depth), (b) topsoils (0-30 cm depth), (c) subsoils (30-120 cm depth). Horizontal bars show the amount of variance explained by each variable (R squared) in the linear models as calculated using the 'lmg' metric in the R package 'relaimpo'. Significant variables (p -value < 0.05) are marked by an asterisk (*). MAP, mean annual precipitation (mm), MAT, mean annual temperature (°C), LAI, leaf area index, clay, percentage of clay (%), CEC, effective cation exchange capacity (mmolc kg⁻¹). The total amount of variance explained (R squared) by each independent linear model is presented in Fig. 4 together with the number of samples used.

Fig. 3: Relative contribution (percentage of R squared) of climatic, vegetation and edaphic variables in predicting the content of SOC across pH classes, for (a) complete mineral soil profiles (0-120 cm depth), (b) topsoils (0-30 cm depth), (c) subsoils (30-120 cm depth). The response variance explained by each environmental variable was normalized to sum to 100 %. MAP, mean annual precipitation (mm), MAT, mean annual temperature (°C), LAI, leaf area index, clay, percentage of clay (%), CEC, effective cation exchange capacity (mmolc kg⁻¹).

Fig. 4: (a) Number of samples and (b) total variance explained (R squared) by each independent linear model as presented in Fig. 1.



Fig. 1:

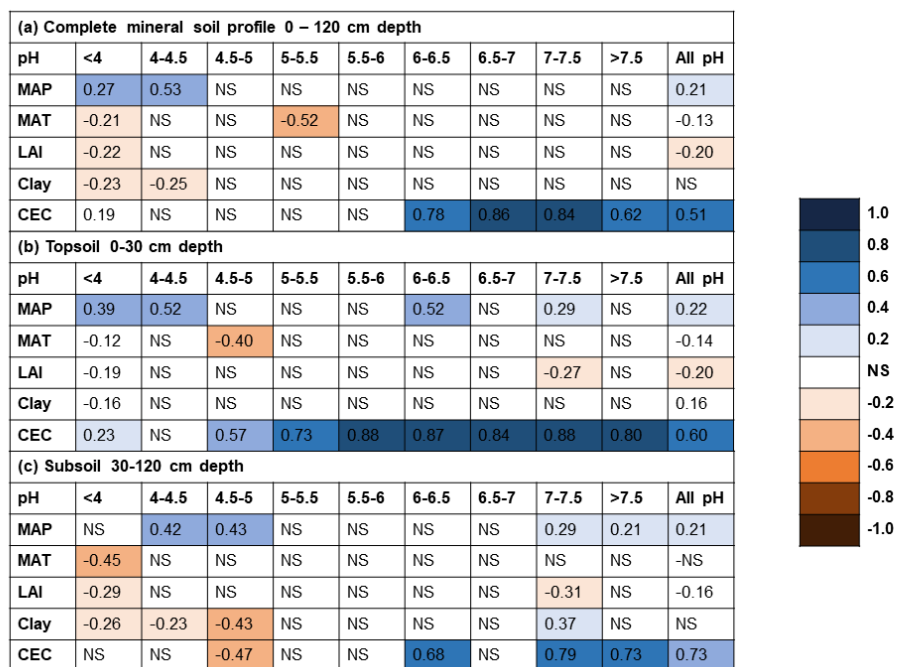




Fig. 2:

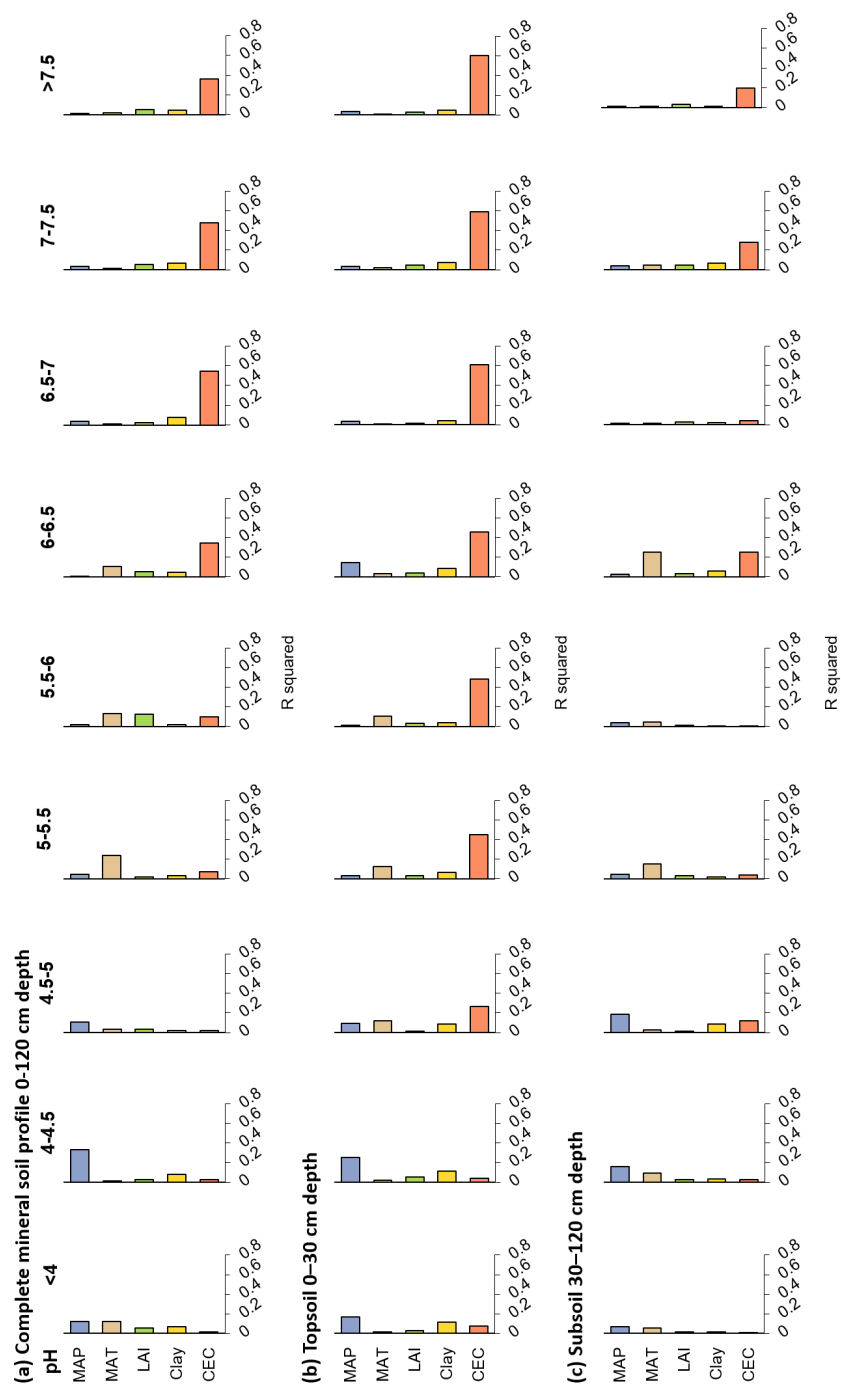




Fig. 3:

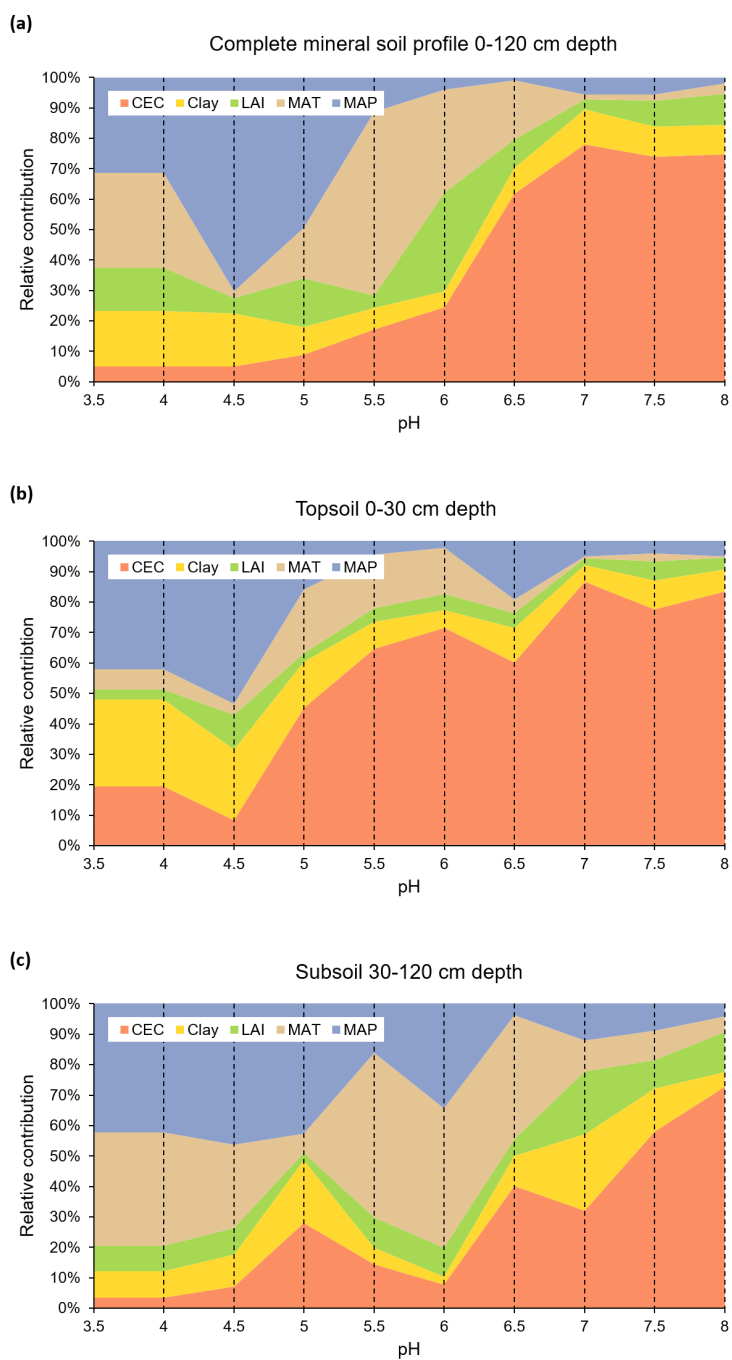




Fig. 4:

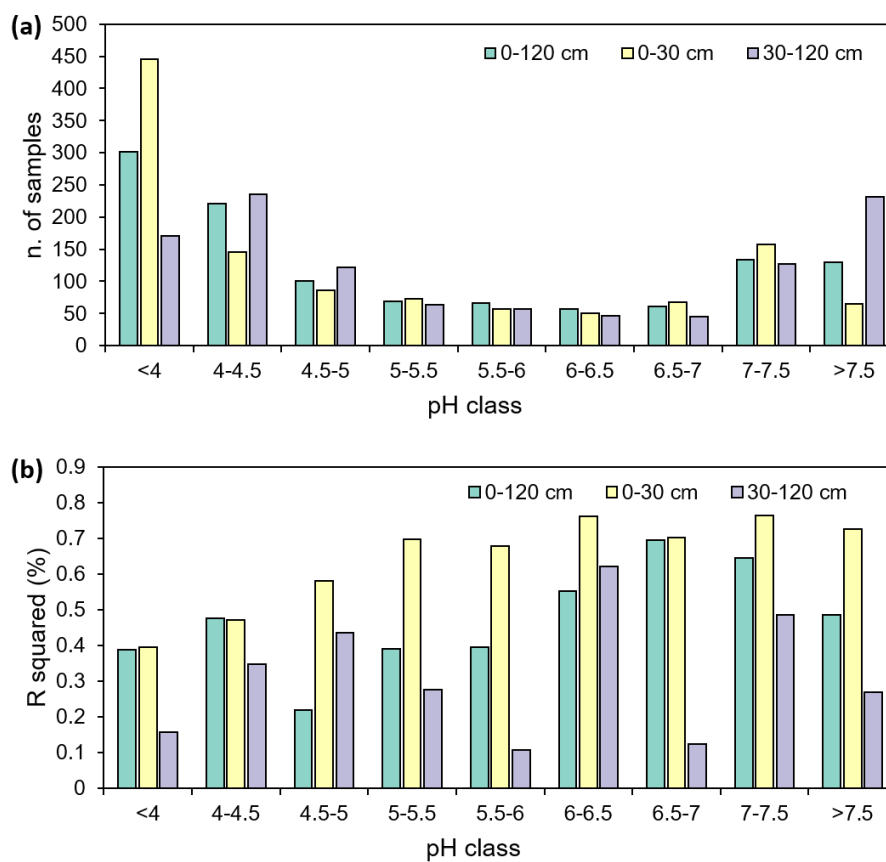




Table 1: Range of climatic, vegetation and edaphic variables for complete mineral soil profiles (0-120 cm depth), topsoils (0-30 cm depth) and subsoils (30-120 cm depth). MAP, mean annual precipitation; MAT, mean annual temperature; LAI, leaf area index; SOC, soil organic carbon content, CEC eff., effective cation exchange capacity.

Soil depth	0-120 cm	0-30 cm	30-120 cm
MAP (mm)	636-2484		
MAT (°C)	0.1-12.0		
Elevation (m a.s.l.)	277-2207		
LAI	2-7.2		
SOC (g kg ⁻¹)	1.3-376.8	6.0-376.8	0-229.0
CEC eff. (mmolc kg ⁻¹)	11.4-753.2	20.4-1046.4	6.2-727.9
Clay (%)	1.2-74.7	1.5-74.6	0.8-75.6
pH	3.0-8.0	2.8-8.0	3.0-8.1



Table 2: (a) Standardized coefficients indicating explanatory power of climatic, vegetation and edaphic variables in predicting the content of SOC, and (b) amount of variance (% of R squared) explained by the explanatory variables for complete mineral soil profiles (0-120 cm depth), topsoils (0-30 cm depth) and subsoils (30-120 cm depth). The R squared of metrics is normalized to sum to 100 %. MAP, mean annual precipitation; MAT, mean annual temperature; LAI, leaf area index; CEC eff., effective cation exchange capacity; n., number of samples; NS, non significant.

	Complete pH range		
Depth (cm)	0-120	0-30	30-120
(a) Standardized regression coefficients in predicting SOC (g kg⁻¹)			
MAP (mm)	0.31	0.30	0.26
MAT (°C)	-0.14	NS	-0.18
LAI	-0.16	-0.13	-0.11
Clay (%)	-0.26	-0.26	-0.23
CEC eff. (mmolc kg ⁻¹)	0.48	0.66	0.32
R squared	0.26	0.39	0.17
n.	1138	1146	1099
(b) Relative importance (% of R squared) in predicting SOC (g kg⁻¹)			
MAP (mm)	26	18	31
MAT (°C)	15	4	28
LAI	17	9	7
Clay (%)	7	9	17
CEC eff. (mmolc kg ⁻¹)	35	60	17