

# Vascular plant-mediated controls on atmospheric carbon assimilation and peat carbon decomposition under climate change

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► **To cite this version:**

Konstantin Gavazov, Remy Albrecht, Alexandre Buttler, Ellen Dorrepaal, Mark Garnett, et al.. Vascular plant-mediated controls on atmospheric carbon assimilation and peat carbon decomposition under climate change. *Global Change Biology*, Wiley, 2018, 24 (9), pp.3911-3921. 10.1111/gcb.14140 . insu-01744835

**HAL Id: insu-01744835**

**<https://hal-insu.archives-ouvertes.fr/insu-01744835>**

Submitted on 28 Nov 2019

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1       **Vascular plant-mediated controls on atmospheric carbon assimilation and**  
2                                   **peat carbon decomposition under climate change**

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4                                   Running head: Vascular plants and peat carbon cycling

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### 34 **KEYWORDS**

35 climate warming, decomposition, ecosystem respiration, net ecosystem CO<sub>2</sub> exchange, peatlands,  
36 rhizosphere priming, vascular plant biomass, elevation gradient

37

38 **Paper type: PRIMARY RESEARCH ARTICLE**

39 **Abstract**

40 Climate change can alter peatland plant community composition by promoting the growth of  
41 vascular plants. How such vegetation change affects peatland carbon dynamics remains,  
42 however, unclear. In order to assess the effect of vegetation change on carbon uptake and release,  
43 we performed a vascular-plant removal experiment in two *Sphagnum*-dominated peatlands that  
44 represent contrasting stages of natural vegetation succession along a climatic gradient. Periodic  
45 measurements of net ecosystem CO<sub>2</sub> exchange revealed that vascular plants play a crucial role in  
46 assuring the potential for net carbon uptake, particularly with a warmer climate. The presence of  
47 vascular plants, however, also increased ecosystem respiration, and by using the seasonal  
48 variation of respired CO<sub>2</sub> radiocarbon (bomb-<sup>14</sup>C) signature we demonstrate an enhanced  
49 heterotrophic decomposition of peat carbon due to rhizosphere priming. The observed  
50 rhizosphere priming of peat carbon decomposition was matched by more advanced humification  
51 of dissolved organic matter, which remained apparent beyond the plant growing season. Our  
52 results underline the relevance of rhizosphere priming in peatlands, especially when assessing the  
53 future carbon sink function of peatlands undergoing a shift in vegetation community composition  
54 in association with climate change.

55

## 56 INTRODUCTION

57 Peatlands are formed under climatic, hydrological and biological conditions that suppress the  
58 decomposition of plant litter, resulting in the accumulation of organic matter as peat. The  
59 imbalance between litter production and decomposition makes peatlands effective long-term  
60 sinks of atmospheric carbon (Yu, 2012). Indeed, despite a distribution limited to c. 3% of the  
61 Earth's land surface, peatlands contain c. 30% of its soil carbon (Yu, 2012). In northern  
62 peatlands, *Sphagnum* mosses play a crucial role in peat accumulation due to the production of  
63 litter particularly resistant to microbial decomposition (Hájek *et al.*, 2011). However, alteration of  
64 the hydrological balance (Talbot *et al.*, 2014; Munir *et al.*, 2015), increase in nitrogen availability  
65 (Bubier *et al.*, 2007; Juutinen *et al.*, 2010) and, more specifically, climate warming (Weltzin *et*  
66 *al.*, 2000; Dieleman *et al.*, 2015) can promote the growth and cover of vascular plants in  
67 peatlands. Such increase in the abundance of vascular plants can potentially reduce the  
68 productivity of *Sphagnum* mosses due to, for example, lower light availability (Chong *et al.*,  
69 2012) and increasing evapotranspiration (Hirano *et al.*, 2016). In addition, considering that the  
70 decomposition rate of vascular plant litter is much faster than that of *Sphagnum* mosses  
71 (Dorrepaal, 2007), it is crucial to clarify the role of a higher vascular plant biomass, particularly  
72 with a warmer climate, with reference to the capability of the system to act as carbon sink  
73 (Breeuwer *et al.*, 2010; Ward *et al.*, 2013; Wang *et al.*, 2015).

74 From a belowground biogeochemical perspective, the presence of vascular plants can supply  
75 soil microbes with labile carbon substrates via rhizosphere exudates, providing additional energy  
76 to invest in decomposition of old organic matter (Fontaine *et al.*, 2007; Schmidt *et al.*, 2011): a  
77 process known as the priming effect (Kuzyakov, 2010). Nevertheless, it is still unknown whether  
78 the priming effect in peatlands is directly linked to the abundance of vascular plants, and whether

79 the priming effect shows any seasonal trend, particularly in relation to plant phenology.  
80 Answering these questions can help to better predict how climate warming will alter the carbon  
81 cycle of northern latitude peatlands when vascular plants become more abundant (Dieleman *et*  
82 *al.*, 2015) and the length of the growing season increases (Piao *et al.*, 2008).

83 To investigate the role of vascular plants in the seasonal net assimilation of atmospheric  
84 carbon and in the decomposition of peat carbon under contrasting climatic conditions, we  
85 performed a vascular plant-removal experiment in two *Sphagnum*-dominated peatlands that were  
86 located at different elevations and thereby naturally differed in mean annual temperature,  
87 growing season length and vascular plant abundance (Table 1). As such, the comparison of our  
88 study sites should be interpreted as a space-for-time substitution (Blois *et al.*, 2013), whereby the  
89 low elevation peatland represents the ecosystem state resulting from a natural response of  
90 vegetation to warmer climate compared to the upslope site (Klaus, 2007). During a full growing  
91 season, we periodically measured the net ecosystem CO<sub>2</sub> exchange (NEE), the ecosystem  
92 respiration (R<sub>eco</sub>) and its radiocarbon signature, and the humification degree of dissolved organic  
93 matter in order to: 1) assess the role of vascular plants in assimilation of atmospheric CO<sub>2</sub>  
94 compared to *Sphagnum* mosses under contrasting climatic conditions; and 2) detect any temporal  
95 link between the presence of vascular plants and enhanced decomposition of peat through  
96 rhizosphere priming and the associated carbon release into both the atmosphere and pore water.

97

## 98 **MATERIAL AND METHODS**

### 99 **Study sites and experimental design**

100 We selected two *Sphagnum*-dominated peatlands located at 1035 m and 1885 m a.s.l. in  
101 Switzerland (Table 1, Table S1). At both sites, dominant vascular plant species were *Eriophorum*

102 *vaginatum*, *Calluna vulgaris* and *Vaccinium* spp., whereas *Sphagnum magellanicum*, *S.*  
103 *capillifolium* and *S. fallax* were the dominant peat moss species (Gavazov *et al.*, 2016). Peat  
104 depth was estimated to be > 1.5 m.

105 At each site, six paired 40x40 cm plots were selected in midsummer 2013. To study the effect  
106 of vascular plants on peat decomposition, we clipped the aboveground biomass of vascular plants  
107 in half of the plots (-V treatment) without disturbing the moss layer, and left the belowground  
108 roots to decompose until measurements commenced the following year (cf. Ward *et al.*, 2009;  
109 Kuiper *et al.*, 2014). We started the field measurements after one year in order to allow the  
110 decomposition of most living roots, in particular the most labile fine roots. Due to the low rate of  
111 root decomposition in peatlands (Laiho *et al.*, 2004; Moore *et al.*, 2007), we are aware that root  
112 biomass did not completely decompose after one year, but the delay of one year in field  
113 measurements after biomass removal is, however, expected to have significantly reduced the  
114 belowground carbon allocation and root exudation in clipped plots. Vascular plants were left  
115 intact in paired control plots (+V treatment) so that our experimental set-up represents a paired-  
116 plot design with three replicates. Individual plots were delimited by 10 cm high quadratic  
117 stainless steel frames pushed to c. 5 cm depth in the living moss layer, which served as collars for  
118 gas flux measurements (see below). At regular intervals during 2013, all plots were trenched  
119 along the collars with a 30-cm long knife to avoid root colonisation. In the -V treatments vascular  
120 plant regrowth was regularly clipped in 2013, whereas no or very limited regrowth was observed  
121 in 2014. Because our primary aim was to study the biogeochemical role of vascular plants on  
122 carbon cycling, we decided to limit any secondary effects associated with vascular plant removal  
123 by shading the clipped plots (-V) with a UV-resistant mesh simulating the original vascular plant  
124 cover as preliminarily measured by photosynthetically active radiation (PAR) extinction

125 underneath the canopy (60% and 30% at low and high elevation, respectively). By doing so, the  
126 presence of a mesh avoided the desiccation of peat mosses, maintained the natural PAR intensity,  
127 and avoided changes in soil microclimate. During gas exchange measurements this mesh was  
128 instead used over the chamber to maintain the natural light intensity. Ancillary measurements of  
129 soil temperature and soil water content in the clipped and control plots at both elevations  
130 confirmed the suitability of this approach (Table S2).

131

### 132 **Plant biomass and cover estimations**

133 In each peatland, total aboveground vascular plant biomass was estimated by destructively  
134 harvesting five random 25x25 cm quadrats at peak standing biomass in 2013. Vascular plant  
135 cover within the experimental plots was estimated non-destructively with the point-intercept  
136 method. In brief, a pin was lowered over the vegetation through a 40x40 cm grid with 361 holes  
137 and the identity of the first intercepted plant was recorded. Species were attributed to one of the  
138 existing five categories: graminoids, shrubs, forbs, *Sphagnum spp.* mosses and standing litter,  
139 where the total surface cover equals 100%. Control plots (+V) as well as vascular plant removal  
140 plots (-V) had 100% *Sphagnum* cover.

141

### 142 **CO<sub>2</sub> flux measurements**

143 In 2014, one year after the start of the vascular plant removal treatment, a series of monthly CO<sub>2</sub>  
144 flux measurements were carried out during the snow-free period at each peatland starting in mid-  
145 April at 1035 m a.s.l. and in mid-June at 1885 m a.s.l. and lasting through to the end of October.  
146 CO<sub>2</sub> fluxes at ecosystem level were measured using a custom made transparent (95% light  
147 transmission) Plexiglas chamber (40x40 cm wide, 50 cm high) equipped with a diffusion infrared



148 gas analyser (GMP343, Vaisala, Finland) and a humidity-temperature probe (HMP57, Vaisala,  
149 Finland). Air inside the chamber was mixed with a system of inbuilt computer fans. The chamber  
150 had a rubber seal on the bottom and a small capped hole on the top which remained open when  
151 the chamber was placed on the permanent stainless-steel collar to avoid pressurisation. Net  
152 ecosystem CO<sub>2</sub> exchange (NEE) measurements were done in full light or and were immediately  
153 followed by ecosystem respiration (R<sub>eco</sub>) measurements for which the chamber was darkened  
154 with a non-transparent cover. All flux measurements were carried out between 10 am and 12 am  
155 local time, ensuring optimal photosynthetic conditions for both *Sphagnum* and vascular plants  
156 (Bragazza *et al.*, 2016) with vapour-pressure deficit (VPD) below 1.5 kPa and PAR intensity  
157 above the vegetation canopy between 1400 and 2100  $\mu\text{mol m}^{-2} \text{s}^{-1}$ . Each measurement lasted 1  
158 minute in order to avoid excessive heat and humidity causing condensation inside the chamber.  
159 The CO<sub>2</sub> flux was calculated as a linear change in concentration (ppm), taking into account  
160 ambient atmospheric pressure and gas temperature. In this study, negative NEE represents a net  
161 CO<sub>2</sub> assimilation by the plant community and the calculated gross ecosystem productivity (GEP)  
162 was derived from the difference between R<sub>eco</sub> and NEE.

163

#### 164 **Radiocarbon analysis and age interpretation**

165 To determine the seasonal contribution of vascular plant-associated R<sub>eco</sub>, we sampled respired  
166 CO<sub>2</sub> for radiocarbon analysis in both the clipped and unclipped plots in July and at the end of  
167 September 2014 (Table S3). We used a passive CO<sub>2</sub> sampling method to determine the  
168 radiocarbon signature of ecosystem respiration (Garnett *et al.*, 2009). In brief, specific PVC  
169 chambers (10 cm diameter, 10 cm height) connected to a zeolite molecular sieve cartridge (MSC)  
170 were gas-tight mounted on collars of similar size pre-installed in 2013 in each plot at 7 cm depth.

171 Prior to sample collection, the atmospheric CO<sub>2</sub> in the chamber headspace was scrubbed by  
172 pumping it at a constant rate (0.5 l min<sup>-1</sup>) through a soda lime column for 10 min while  
173 monitoring the concentration. The chambers were then left in place for 10 days until, based on  
174 CO<sub>2</sub> production rates, a sufficient amount of CO<sub>2</sub> (i.e. ≥ 3 ml) was passively trapped on the  
175 MSCs by diffusion without the use of an external pump. The trapped CO<sub>2</sub> was thermally  
176 recovered (425 °C) while purging with high-purity nitrogen gas, converted to graphite by Fe/Zn  
177 reduction and analysed by acceleration mass spectrometry (AMS) at the NERC Radiocarbon  
178 Facility in Scotland, UK (Garnett & Murray, 2013). Subsamples of CO<sub>2</sub> were measured on a dual  
179 inlet stable isotope mass spectrometer (Thermo Fisher Delta V) to determine their δ<sup>13</sup>C signature.

180 In addition, we evaluated the apparent carbon accumulation rate at the two peatlands by  
181 splitting one 20-cm long peat core from each site into 5 cm segments. From these segments,  
182 vascular plant remnants were removed, after which the carbon content, peat density and peat age  
183 were determined (Table S4). After the combustion of these samples in a high-pressure bomb in  
184 the presence of oxygen, CO<sub>2</sub> was converted to graphite as above. The peat age was estimated by  
185 matching the <sup>14</sup>C content with a known record (Levin *et al.*, 2013) of atmospheric <sup>14</sup>CO<sub>2</sub> in order  
186 to estimate the date of carbon fixation (Goodsite *et al.*, 2001) according to Cali-Bomb program  
187 for post-bomb <sup>14</sup>C samples (see Reimer *et al.*, 2004).

188 Following convention (Stuiver & Polach, 1977), all radiocarbon data were corrected for mass  
189 dependent fractionation by normalising to δ<sup>13</sup>CVPDB values of -25‰ using the measured δ<sup>13</sup>C  
190 values, and reported as %Modern with reference to the Oxalic Acid international radiocarbon  
191 standard. These data (Table S3) were not subjected to further corrections for atmospheric air  
192 contamination during chamber enclosure (Czimczik *et al.*, 2006; Natali *et al.*, 2011; Hartley *et*  
193 *al.*, 2012; Hicks Pries *et al.*, 2013) as the fraction of atmospheric CO<sub>2</sub> in the recovered samples

194 proved low and subsequent  $^{14}\text{C}$  corrections remained within the AMS measurement uncertainty  
195 ( $\pm 0.5\%$ Modern).

196 To distinguish between vascular plant-derived respiration and respiration from peat induced  
197 by the presence of vascular plants (i.e. the rhizosphere priming effect), we made a common-  
198 practice assumption that vascular plants respire contemporary carbon with a  $^{14}\text{C}$  signature  
199 identical to the current atmosphere (Subke *et al.*, 2011; Hartley *et al.*, 2012), whereas subsurface  
200 peat respire older carbon (Hardie *et al.*, 2007), which has become very likely incorporated  
201 during the post-1963 bomb- $^{14}\text{C}$  spike at our studied sites (Table S3). Experimental evidence from  
202 peatlands dominated by herbaceous vegetation supports this assumption for vascular plant shoots  
203 (Czimczik *et al.*, 2006; Hicks Pries *et al.*, 2013), and further indicates only a small contribution  
204 of carbon fixed in the preceding year (i.e. up to 0.7 %Modern enrichment) for roots (Hicks Pries  
205 *et al.*, 2013, 2015). A sensitivity analysis confirmed that our conclusions were robust regardless  
206 of whether we used current year atmospheric  $^{14}\text{C}$  values or those from the preceding year. We  
207 used data from the nearby Jungfraujoch (53°20' N, 9°54' W, 3580 m a.s.l.) long-term atmospheric  
208  $^{14}\text{C}$  monitoring station (Levin *et al.*, 2013) to calculate a mean seasonal value (June, July, August  
209 and September) for the expected vascular plant-derived  $^{14}\text{C}$  signature for the 2014 growing  
210 season, which was 102.91 %Modern  $^{14}\text{C}$ . Elevation differences between the study sites and the  
211  $^{14}\text{C}$  monitoring station at the Jungfraujoch are expected not to affect the  $^{14}\text{C}$  values due to  
212 atmospheric mixing (Levin *et al.*, 2008). To this value, we compared the  $^{14}\text{C}$  signature of the  
213 vascular plant-associated respiration ( $D_{\text{V\_plant\_associated}}$ ) in our experiment. Following Hardie *et al.*  
214 (2009), the latter was calculated using a two pool mixing model:

$$215 \quad D_{\text{V\_plant\_associated}} = (D_{+V} \cdot R_{+V} - D_{-V} \cdot R_{-V}) / (R_{+V} - R_{-V})$$

216 where R represents the rate of ecosystem respiration measured on the day of chamber enclosure  
217 and D its  $^{14}\text{C}$  signature in plots with (+V) and without (-V) vascular plants. The vascular plant-  
218 associated respiration in our experiment consisted of vascular plant-derived respiration and,  
219 potentially, of vascular plant-induced peat respiration. A significant deviation in the calculated  
220  $^{14}\text{C}$  signature of vascular plant associated respiration from that of the expected vascular plant-  
221 derived  $^{14}\text{C}$  signature (ambient atmosphere) was interpreted as an extra source of heterotrophic  
222 peat respiration in the presence of vascular plants, i.e. the rhizosphere priming effect.

223

#### 224 **Pore-water sampling and chemical analyses**

225 Representative pore-water samples were collected monthly during May-October 2014 from four  
226 permanent microporous (0.20  $\mu\text{m}$ ) rhizons (Rhizosphere Research Products, The Netherlands)  
227 installed in each plot at the rooting depth, i.e. from 5 to 15 cm below the surface. Concentration  
228 of ammonium ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ) were obtained colorimetrically on a continuous-flow  
229 autoanalyser (SEAL Analytical, Germany), whereas total nitrogen (TN) and dissolved organic  
230 carbon (DOC) were determined by combustion on a Shimadzu analyser (TOC-V CPHCTNM-1).  
231 In order to characterise the quality of dissolved organic matter (DOM) and its level of  
232 humification, lyophilised subsamples were analysed on a Frontier FT-NIR/MIR Spectrometer  
233 (PerkinElmer, USA). The recorded spectra (4000 to 400  $\text{cm}^{-1}$ ) of diamond attenuated total  
234 reflectance provide information on the DOM functional groups aliphatics (2943  $\text{cm}^{-1}$  region),  
235 carboxylic acids and aromatic esters (1720  $\text{cm}^{-1}$  region), aromatics (1630  $\text{cm}^{-1}$  region), lignins  
236 (1510  $\text{cm}^{-1}$  region), phenols (1420  $\text{cm}^{-1}$  region), and polysaccharides (1090  $\text{cm}^{-1}$  region)  
237 (Niemeyer *et al.*, 1992; Biester *et al.*, 2014). During peat decomposition, substances enriched in  
238 carboxylic, aromatic and phenolic groups accumulate with respect to labile polysaccharides,

239 thereby increasing the specific ratios between these moieties (Biester *et al.*, 2014). Commonly  
240 referred to as humification indices, the ratios 2943/1090, 1720/1090, 1630/1090, 1510/1090,  
241 1420/1090 can be used as an indication of the level of organic matter decomposition (Broder *et*  
242 *al.*, 2012; Hodgkins *et al.*, 2014).

243

#### 244 **Statistical analysis**

245 Data on seasonal CO<sub>2</sub> fluxes and pore-water chemistry were analysed as a paired-plot design for  
246 the effect of vascular plant removal in each peatland. The hierarchical structure was coded in  
247 R3.3 (R Core Team, 2016) as a linear mixed-effects model using the *nlme* package (Pinheiro *et*  
248 *al.*, 2016), accounting for the spatial proximity of +V (control) and -V (clipped) pairs and the  
249 repeated measurements in individual plots. Assumptions of normality and homoscedasticity of  
250 the residuals in all final models were verified visually using diagnostic plots, and the simplest  
251 models were retained by pooling non-significant interactions with the error term. Comparisons  
252 between the radiocarbon signature of the atmosphere and the estimated vascular plant-associated  
253 CO<sub>2</sub> were done in R using One Sample t-tests for each site and sampling date.

254

#### 255 **RESULTS**

256 The main hydrological (water-table depth) and hydro-chemical (water pH and electrical  
257 conductivity) parameters were comparable between the two peatlands and overall typical of  
258 ombrotrophic peatlands, i.e. rain-fed bogs (Table 1). The main differences between the two sites  
259 were related to climatic conditions and abundance of vascular plants, with characteristically  
260 higher air temperature, lower precipitation and higher shrub biomass at low elevation (Table 1,  
261 Table S1). Because the cover of peat mosses at plot level did not differ between the two sites

262 (100% at both sites), the study sites can be regarded as a natural climate change experiment  
263 where the natural climatic gradient resulted in similar plant community composition, but with  
264 different abundance of vascular plants in response to soil microclimate (Table 1, Table S2).

265 Overall, the net ecosystem exchange of atmospheric carbon (i.e., NEE) was weaker (i.e.  
266 smaller sink capacity) at low elevation with warmer climatic conditions ( $F_{1,4} = 15.5$ ,  $P = 0.017$ )  
267 despite the larger vascular plant biomass (Fig. 1a). Nevertheless, in both peatlands the presence  
268 of vascular plants (+V treatment) increased ( $F_{1,35} = 19.4$ ,  $P < 0.001$ ) the net CO<sub>2</sub> assimilation by  
269 c. 50% compared to the treatment with *Sphagnum* mosses alone (-V treatment) (Fig. 1a).  
270 Furthermore, at low elevation the absence of vascular plants prevented a net assimilation of  
271 atmospheric carbon during most of the growing season (Fig. 1a).

272 During the peak of the growing season, vascular plants contributed to about 50% to gross  
273 photosynthesis at both elevations (Fig. 1b) as indicated by the two-fold reduction of potential  
274 gross ecosystem productivity (GEP) upon vascular plant removal ( $F_{1,35} = 50.2$ ,  $P < 0.001$ ).  
275 Although vascular plant biomass was significantly larger at low elevation (Table 1), the GEP was  
276 similar at both sites in the presence of vascular plants (+V). In the absence of vascular plants (-  
277 V), GEP of *Sphagnum* mosses was also comparable between the two sites (Fig. 1b).

278 Overall, ecosystem respiration ( $R_{\text{eco}}$ ) was slightly larger at low elevation as compared to high  
279 elevation site ( $F_{1,4} = 6.4$ ,  $P = 0.064$ ) and at both sites the presence of vascular plants increased  
280  $R_{\text{eco}}$  ( $F_{1,35} = 46.9$ ,  $P < 0.001$ ) (Fig. 1c). By taking into account the CO<sub>2</sub> flux and the  
281 corresponding <sup>14</sup>C signature in plots with and without vascular plants, the two-pool mixing model  
282 revealed that late in the growing season the vascular plant-associated respiration was more  
283 enriched in bomb-<sup>14</sup>C than would be expected from autotrophic contributions alone at both low  
284 ( $t_{1,2} = 8.8$ ,  $P = 0.006$ ) and high ( $t_{1,2} = 2.7$ ,  $P = 0.053$ ) elevation (Fig. 2). An enrichment in bomb-

285  $^{14}\text{C}$  likely occurred also during the peak of the growing season in July (Fig. 2); however, it was  
286 masked by larger variability at both low ( $t_{1,2} = 1.4$ ,  $P = 0.153$ ) and high elevation ( $t_{1,2} = 1.9$ ,  $P =$   
287 0.096).

288 On the basis of pore-water chemistry, the peatland at low elevation was characterized by a c.  
289 30% greater concentration of dissolved organic carbon (DOC) (Table 1). Furthermore, the FT-IR  
290 spectroscopy demonstrated that the presence of vascular plants (+V) was associated with a  
291 consistently higher humification of dissolved organic matter in both peatlands. This was  
292 indicated by higher concentrations of aliphatic, carboxylic, aromatic, lignin, and phenolic  
293 compounds in proportion to more labile polysaccharides (Fig. 3).

294

## 295 **DISCUSSION**

296 Our net ecosystem exchange (NEE) measurements under optimal conditions and during the peak  
297 of diurnal photosynthetic activity provide an objective assessment of the potential contribution of  
298 vascular plants and *Sphagnum* mosses to the exchange of atmospheric  $\text{CO}_2$  in the two contrasting  
299 peatlands (Bahn *et al.*, 2009; Bragazza *et al.*, 2016). The NEE results demonstrate that the  
300 presence of vascular plants is crucial to maintain high levels of net  $\text{CO}_2$  assimilation in the two  
301 peatlands during the growing season (Laine *et al.*, 2012; Ward *et al.*, 2013; Kuiper *et al.*, 2014).  
302 *Sphagnum* mosses alone were much less efficient in offsetting ecosystem respiratory  $\text{CO}_2$  losses  
303 under warmer conditions. Concurrently, gross ecosystem productivity (GEP) in both peatlands  
304 was much higher in the presence of vascular plants, in accordance with the higher photosynthetic  
305 efficiency of vascular plants compared to mosses (Ward *et al.*, 2009; Armstrong *et al.*, 2015).  
306 Despite the larger aboveground plant biomass at lower elevation, GEP was not significantly  
307 different between the two peatlands, a result that can be at least partly explained by a larger

308 abundance of shrubs with a greater portion of ligneous, non-photosynthetic tissues at low  
309 elevation (Table 1; Fig. S1) (Bubier *et al.*, 2003; Leppälä *et al.*, 2008; Juutinen *et al.*, 2010). On  
310 the basis of our field measurements, *Sphagnum* mosses in the two peatlands contributed equally  
311 to GEP per surface area, indicating that under suitable conditions of temperature and moisture the  
312 photosynthetic potential was the same at both elevations even if the annual productivity can be  
313 different (Bragazza *et al.*, 2013). Indeed, albeit a longer growing season (Fig. 1), both vascular  
314 plants and *Sphagnum* mosses are likely to experience more limiting photosynthetic conditions at  
315 lower elevation due to higher VPD values (Table 1).

316 The overall greater  $R_{\text{eco}}$  in the presence of vascular plants, particularly at low elevation, is  
317 likely due to a higher contribution of autotrophic respiration, in line with: the larger vascular  
318 plant biomass (Ward *et al.*, 2013; Kuiper *et al.*, 2014; Hicks Pries *et al.*, 2015), the corresponding  
319 larger biomass of decomposing roots (Murphy *et al.*, 2009), as well as to an enhancement of  
320 heterotrophic respiration, i.e. a boosting of microbial metabolism. The latter can be directly  
321 stimulated by the improved soil physical conditions due to warmer climate (Updegraff *et al.*,  
322 2001; Dorrepaal *et al.*, 2009; Conant *et al.*, 2011; Philben *et al.*, 2014) or indirectly promoted by  
323 vascular plants through the rhizosphere priming. The two-pool mixing model, taking into account  
324 the  $\text{CO}_2$  efflux and the corresponding  $^{14}\text{C}$  signature in plots with and without vascular plants at  
325 each peatland, shows a consistent enrichment of vascular plant-associated respiration with older  
326 carbon, a result that clearly indicates a stimulation of heterotrophic peat decomposition through  
327 the rhizosphere priming effect (Hardie *et al.*, 2009; Basiliko *et al.*, 2012; Walker *et al.*, 2016).  
328 Although we cannot exclude a contribution of residual decomposing roots to the priming (even  
329 after one year of decomposition), if this should take place in the clipped plots it means that the



330 differences in the  $^{14}\text{C}$  enrichment with the control plots would be still larger in total absence of  
331 roots in the peat.

332 A sustained expression of the rhizosphere priming towards the end of the growing season is  
333 intriguing because it indicates that the priming can still be active beyond the plant growing  
334 season, i.e. when soil and air temperatures as well as GEP already decline (Fig. 1, Table S2). We  
335 interpret this apparent temporal asynchrony between aboveground plant productivity and  
336 belowground microbial decomposition as result of: i) the low thermal diffusivity of peat that  
337 maintained favourable soil temperatures later into the growing season (Table S2), ii) the  
338 preferential allocation of carbon resources by vascular plants to their roots well beyond their  
339 aboveground senescence (Abramoff & Finzi, 2015; Blume-Werry *et al.*, 2016), and iii) the  
340 leaching from fresh leaf litter (Singh *et al.*, 2014) providing soil microbes with labile carbon  
341 substrates to access older organic matter (Qiao *et al.*, 2014).

342 On the basis of FT-IR spectroscopy, at both studied sites there was a higher humification  
343 degree of dissolved organic matter in plots with intact vascular plants (Fig. 3), a result that seems  
344 to reflect an enhanced microbial metabolism (Glatzel *et al.*, 2003; Höll *et al.*, 2009; Ward *et al.*,  
345 2013; Lou *et al.*, 2014; Dieleman *et al.*, 2016). The removal of vascular plants is indeed expected  
346 to reduce the availability of more labile, root-mediated carbon (Gogo *et al.*, 2011) that is used by  
347 microbes for synthesising extracellular enzymes (Robroek *et al.*, 2016). Additionally, we observe  
348 that warmer climatic conditions and larger vascular plant biomass are ultimately associated with a  
349 larger release of dissolved organic carbon (DOC) in the peat soil at low elevation (Table 1). This  
350 latter result points to the synergetic role of climate and vegetation in increasing the production  
351 and release of DOC from peatlands (Neff & Hooper, 2002; Frey & Smith, 2005; Ward *et al.*,  
352 2013; Kane *et al.*, 2014).

353 On the basis of the  $^{14}\text{C}$  signature in the subsurface peat (Table 1), the estimated age of top 20  
354 cm peat, particularly for the low elevation site, was in line with other studies (see e.g. Shotyk *et*  
355 *al.*, 1997) suggesting a relatively recent peat accumulation, i.e. primarily after the bomb-  $^{14}\text{C}$  peak  
356 of 1963. We conclude that the carbon released by the priming effect was only a few decades old  
357 ( $< 20$  years) and stored above the mean water-table depth (Table 1). This observation highlights  
358 the importance of water table in protecting peat from microbial decomposition (Ise *et al.*, 2008),  
359 but also indicates the potential vulnerability of peat carbon if hydrological feedbacks to climate  
360 change increase soil oxygenation (Waddington *et al.*, 2015) and, consequently, promote the  
361 spreading of vascular plants (Dieleman *et al.*, 2015; Potvin *et al.*, 2015). The apparent rate of  
362 carbon accumulation in the peat layers above the mean-water table depth approximated c.  $90 \text{ g C}$   
363  $\text{m}^{-2} \text{y}^{-1}$  for the low elevation site and c.  $154 \text{ g C m}^{-2} \text{y}^{-1}$  for the high elevation site over a reference  
364 period of 26-30 years for both sites, a result suggesting a lower carbon sink capacity of peatlands  
365 at the lower end of their altitudinal distribution (Millar *et al.*, 2017). The effective annual  
366 contribution of the rhizosphere priming to the observed difference in carbon accumulation rate in  
367 relation to the dominant vascular plant functional types and their symbiotic microorganisms  
368 remains an open question that deserves further attention (Gavazov *et al.*, 2016; Walker *et al.*,  
369 2016; Sulman *et al.*, 2017).

370 Our  $\text{CO}_2$  exchange measurements, whilst covering only a single growing season, show that the  
371 presence of vascular plants is crucial to sustain high potential levels of net atmospheric carbon  
372 assimilation in peatlands, particularly with warmer climate. Differently, *Sphagnum* mosses alone  
373 could not keep pace with the observed higher ecosystem respiratory C-losses with warmer  
374 climate. A sustained temporal expression of the rhizosphere priming effect, although deserving  
375 further investigation (Luo *et al.*, 2016), suggests that the decomposition of older peat can be

376 promoted even beyond the plant growing season, so affecting the humification of peat and loss of  
377 C in both gaseous and dissolved form. We argue that to accurately predict the future capacity of  
378 peatlands to act as atmospheric carbon sinks the synergetic interactions among vegetation  
379 dynamics, plant phenology and soil microbes must be taken into account, particularly if the  
380 rhizosphere priming effect can be further stimulated in warmer soils (Zhu & Cheng, 2011),  
381 thereby exerting a positive feedback to carbon emissions from organic rich soils.

382

### 383 **ACKNOWLEDGEMENTS**

384 We thank Lucas Wettstein and Adrian Pulgarin for field assistance and to Vincent Jassey and  
385 Laurent Jeanneau for laboratory assistance. Thanks are also due to Ingeborg Levin and Samuel  
386 Hammer for providing data on <sup>14</sup>C signature of atmospheric CO<sub>2</sub>. The Service des Forêts, de la  
387 Faune et de la Nature (Canton de Vaud) and the Service de la promotion de la nature – Office de  
388 l'agriculture et de la nature (Canton de Berne) are acknowledged for giving the permission to  
389 access the studied peatlands. This work was supported by the Swiss National Science Foundation  
390 grant number: 205320\_144024 to L.B.

391

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- 600

**TABLE 1** Geographical location, climatic conditions for the year 2014 and the average for the period 2005-2013 (in brackets), cumulative hours of vapour-pressure deficit (VPD) and water-table depth during plant growing season 2014, vascular plant biomass and surface cover (%), pore-water chemistry, and estimated age of surface peat (with corresponding  $^{14}\text{C}$  signature) at the two study sites. Aboveground plant biomass is the mean of 5 replicates for each site. Water table depth is the seasonal mean of continuous measurements collected in one representative piezometer during the plant growing season at each site. Plant cover estimates are mean ( $\pm 1$  SE) of 3 replicates for each site. Pore-water chemistry is the seasonal mean ( $\pm 1$  SE) of 3 replicates for each site as measured in the control plots where vascular plants were not clipped (+V treatment). Different superscripts indicate significant differences between the peatlands ( $P < 0.05$ ). The age of the peat was calculated from a reference dataset of atmospheric  $^{14}\text{C}$  measurements carried out at the Jungfraujoch station and refers to years before 2014.

	Praz Rodet	Hochrajen
Elevation (m a.s.l.)	1035	1885
Latitude and longitude	46°33'N, 6°10'E	46°36'N, 7°58'E
Mean annual air temperature (°C)	7.0 (6.2)	3.7 (3.3)
Mean annual precipitation (mm)	1219 (1264)	1427 (1372)
VPD > 1.5 kPa (hours)	150	53
Mean water-table depth (cm)	-17.8	-15.6
Total aboveground vascular plant biomass ( $\text{g m}^{-2}$ )	160 <sup>a</sup> $\pm$ 21	74 <sup>b</sup> $\pm$ 7
Total vascular plant cover (%)	63.0 <sup>a</sup> $\pm$ 2.0	35.4 <sup>b</sup> $\pm$ 5.3
Graminoids (%)	26.5 <sup>a</sup> $\pm$ 3.3	19.0 <sup>a</sup> $\pm$ 3.4
Shrubs (%)	20.0 <sup>a</sup> $\pm$ 2.6	8.3 <sup>b</sup> $\pm$ 1.8
Forbs (%)	1.2 <sup>a</sup> $\pm$ 0.5	1.8 <sup>a</sup> $\pm$ 1.8
Standing litter (%)	15.2 <sup>a</sup> $\pm$ 1.4	6.3 <sup>b</sup> $\pm$ 1.9
Total moss cover (%)	100 <sup>a</sup> $\pm$ 0.0	100 <sup>a</sup> $\pm$ 0.0
pH	4.25 <sup>a</sup> $\pm$ 0.02	4.37 <sup>a</sup> $\pm$ 0.15
Conductivity ( $\mu\text{S cm}^{-1}$ )	31.03 <sup>a</sup> $\pm$ 0.64	27.81 <sup>a</sup> $\pm$ 7.34
Total N ( $\text{mg l}^{-1}$ )	0.39 <sup>a</sup> $\pm$ 0.03	0.30 <sup>b</sup> $\pm$ 0.02
NH <sub>4</sub> <sup>+</sup> ( $\text{mg l}^{-1}$ )	0.018 <sup>a</sup> $\pm$ 0.003	0.007 <sup>b</sup> $\pm$ 0.002
NO <sub>3</sub> <sup>-</sup> ( $\text{mg l}^{-1}$ )	0.034 <sup>a</sup> $\pm$ 0.002	0.032 <sup>a</sup> $\pm$ 0.001
DOC ( $\text{mg l}^{-1}$ )	22.14 <sup>a</sup> $\pm$ 1.12	16.57 <sup>b</sup> $\pm$ 1.53
Age at 5-10 cm (years / %Mod <sup>14</sup> C $\pm$ 1 $\sigma$ )	16 / 110.23 $\pm$ 0.48	1 / 103.41 $\pm$ 0.47
Age at 10-15 cm (years / %Mod <sup>14</sup> C $\pm$ 1 $\sigma$ )	30 / 120.75 $\pm$ 0.53	16 / 110.01 $\pm$ 0.48
Age at 15-20 cm (years / %Mod <sup>14</sup> C $\pm$ 1 $\sigma$ )	40 / 139.28 $\pm$ 0.61	26 / 117.12 $\pm$ 0.51

## FIGURE CAPTIONS

**Fig. 1** Seasonal dynamics of ecosystem CO<sub>2</sub> fluxes in relation to the presence or absence of vascular plants in two peatlands at different elevations. (a) Net ecosystem exchange (NEE), (b) Gross ecosystem productivity (GEP), (c) Ecosystem respiration (R<sub>eco</sub>). The two peatlands were located at low (1035 m a.s.l.) and high elevation (1885 m a.s.l.) and two treatments were applied, i.e. mosses plus vascular plants present (+V, controls) or removal of vascular plants by clipping (-V, *Sphagnum* mosses alone). Panels on the left show the seasonal dynamics of mean values ( $\pm 1$  SE,  $n = 3$ ), whereas those on the right show the overall seasonal means ( $\pm 1$  SE,  $n = 3$ ). Asterisks indicate significant differences of mean CO<sub>2</sub> fluxes between treatments at each site and between elevations (\*' =  $P < 0.1$ ; \* =  $P < 0.05$ ; \*\*\* =  $P < 0.001$ ). Negative values of NEE indicate a net assimilation of atmospheric CO<sub>2</sub>.

**Fig. 2** <sup>14</sup>C content of ecosystem respired CO<sub>2</sub> associated with the presence of vascular plants in two peatlands at low and high elevations (1035 and 1885 m a.s.l., respectively) at peak biomass (July) and late in the growing season (end of September). Median and range ( $n = 3$ ) of respired <sup>14</sup>C-CO<sub>2</sub> associated with the presence of vascular plants (DV\_plant\_associated). Dotted line indicates the mean atmospheric <sup>14</sup>C-CO<sub>2</sub> signature (102.91 ‰Modern) as measured in June, July, August and September 2014 at the Jungfraujoch atmospheric research station. Numbers beneath the dotted line are  $P$ -values from t-tests for differences of each date and elevation to this reference line. Significant differences ( $P < 0.05$ ) are interpreted as a signal of plant-induced heterotrophic respiration of peat carbon through the rhizosphere priming effect.

**Fig. 3** Mean seasonal values ( $\pm 1$  SE,  $n = 3$ ) of humification indices of dissolved organic matter based on FT-IR spectra. Pore-water samples were collected monthly from May through October 2014 in the two peatlands at low and high elevations (1035 and 1885 m a.s.l., respectively) in relation to the presence (+V) or absence (-V) of vascular plants. The selected functional groups are: aliphatics (2943 cm<sup>-1</sup> region), carboxylic acids and aromatic esters (1720 cm<sup>-1</sup> region), aromatics (1630 cm<sup>-1</sup> region), lignins (1510 cm<sup>-1</sup> region), phenols (1420 cm<sup>-1</sup> region) and they are expressed as a ratio to polysaccharides (1090 cm<sup>-1</sup> region). Significant differences between treatments are indicated with asterisks (\*' =  $P < 0.1$ , \* =  $P < 0.05$ , \*\* =  $P < 0.01$ ; \*\*\* =  $P < 0.001$ ), whereas no significant differences were observed between the two sites.







