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1 **Role of recent climate change on carbon sequestration in peatland systems**

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6 **Highlights**

- 7 • Mean rates of carbon accumulation since 1850 were $11.26 \text{ t} \pm 0.68 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ for
8 valley mire and $11.77 \text{ t} \pm 0.88 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ for blanket bog
- 9 • Contemporary rate of CO₂ sequestration was $9.13 \text{ t} \pm 0.98 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$
- 10 • Past and contemporary peatland carbon sinks were found to be at the upper limits of
11 those reported in the literature
- 12 • Recent changes in climate appear to have had minimal impact on the strength of
13 peatland carbon sinks in South West England

14 **Abstract**

15 This paper provides information on the impact of recent climate change on carbon
16 sequestration in peatland systems in South West England. This is important because
17 peatlands have the potential to sequester and hold large quantities of anthropogenically
18 released CO₂. This paper investigates whether there has been a reduction in the strength of
19 carbon sinks in a valley mire and blanket bog; which occur on the limits of the
20 biogeographical envelop for peatlands in Britain. Past rates of carbon accumulation were
21 determined from peat depth and the sequential analysis of peat age, bulk density and carbon
22 content from cores taken from valley mire and blanket bog. At the valley mire site
23 contemporary net ecosystem carbon balance (NECB) was calculated by measuring inputs to

24 the peat body, via net primary productivity (NPP), of *Sphagna*. Losses of C from the peat
25 body were calculated by measuring CH₄, and aquatic carbon; calculated from catchment
26 export of particulate and dissolved organic carbon. The study found similar mean rates of
27 carbon accumulation since 1850 of $11.26 \pm 0.68 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ ($307 \text{ g C m}^{-2} \text{ yr}^{-1}$) in
28 valley mire and $11.77 \pm 0.88 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ ($321 \text{ g C m}^{-2} \text{ yr}^{-1}$) in blanket bog. The mean
29 present-day CO₂ sequestration rate for *Sphagna* on valley mire was calculated to be
30 $9.13 \pm 0.98 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ ($249 \text{ g C m}^{-2} \text{ yr}^{-1}$). Both past and contemporary rates of CO₂
31 sequestration were found to be at the upper limits of those reported in the literature for
32 temperate peatlands. NPP was found to vary according to microform with higher rates of
33 carbon sequestration found in lawn and hummock microforms compared with pools. Our
34 work suggests that recent changes in the climate appear to have had limited impact on the
35 strength of peatland carbon sinks in South West England.

36 **Key Words**

37 CO₂ sequestration; peatlands; *Sphagnum*; net ecosystem carbon balance; climate change; peat
38 accumulation

39 The authors use the term net ecosystem carbon balance (NECB), as defined in Chapin *et al.*,
40 (2006) to describe carbon uptake in peatlands. All values for carbon are presented as CO₂
41 equivalents ($\text{t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$), where carbon (C) is converted to CO₂ based on molecular
42 mass difference by multiplying the amount of C by 3.667. Where values are cited from the
43 literature the original units are reported, along with converted values in $\text{t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ for
44 comparison. ‘Carbon accumulation’ refers to carbon accumulated as peat. The term ‘Carbon
45 exchange’ has been used where CO₂ fluxes have been measured. ‘Carbon balance’ is the
46 difference between CO₂ uptake by the peatland ecosystem (photosynthesis) and CO₂ loss to

47 the atmosphere by respiration. ‘Carbon sequestration’ refers to is the removal and storage of
48 carbon from the atmosphere in peat.

49 **1.0 Introduction**

50 Peatlands have the highest carbon storage capacity per unit area of all terrestrial ecosystems
51 (Brooks & Stoneman, 1997; Worrall *et al.* 2009; Yu *et al.* 2011b). Cox *et al.* (2000)
52 estimated globally that 60 gigatonnes of carbon (Gt C) are removed each year from the
53 atmosphere by NPP of photosynthetic plants. Known peatlands are estimated to cover 3–4%
54 of the world’s land area (Gorham, 1991; Parish *et al.* 2008; Xu *et al.* 2018) and contain
55 ~612 Gt C (Yu *et al.* 2011b). Variation in the size of the peatland carbon sink could have a
56 significant cumulative effect on global atmospheric CO₂ concentrations (Chambers &
57 Charman, 2004; Charman *et al.* 2013). Estimates of global carbon accumulation by peatlands
58 vary from 0.09 to 0.5 Gt C yr⁻¹ (Gorham, 1991; Yu, 2011a). These figures represent 1–5% of
59 global annual anthropogenic greenhouse gas (GHG) emissions (Friedlingstein *et al.* 2014).
60 Globally, appropriate protection and management of peatlands is one of the most cost-
61 effective measures in reaching the ultimate goal of zero net carbon emissions from the land-
62 use management sector (Ostle *et al.* 2009).

63 Peatlands cover 24,600 km² or ~15% of the land area and store 2.3–3.12 Gt C in the UK
64 (Billett *et al.* 2010; Lindsay & Clough 2017). Peatlands have the potential to sequester and
65 hold large quantities of anthropogenically-released atmospheric CO₂, making a significant
66 contribution to international GHG budgets (Waddington *et al.* 2010; Bain *et al.* 2011; Yu,
67 2011a). Research on rates of carbon sequestration on peatlands has focused on two
68 approaches: contemporary gaseous exchange of CO₂ using eddy covariance measurements
69 (Billett *et al.* 2010; Helfter *et al.* 2015; Levy & Gray 2015; Wilson *et al.* 2016) and Holocene
70 rates of carbon accumulation established from peat cores (Pendea & Chmura 2012; Charman

71 *et al.* 2013). Chamber studies have also been widely used in the UK and elsewhere to
72 investigate net carbon balance (Rowson *et al.* 2010; Dixon *et al.* 2014; Gatis *et al.* 2015;
73 Green *et al.* 2018).

74 Net ecosystem carbon balance (NECB: Chapin *et al.* 2006) models can be used to assess
75 contemporary rates of carbon gain and loss from peatlands. In recent years there has been a
76 significant amount of work to understand the factors effecting site-level NECB values.
77 Dinsmore *et al.* (2010) found contemporary site-level NECB of 3.52 t CO₂e ha⁻¹ yr⁻¹ (352 g
78 CO₂ m⁻² yr⁻¹) in a UK ombrotrophic peatland whilst Billett *et al.* (2010) report contemporary
79 site-level NECB in two ombrotrophic peatlands of 2.05–2.64 t CO₂e ha⁻¹ yr⁻¹ (56–72 g C m⁻²
80 yr⁻¹). Values reported for NECB in boreal and northern continental peatlands of the Northern
81 Hemisphere are typically at the lower end of the range reported for undisturbed peatlands at
82 0.79 t CO₂e ha⁻¹ yr⁻¹ (21.5±39.0 g C m⁻² yr⁻¹) (Roulet *et al.* 2007; Payne *et al.* 2016). These
83 findings suggest that there is a great deal of variability in NECB due to latitude and
84 geographical location as well as mire community type (Billett *et al.* 2010; Dinsmore *et al.*
85 2010; House *et al.*, 2010; Koehler *et al.* 2011).

86 Gorham (1991) estimated mean rates of accumulation of 0.84 t CO₂e ha⁻¹ yr⁻¹ for boreal and
87 subarctic peatlands during the Holocene based on peat cores and these values are broadly
88 similar to NECB for boreal and northern continental peatlands. In Canada, Roulet *et al.*
89 (2007) compared contemporary carbon exchange with apparent C accumulation over 3000
90 years and found similar levels of carbon accumulation in contemporary site-level net
91 ecosystem C exchange (0.78 t ± 1.43 t CO₂e ha⁻¹ yr⁻¹) and dated peat cores (0.8 t ± 0.1–
92 0.51 ± 1.37 t CO₂e ha⁻¹ yr⁻¹). In spite of this apparent agreement there is a great deal of
93 variability in rates of peat accumulation from peat cores in response to climate and
94 geographical location (Belyea & Clymo, 2001). For example, Belyea and Malmer (2004)
95 report values between 0.51–2.64 t CO₂e ha⁻¹ yr⁻¹ (14–72 g C m⁻² yr⁻¹), with higher rates

96 associated with climatic optima during periods of higher temperatures and rainfall. Levy and
97 Gray (2015) found that the contemporary carbon sink in blanket bog in northern Scotland was
98 larger than estimates from local peat cores, based on peat accumulation over the last several
99 thousand years. Whilst mean rates of carbon accumulation across Holocene time scales
100 appears to match contemporary carbon exchange we can observe significant variation
101 through the course of the Holocene [illustrated by Belyea & Malmer, 2004], with variation in
102 carbon sequestration controlled by changes in net primary productivity forced by temperature
103 and cloudiness variability (Charman *et al.* 2013).

104 Net primary productivity (NPP) is by far the largest constituent of a NECB model in an active
105 peatland (Moore *et al.* 2002; Nilsson *et al.* 2008; Billett *et al.* 2010). Koehler *et al.* (2011)
106 measured components of site-level NECB over a six year period in an ombrotrophic mire in
107 southern Ireland, and found mean annual carbon uptake was 29.7 ± 30.6 (± 1 SD) $\text{g C m}^{-2}\text{yr}^{-1}$
108 ($1.09 \text{ t} \pm 1.12 \text{ t}$ (± 1 SD) $\text{CO}_2\text{e ha}^{-1}\text{yr}^{-1}$). The main components of their NECB were
109 as follows: carbon uptake in CO_2 from the atmosphere was 47.8 ± 30.0 $\text{g C m}^{-2}\text{yr}^{-1}$
110 ($1.75 \text{ t} \pm 0.01 \text{ t CO}_2\text{e ha}^{-1}\text{yr}^{-1}$); carbon loss as CH_4 was 4.1 ± 0.5 $\text{g C m}^{-2}\text{yr}^{-1}$
111 ($0.15 \text{ t} \pm 0.018 \text{ t CO}_2\text{e ha}^{-1}\text{yr}^{-1}$); and the carbon exported as stream-dissolved organic carbon
112 (DOC) was a loss of 14.0 ± 1.6 $\text{g C m}^{-2}\text{yr}^{-1}$ ($0.51 \text{ t} \pm 0.059 \text{ t CO}_2\text{e ha}^{-1}\text{yr}^{-1}$). For two out of the
113 six years, the site was a source of carbon with the sum of CH_4 and DOC flux exceeding the
114 carbon sequestered as CO_2 .

115 In northern peatlands, *Sphagnum* mosses dominate the surface cover of pristine,
116 ombrotrophic bogs and often account for a significant proportion of past accumulated peat.
117 *Sphagnum* productivity is controlled by mean annual temperature, precipitation and
118 photosynthetically active radiation (PAR) (Gunnarsson, 2005; Loisel *et al.* 2012; Nijp *et al.*
119 2015). As previously outlined, Charman *et al.* (2013) found that total carbon accumulated
120 over the last 1000 years is linearly related to growing season length and PAR, demonstrating

121 changes in peat body carbon sequestration with climatic change. Climate change alters rates
122 of carbon sequestration primarily through changes in the frequency and amount of
123 precipitation and secondarily via temperature. Increased mean seasonal temperatures have
124 positive impacts by increasing the length of the growth season and negative impacts by
125 increasing rates of microbial decomposition and evapotranspiration. Blanket bog is a globally
126 restricted peatland habitat confined to cool, high rainfall, typically flat upland areas with low
127 levels of evapotranspiration. In Europe this habitat type typically occurs in oceanic climates
128 along the Atlantic coast of the UK and Ireland with southern limits in Brittany and northern
129 Spain (Joosten *et al.* 2017). It has been suggested that future climatic changes will result in a
130 contraction of the distribution of active blanket bog in the UK towards the north and west,
131 and outside this distribution peatlands may cease active growth (Gallego-Sala *et al.* 2010;
132 Gallego-Sala & Prentice, 2013). An understanding of recent changes in rates of carbon
133 sequestration in regions such as South West England, indicated as marginal to growth, is
134 therefore vital to our understanding of how sensitive these peatlands are to present and future
135 climate change.

136 This paper addresses the challenge of understanding the impact of recent climatic change in a
137 potentially marginal blanket bog setting (the southwest UK uplands) by adopting a NECB
138 approach and comparing current rates of CO₂ sequestration in *Sphagnum*-dominated south-
139 west UK temperate peatlands to CO₂ equivalent, carbon accumulation rates that occurred at
140 the same sites over the last 160 years and relating these findings to instrumental records of
141 climate change over this period.

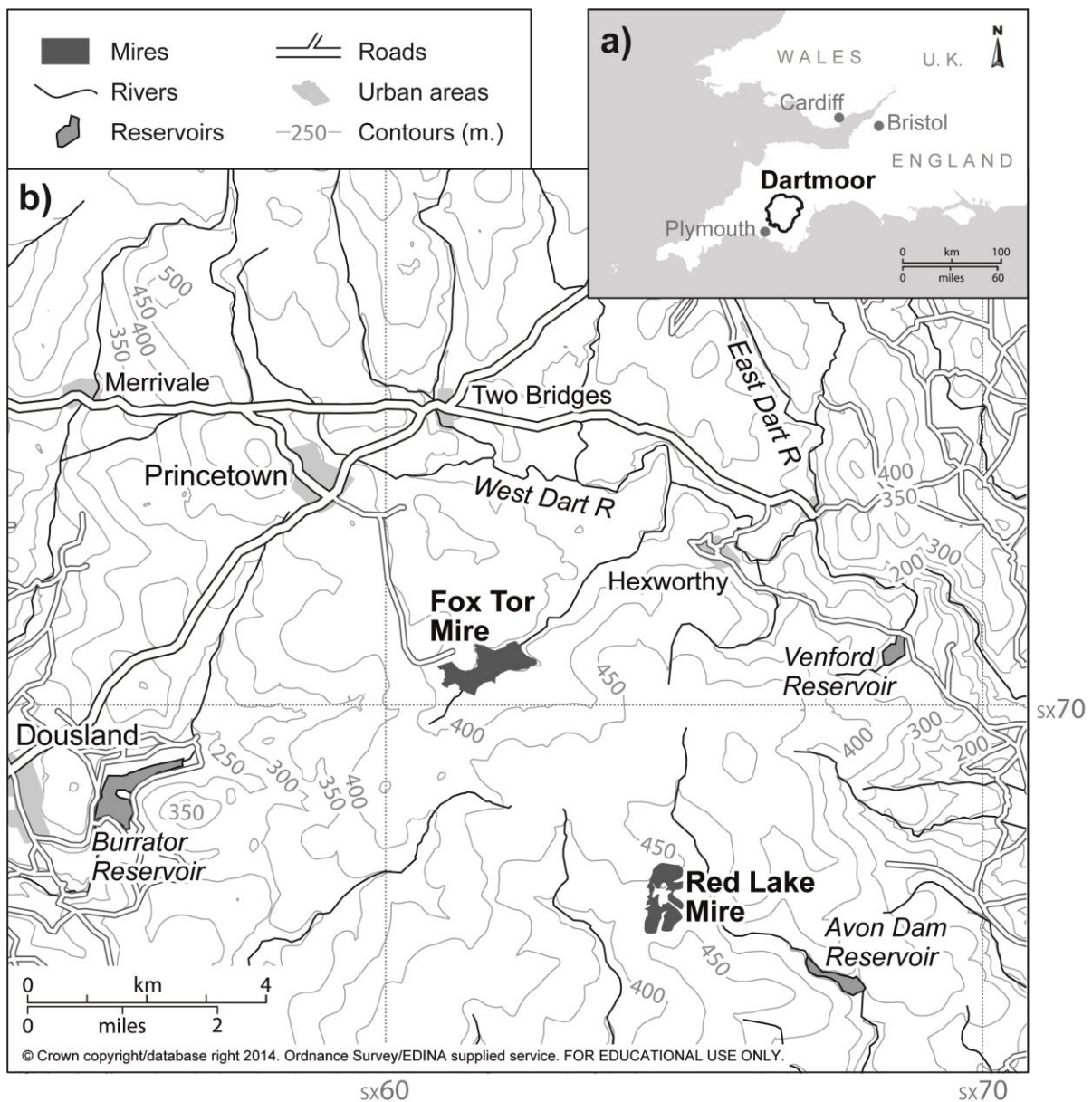
142 **1.1 Study site description**

143 Dartmoor represents the largest extent of blanket mire in southern England with an estimated
144 158 km² of peat having a depth greater than 0.4 m (Gatis *et al.* 2019). The upland is

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145 composed of an eroded granite plateau, of elevation range 300–623 m, with an annual mean
146 temperature of 8° C at 400 m. Mean monthly air temperatures range from 0.8° C (Feb) to
147 17.7° C (July) with a mean rainfall of 1974 mm yr⁻¹ and ca. 180.9 days of rainfall (> 1 mm),
148 (Met Office 2017: 1971–2000 averages). All months have an average of over 100 mm
149 rainfall, with the four wetter months over 200 mm.

150



152 Fig. 1 (a) Regional map showing the location of Dartmoor within South West England; (b)
153 Locations of Fox Tor Mire and Red Lake Mire study sites

154 **Footnote** *Fox Tor Mire provided the inspiration for Arthur Conan Doyle's fictional Grimpen*
155 *Mire, in the Sherlock Holmes story, The Hound of the Baskervilles.*

156 Data were collected from two contrasting intact mire sites on Dartmoor, Fox Tor Mire and
157 Red Lake (Fig. 1). Fox Tor Mire is a valley mire, with a 58.3 ha peat body, located 4 km
158 south-east of Princetown (50.517°N, 03.956°W) at an elevation of 351 m. Almost all of the
159 previous peat deposits at Fox Tor Mire were removed during commercial peat mining
160 operations which ceased in the 1850s (Wright, 1884). A layer of mine washings occurred at
161 the base of the peat column, which was dated to a period of extensive mining at White Works
162 on the periphery of the mire, in 1876 (Wright, 1884). All subsequent peat developed in the
163 period following 1876. Plant communities are intermediate between soligenous and
164 ombrogenous mire. Sample areas were permanently saturated and *Sphagnum*-dominated,
165 consisting primarily of National Vegetation Classification (NVC) communities M15b and
166 M6, *Scirpus cespitosus*–*Erica tetralix* wet heath and *Carex echinata*-*Sphagnum*
167 *fallax/denticulatum* mire (Rodwell, 1991). The three dated peat cores were taken from
168 separate areas with surface vegetation typical of nutrient poor fen, constant species included
169 *Eriophorum angustifolium*, *Sphagnum papillosum*, *Sphagnum fallax*, *Sphagnum*
170 *denticulatum*, *Molinia caerulea* and *Menyanthes trifoliata*.

171 Red Lake Mire is a precipitation-only ombrotrophic blanket bog, situated 8.5 km south-east of
172 Princetown, (50.488°N, 03.910°W) at an elevation of 470 m. The main vegetation community
173 consists of *Scirpus cespitosus*–*Eriophorum vaginatum* blanket mire (NVC code M17) with a
174 *Sphagnum* base layer overlying a hummock and hollow microtopography. Peat cores were
175 taken from an area to the north of Red Lake, with an intact primary bog surface. Ground and

176 LIDAR observations showed several drainage ditches local to the area which were infilled with
177 peat-forming vegetation. *Sphagna* were present in all quadrats, with *S. papillosum* (87%) and
178 *S. cuspidatum* (61%) having the highest abundance. Other constant species included
179 *Eriophorum angustifolium* (85%), *E. vaginatum* (71%), *Narthecium ossifragum* (71%) and
180 *Trichophorum cespitosum* (59%).

181 **2.0 Methods**

182 **2.1 Measurement of past rates of carbon accumulation**

183 Apparent past rates of carbon accumulation were determined for Red Lake Mire (blanket
184 bog) and Fox Tor Mire (valley mire) using a multi-technique approach on replicate peat
185 cores, extracted using a 5 cm diameter semi-circular Russian peat corer.

186 Three cores were extracted from three separate areas of Fox Tor Mire. Cores were ~ 150 cm
187 in length and consisted of the entire column of peat, down to the mineral layer. Cores were
188 dated using sequential analysis of concentrations of Spheroidal Carbonaceous Particles
189 (SCPs), combined with the presence of a definitive alluvial deposit dated to 1876.

190 In addition to the three cores taken for SCP analysis, a further 20 cores were extracted from
191 across Fox Tor Mire. Mean rates of peat accumulation on these cores were determined by the
192 presence of an alluvial mineral layer, widely deposited at the base of peat cores by washings,
193 from the White Works mine on the periphery of the mire. This layer provided a definitive
194 marker dated to 1876.

195 At Red Lake Mire, four 100 cm long cores were extracted from three separate unmodified
196 active mire areas. Three cores were dated using sequential analysis of SCPs, combined with
197 X-Ray Florescence (XRF) readings and a fourth core was dated using known peaks in the
198 radionuclides ^{210}Pb and ^{137}Cs .

199 **2.1.1 Dating ranges using Spheroidal Carbonaceous Particles (SCPs)**

200 Analysis of SCPs was the principal method used to obtain dates and dating ranges (Swindles,
 201 2010). SCP analysis was undertaken on cores following the method outlined by Rose *et al.*
 202 (1995). Peat cores were cut into 2 cm segments at 5 cm intervals throughout their depths.
 203 SCP densities and linear accumulation rates were calculated for individual segments down
 204 the core.

205 Laboratory protocol for measurement of bulk density and calculation of ash-free carbon
 206 content (g C cm^{-3}) followed the method outlined by Chambers *et al.* (2011). Bulk density (g
 207 cm^{-3}) was determined by measuring the dry weight (g) divided by fresh sample volume (cm^3).
 208 To increase accuracy, sample volumes were measured by water displacement following the
 209 method set out by Buffam *et al.* (2010). Samples were oven dried (100°C) to constant weight
 210 and ashed in a furnace at 550°C for 4 hours to determine ash-free dry weight and organic
 211 matter content (Chambers *et al.* 2011). Ash-free carbon content (g C cm^{-3}) was calculated by
 212 multiplying the bulk density by 51% (mean % fraction of ash-free carbon for *Sphagnum*
 213 peat). Carbon masses were up-scaled to $\text{t C ha}^{-1} \text{cm}^{-1}$, and converted to CO_2 ($\text{t CO}_2\text{e ha}$)
 214 (using a carbon mass to CO_2e multiple of 3.667), which was then multiplied by the average
 215 accumulation rate (cm yr^{-1}) to produce the average CO_2 accumulation rate ($\text{t CO}_2\text{e ha}^{-1} \text{yr}^{-1}$)
 216 (Pendea & Chmura, 2012).

217 Equation: Peat Accumulation Rate (AR) in cm yr^{-1}

$$218 \quad AR = D \div T$$

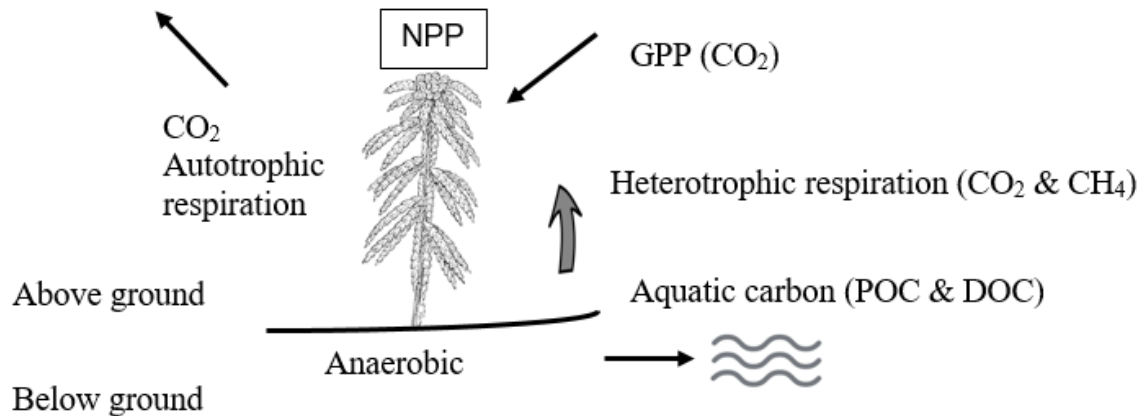
219 Where D is distance between date markers (cm) and T is time between date markers.

220 CO_2 Accumulation Rate (CO_2AR) in $\text{t CO}_2\text{e ha}^{-1} \text{yr}^{-1}$

$$221 \quad \text{CO}_2\text{AR} = BD \times 0.51 \times 3.667 \times AR \times 100$$

222 Where BD is Bulk Density (g cm^{-3})

223 **2.2 Estimates of contemporary rates of net ecosystem carbon balance in *Sphagnum*-**
 224 **dominated valley mire**



225

226 Fig. 2 Schematic representation of peatland carbon exchange. *Net Primary Productivity*
 227 (NPP) = *Gross Primary Productivity (GPP)* – *Ecosystem Respiration (ER)*. ER = *autotrophic*
 228 *respiration + heterotrophic aerobic respiration + heterotrophic anaerobic respiration*.

229 Greenhouse gas (GHG) balance measurements, calculated for Fox Tor Mire, were used to
 230 produce a model for contemporary net ecosystem carbon balance (NECB). The NECB
 231 balance of a peat body is measured by quantifying the amount of gaseous and aquatic C
 232 gained or lost (fluxes) per surface unit area (Fig. 2). Values calculated for *Sphagnum* NPP
 233 were used as estimates of CO₂e inputs in the peatland model. Export of carbon from the
 234 peatland model occurs via methane (CH₄) emissions and aquatic carbon pathways (Fig. 2).

235 **2.2.1 Model Formula**

236 Net ecosystem carbon balance $NECB = NPP$ (CO₂ assimilation based on *Sphagnum* growth) -
 237 Carbon losses as aquatic DOC & POC – carbon losses as CH₄ and CO₂*

238 * No measure was taken of direct losses of CO₂ from the peat body resulting from aerobic
239 heterotrophic respiration. Average values for ombrotrophic sites have been used from the
240 literature to quantify potential losses from heterotrophic aerobic respiration (Section 4.4).

241 **2.2.2 Measurement of *Sphagnum* growth and net primary production**

242 Measures of annual increase in *Sphagnum* stem lengths, over a two year period, were used to
243 calculate NPP and provide estimates of present-day levels of CO₂e sequestration. Single-
244 species stands of aquatic and terrestrial *Sphagna* were harvested from replicate 100 cm²
245 (1 dm⁻²) sample areas in December 2012 and 2013. The current year's annual growth was
246 separated from the previous year's growth at the point of 'growth shut down', denoted by a
247 kink in the stem and aggregation of stem branches (Clymo, 1970). Arising's were dried to
248 constant mass, ground to a fine powder and the carbon content analysed in a CHN Elemental
249 Analyser (EA1110). Carbon density was derived by multiplying dry weight (g cm⁻²) by the
250 carbon content measured for individual species samples. In addition, mean annual increase in
251 stem length (cm yr⁻¹) and mean stem density (number of capitula dm⁻²) was calculated and
252 presented for each *Sphagnum* species.

253 **2.2.3 Export of aquatic carbon**

254 Continuous stream discharge flow rates were measured for the stream which drained the Fox
255 Tor Mire *Sphagnum* and methane sample sites. Automated samples of drainage water were
256 collected during the summer of 2011, under storm flow and base flow conditions to
257 determine export of DOC and particulate organic carbon (POC). DOC was analysed using a
258 Shimadzu TOC 5000a analyser coupled to an ASI 5000A auto-sampler and a Sievers NCD
259 255 Detector. POC was collected on filter paper and analysed using a CHN Elemental
260 Analyser (EA1110). The concentrations of DOC and POC, over the monitoring period, were
261 multiplied by the associated stream discharge (Q) to provide continuous load data in mg s⁻¹.

262 Summer values for continuous load were used to estimate annual load by multiplying mean
263 daily load by the annual discharge (Hope *et al.* 1994). Flux was calculated by dividing load
264 by the peatland area (58.3 ha), giving the flux as Total Organic Carbon (TOC).

265 **2.2.4 Methane emissions associated with *Sphagnum*-dominated microforms**

266 Methane emissions were collected over lawn, pond and hummock microforms, using static
267 chambers, during the summers of 2014 and 2015. Chambers, consisting of transparent 4.5 L
268 PET plastic demijohns with a footprint of 130 mm² and a total headspace of ca. 4 L were
269 levelled and inserted into the peat or water surface to a depth of 5 cm (Moore & Roulet,
270 1991). Floatation aids were attached to the sides of the chambers that were to be placed in the
271 pool microform. Temperatures in the chamber headspace were not dissimilar to ambient
272 temperature, which ranged from 8-24⁰C.

273 A total of 15 chambers were positioned, five replicates over each microform and weekly
274 samples taken. Chambers were fitted with sample points and extracted gas transferred to the
275 laboratory for analysis in sterile vacuum sample bags. Accumulated gas was analysed using a
276 Bruker IFS-66 spectrometer and Fourier Transform Infrared (FT-IR) analysis (as described
277 by Christian *et al.*, 2014). Outputs from the FT-IR were calibrated using a series of known
278 concentrations of CH₄. Methane values were converted from a volume to a mass using the
279 Ideal Gas Law $PV = nRT$; where P = atmospheric pressure (Pa), V = volume (m³), n = molar
280 mass (g mol⁻¹), R is the ideal gas constant (m³ Pa K⁻¹ mol⁻¹), and T = temperature of the gas
281 (K). CH₄ fluxes were converted to CO₂ equivalent values (t CO₂e ha⁻¹ yr⁻¹) using a global
282 warming potential (GWP) of 28 times that of CO₂ over a 100 year period (Myhre *et al.* 2013).

283 **2.3 Statistical Analyses**

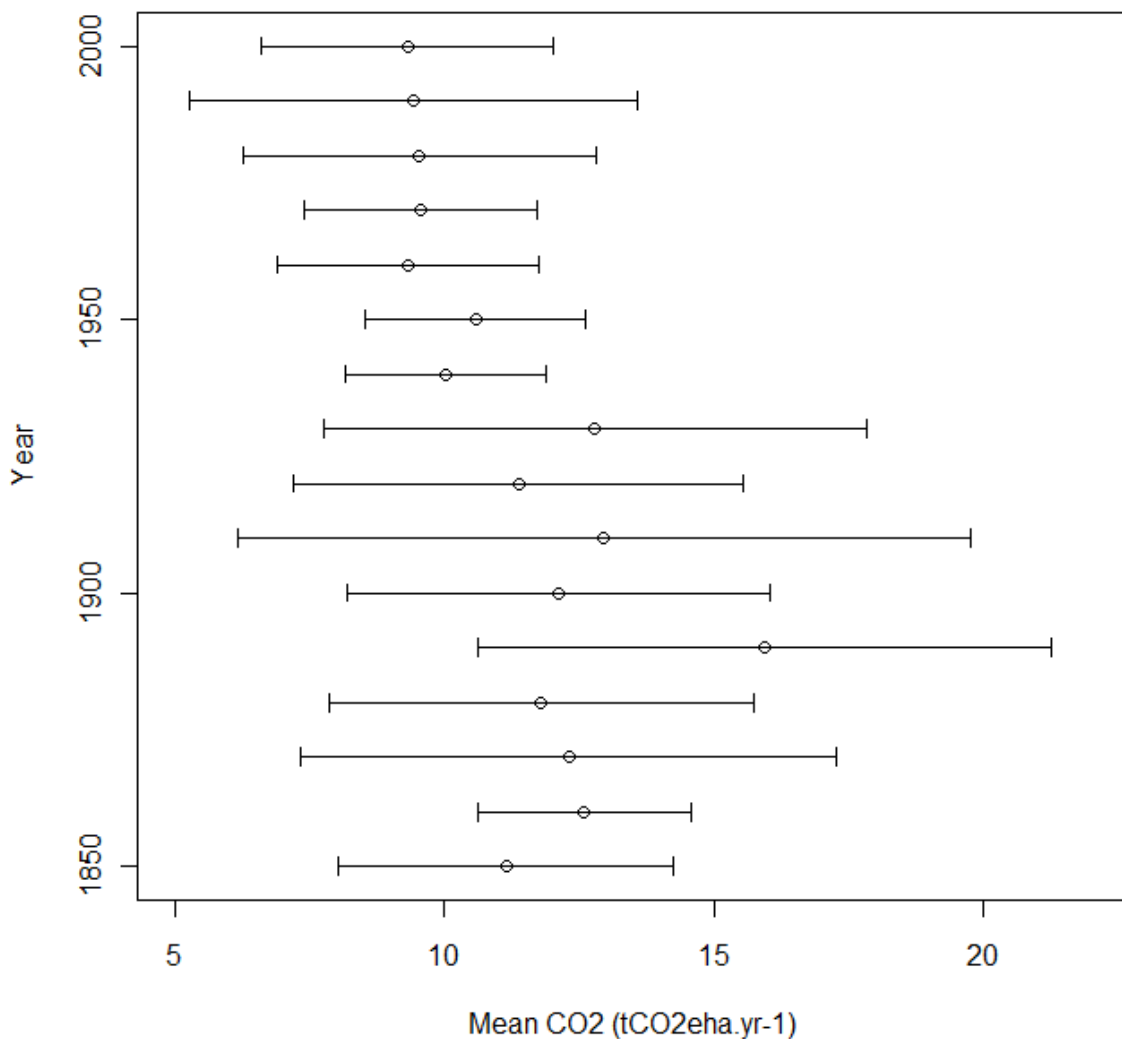
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284 All statistical comparison ($P \leq 0.05$) of rates of carbon sequestration between sites and
285 between past and contemporary periods were evaluated using Kruskal-Wallis and Mann-
286 Whitney U -tests. Site measures of central tendency and variation are reported as mean \pm
287 standard error (SE) with replicate numbers (n) unless otherwise indicated.

288

289 3.0 Results

290 3.1 Past rates of CO₂ accumulation in valley mire and blanket bog



291

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292 Fig. 3 Past rates of carbon accumulation (expressed as CO₂e) at the valley mire site (1850–
 293 2010). *Data were obtained from Fox Tor Mire, Dartmoor, via sequential analyses of carbon*
 294 *densities in peat core segments dated using SCP techniques. Values represent the means of*
 295 *three cores taken in 2011. Error bars represent ± 1 standard deviation.*

296

297 Mean rates of CO₂ accumulation in the valley mire (Fig. 3) appear stable around 12 t CO₂e
 298 ha⁻¹ yr⁻¹ until 1930. Fig. 3 shows a step change in the mean rate of CO₂ sequestration from
 299 1940 onwards, with a decrease to a mean of less than 10 t CO₂e ha⁻¹ yr⁻¹. There is a large
 300 variability around the means, particularly in the late 1800s and early 1900s with maximum
 301 values for CO₂ sequestration of 21.6 t CO₂e ha⁻¹ yr⁻¹ and minimum values of
 302 5.7 t CO₂e ha⁻¹ yr⁻¹. The alluvial marker showed mean depths of peat of 127.5cm and rates of
 303 peat accumulation of 9.51 mm ± 2 mm yr⁻¹ (Table 1). This rate was broadly in agreement
 304 with mean peat accumulation rates determined using the SCP dating method
 305 (7.86 mm ± 0.23 mm yr⁻¹), providing validation of this method; values were considerably
 306 higher than rates for valley mire in the published literature (Gorham, 1991; Barber *et al.*
 307 1994; Tallis, 1998). Bulk density was comparatively low at 0.079 ± 0.004 g cm⁻³ dry matter
 308 (Table 1), compared to values published in the literature.

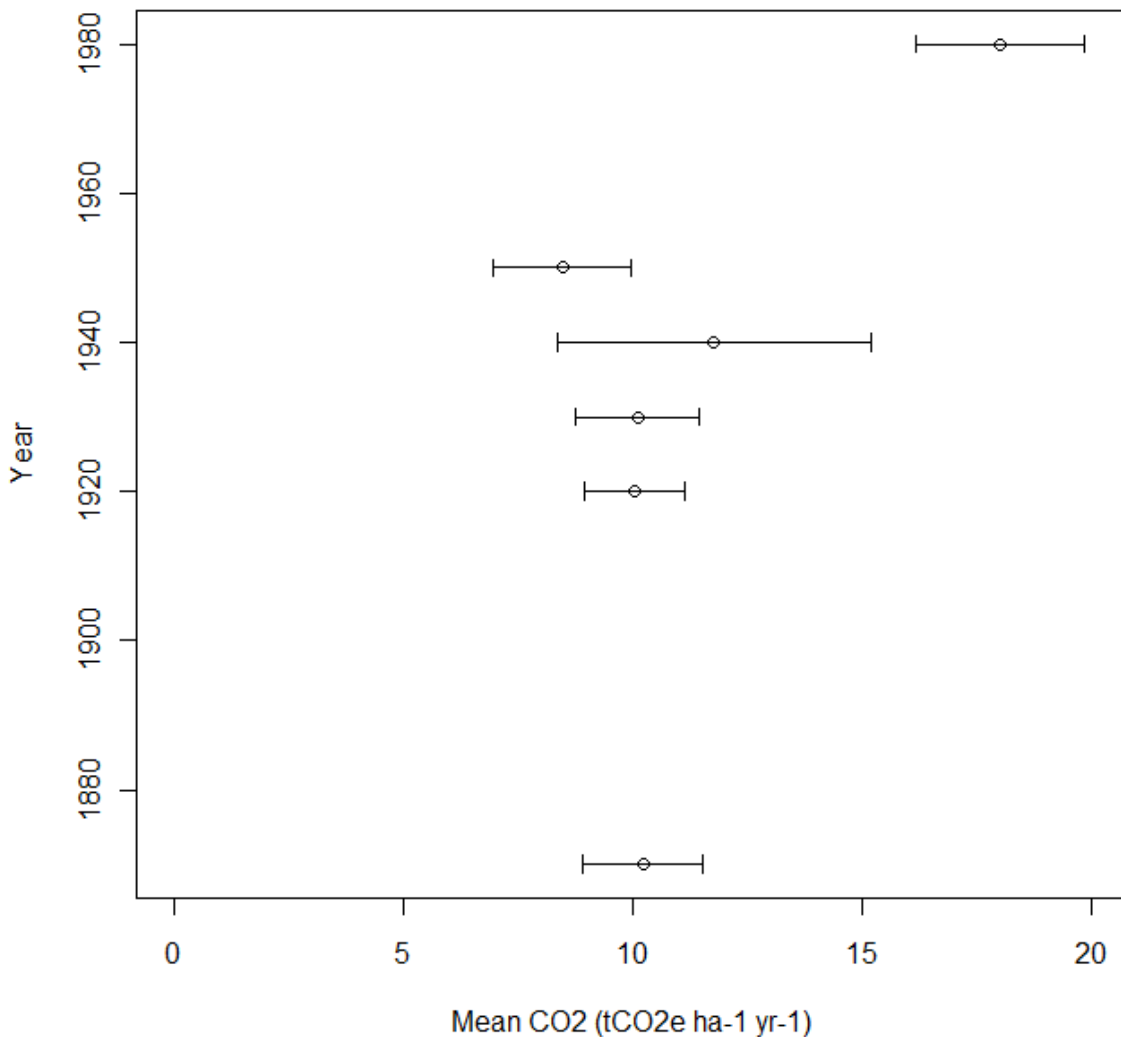
309 Table 1 Rates of peat growth, bulk density, carbon accumulation and CO₂ sequestration in
 310 valley mire (1876–2010). *Estimates were based on an alluvial clay marker dated to 1876.*
 311 *Values represent the means of 20 cores at all depths. Values ± mean show standard error.*

Number of peat cores	Rate of peat accumulation (mm yr ⁻¹)	Bulk density of peat (g cm ⁻³)	Ash-free carbon content (%)	Carbon accumulation (t C ha ⁻¹ yr ⁻¹)	CO ₂ sequestration (t CO ₂ e ha ⁻¹ yr ⁻¹)
20	9.51 ± 2	0.079 ± 0.004	51 ± 3.49	3.61 ± 0.45	13.23 ± 1.64

312

Temperate peatland carbon exchange model

313 Using the mean accumulation rate of $11.26 \text{ t} \pm 0.68 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ ($307 \text{ g C m}^{-2} \text{ yr}^{-1}$),
314 calculated using the SCP method, (Fig. 3), we can estimate that 88,000 tonnes of CO_2 have
315 been sequestered in the valley mire over the 134 years (1876-2010) <https://plymu.ni/peat->
316 [animation](#) .



317

318 Fig. 4 Past rates of carbon accumulation (expressed as CO_2e) at the blanket bog site (1850–
319 1980 AD). *Data were obtained from Red Lake Mire, Dartmoor, via sequential analyses of*
320 *carbon densities in peat core segments dated using SCP techniques. Values represent the*
321 *means of four cores taken in 2011. Error bars represent ± 1 standard deviation.*

Temperate peatland carbon exchange model

322 Rates of CO₂ sequestration in blanket bog ranged from 7.3 to 19.2 t CO₂e ha⁻¹ yr⁻¹ (Fig. 4).
 323 Mean values of ~10 t CO₂e ha⁻¹ yr⁻¹ occur until 1950. The most recent record from 1980
 324 showed an apparent increase to 18 t CO₂e ha⁻¹ yr⁻¹. Rose and Appleby (2005) acknowledge
 325 that SCP dating methods are only accurate to within 15 years of the actual date. Any error
 326 could be further compounded in the surface peat layers, where there is greater physical
 327 difficulty in obtaining intact cores, due to the abundance of *Eriophorum* roots.

328 Table 2 Mean rates of peat accumulation and CO₂ sequestration (1850–2010) in blanket bog
 329 dated using the spheroidal carbonaceous particle (SCP) method. *Values ± mean show*
 330 *standard error.*

	Core 1	Core 2	Core 3	Core 4	Mean
Peat accumulation mm yr ⁻¹	6.83	6.97	6.97	5.7	6.62 ± 0.31
CO ₂ sequestration t CO ₂ e ha ⁻¹ yr ⁻¹	11.92 ± 1.69	11.72 ± 2.26	11.74 ± 2.4	11.74 ± 1.79	11.77 ± 0.88

331 Mean rates of peat accumulation (Table 1) were significantly higher (9.51 ± 2 mm yr⁻¹) in the
 332 less consolidated valley mire peat compared to values shown in Table 2, for the higher
 333 density blanket bog peat cores (6.62 mm ± 0.31 mm yr⁻¹). However, means rate of CO₂
 334 sequestration for valley mire (Table 1) and blanket bog were not significantly different ($P \leq$
 335 0.05).

336 3.2 Net primary productivity of *Sphagnum* species on blanket bog and valley mire sites

337 Table 3 Capitulum density and annual increase in stem length for four *Sphagnum* species on
 338 Dartmoor. *Samples were collected from blanket bog and valley mire sites in the Decembers*

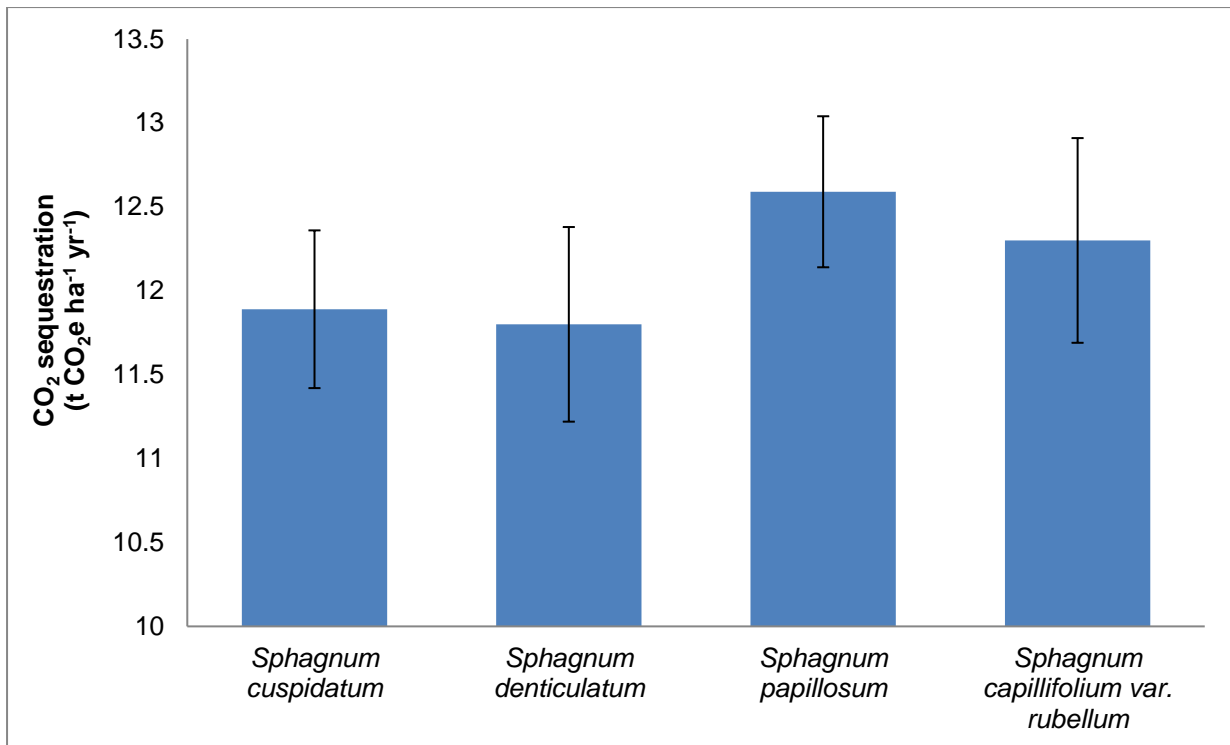
Temperate peatland carbon exchange model

339 of 2012 and 2013. Values following the means shown as \pm denote standard error. Values with
 340 different letters differ significantly ($P \leq 0.05$). Differences of variables were analysed with
 341 the Kruskal Wallis test and a multiple comparison test after Siegel & Castellan (1988).

	<i>Sphagnum cuspidatum</i>	<i>Sphagnum denticulatum</i>	<i>Sphagnum papillosum</i>	<i>Sphagnum capillifolium var. rubellum</i>
Number of replicate sample plots (dm^{-2})	26	26	26	26
Mean density of capitulum (dm^{-1})	$103 \pm 9.8\text{b}$	$60 \pm 6.2\text{a}$	$105 \pm 11.1\text{b}$	$117 \pm 19.2\text{b}$
Number of stem measurements	272	272	272	272
Mean annual growth of stem (cm yr^{-1})	$6.9 \pm 0.22\text{b}$	$5.5 \pm 0.11\text{a}$	$7.35 \pm 0.17\text{c}$	$6.85 \pm 0.37\text{b}$

342
 343 *Sphagnum capillifolium var. rubellum* had the highest capitulum density followed by *S.*
 344 *papillosum* and *S. cuspidatum* (Table 3). *S. denticulatum* was found to have a significantly (P
 345 ≤ 0.05) lower capitulum density when compared with the three other species. *S. papillosum*
 346 had the highest annual increase in length of $7.35 \text{ cm} \pm 0.17 \text{ cm yr}^{-1}$, which was significantly
 347 greater than the three other species. Krebs *et al.* (2016) reported that globally rates of growth
 348 of *S. papillosum* range from 0.4 cm to 4.6 cm yr^{-1} , with mean capitulum density ranging from
 349 125 dm^{-2} to 175 dm^{-2} . In Georgia, Black Sea, Krebs *et al.* (2016) found a mean increase in
 350 stem length of 5 cm yr^{-1} for *S. papillosum* with a range from $2.3 \text{ cm} \pm 1.3 \text{ cm}$ to
 351 $10.2 \text{ cm} \pm 3.0 \text{ cm yr}^{-1}$ and significantly higher mean values of over 12 cm yr^{-1} for *S. palustre*.

Temperate peatland carbon exchange model

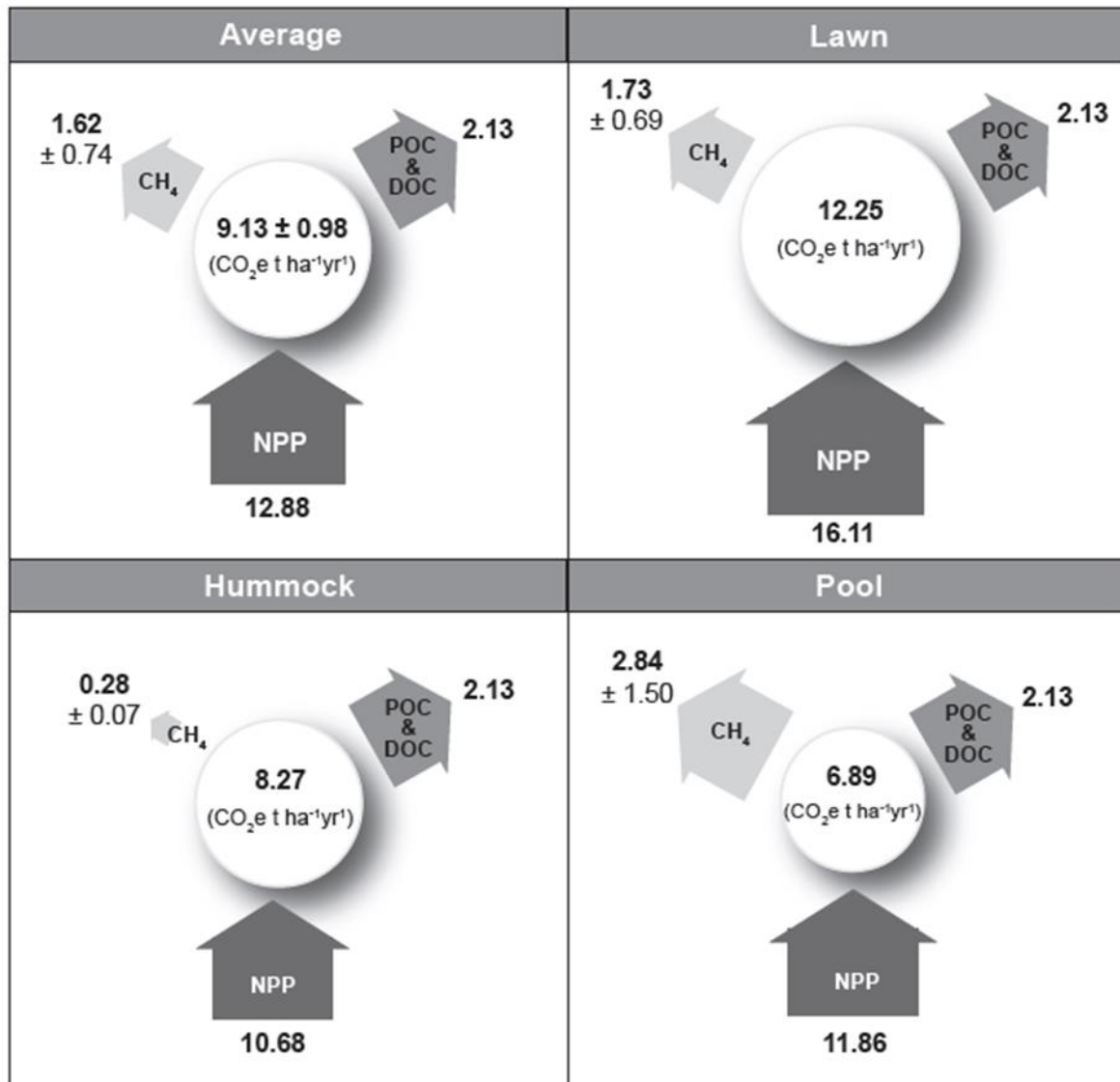


352

353 Fig. 5 Mean rates of net primary productivity of four *Sphagnum* species on Dartmoor, during
 354 2012 and 2013. Samples were collected from blanket bog and valley mire sites in the
 355 Decembers of 2012 and 2013 and are based on 1 year's growth. Bars show standard error
 356 plus and minus the mean. Values represent the means for replicated sample plots (dm²); *S.*
 357 *cuspidatum* n = 25, *S. denticulatum* n = 10, *S. papillosum* n = 24 and *S. capillifolium var.*
 358 *rubellum* n = 15. No significant differences ($P \leq 0.05$) were found in NPP between the four
 359 species, using the Kruskal Wallis test.

360 Fig. 5 shows that *S. papillosum* had the highest NPP ($12.59 \text{ t} \pm 0.45 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$),
 361 followed by *S. capillifolium var. rubellum* ($12.3 \text{ t} \pm 0.61 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$) and, the aquatic
 362 *Sphagna*: *S. cuspidatum* ($11.89 \text{ t} \pm 0.47 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$) and *S. denticulatum* ($11.8 \text{ t} \pm 0.58 \text{ t}$
 363 $\text{CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$). Rates were not found to be significantly different at $P \leq 0.05$. Higher rates
 364 of NPP were found for *S. papillosum* ($16.11 \text{ t} \pm 0.45 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$) in the lawn microform
 365 compared with *S. papillosum* in hummock microform ($9.06 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$).

366 3.3 Net ecosystem carbon balance for the valley mire



367

368 Fig. 6 Net ecosystem carbon balance for three peatland microforms (2011–2015). All values

369 are in t CO₂e ha⁻¹ yr⁻¹. Net primary productivity (NPP) of the *Sphagnum* species from each

370 microform were calculated from annual stem increment data. Mean NPP of *Sphagnum*

371 *capillifolium* var. *rubellum* (12.3 t ± 0.61 t CO₂e ha⁻¹ yr⁻¹) and *Sphagnum papillosum*

372 (9.06 t CO₂e ha⁻¹ yr⁻¹) for hummock microforms; *Sphagnum papillosum*

373 (16.11 t ± 0.45 t CO₂e ha⁻¹ yr⁻¹) for lawn microforms; and *Sphagnum cuspidatum*

374 (11.89 t ± 0.47 t CO₂e ha⁻¹ yr⁻¹) and *Sphagnum denticulatum* (11.8 t ± 0.58 t CO₂e ha⁻¹ yr⁻¹)

375 for pool microforms. Aquatic loss of carbon of $2.13 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ was calculated from
376 annual export of POC and DOC estimated for the entire peat body. CH_4 emissions were
377 monitored for microforms during 2014 and 2015 and converted to CO_2e . CO_2e losses from
378 CH_4 , POC and DOC were subtracted from NPP CO_2e inputs to give NECB values.

379 The values in the central circles of the NECB model (Fig. 6) show that all three of the
380 *Sphagnum*-dominated microforms in the valley mire were significant sinks for CO_2 during
381 the study period, with mean sequestration rates of $9.13 \text{ t} \pm 0.98 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ (249 g C
382 $\text{m}^{-2} \text{ yr}^{-1}$). The lawn microform was found to be the largest sink for CO_2 , followed by the
383 hummock and pool microforms, due largely to higher rates of *Sphagnum* NPP (Fig. 6).
384 Average summer CH_4 emissions were highest for the pool microform,
385 $2.84 \text{ t} \pm 1.5 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$, and lowest for the hummock microform,
386 $0.28 \text{ t} \pm 0.07 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$; the lawn microform had intermediate losses of CH_4 at
387 $1.73 \text{ t} \pm 0.69 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$.

388 4.0 Discussion

389 4.1 Past rates of peat accumulation

390 Actively growing peatlands sequester carbon, accumulating organic mass as the excess of
391 vegetation production over decay. In temperate peatlands, peat accumulation rates vary
392 according to differences in growing season, depth of oxygen diffusion, microform and plant
393 species composition (Clymo, 1984; Tallis, 1998; Charman, 2002; Ukonmaanaho *et al.* 2006;
394 Chambers *et al.* 2011). Our study suggests that since the industrial revolution (1850), rates of
395 peat accumulation averaged $9.51 \text{ mm} \pm 2 \text{ mm yr}^{-1}$ for valley mire (Table 1) and
396 $6.62 \text{ mm} \pm 0.31 \text{ mm yr}^{-1}$ for blanket bog (Table 2). These rates far exceed the average
397 historical rates described for more northerly, boreal and continental peatlands (Gorham,
398 1991; Clymo *et al.* 1998; Tallis, 1998; Roulet *et al.* 2007). Higher values were estimated by

399 Botch and Masing (1983) of up to 3 mm yr⁻¹ for boreal mires and 30.3 mm yr⁻¹ for lowland
 400 warm and humid mires in Georgia, Black Sea (Krebs *et al.* 2016). Long-term records for
 401 temperate systems suggest an average peat accumulation of 0.2–1 mm yr⁻¹ (Aaby & Tauber,
 402 1975), with blanket bogs reported as having a large range 0.1–1.2 mm yr⁻¹ (Tallis, 1998) and
 403 raised mires at rates of 0.5–1 mm yr⁻¹ (Charman, 2002; Roulet *et al.* 2007). The surface
 404 profile and vegetation composition of mires are in a constant state of change as shifts in peat
 405 accumulation rates are influenced by various factors, including changes in climate (Clymo &
 406 Pearce, 1995). Vegetation on the peat surface may show poor affiliation with depth of peat .
 407 Under natural conditions, acrotelm peat layers tend to show higher rates of carbon
 408 accumulation than the catotelm layers. This may arise because the fresh peat at the base of
 409 the acrotelm is still subject to occasional aerobic decomposition, or because of differences in
 410 vegetation composition in the past, or because there have been periods in the past when
 411 conditions were sub-optimal for peat formation (Charman, 2002; Holden *et al.* 2007;
 412 Lindsay, 2010; Charman *et al.* 2013).

413 **4.2 Comparison of past rates of carbon accumulation**

414 Our calculations of past (1850–2010) rates of carbon accumulation in temperate mires show
 415 similar rates for valley mire, 11.26 t ± 0.68 t CO₂e ha⁻¹ yr⁻¹ (307 g C m⁻² yr⁻¹) (Fig. 3) and
 416 blanket bog, 11.77 t ± 0.88 t CO₂e ha⁻¹ yr⁻¹ (321 g C m⁻² yr⁻¹) (Table 2). When compared to
 417 CO₂ sequestration recorded for boreal and high latitude northern peatlands (Gorham, 1991;
 418 Vitt *et al.* 2000; Turunen *et al.* 2002), our rates are at the upper limits of those recorded.
 419 According to Roulet *et al.* (2007) the rate of C accumulation in northern peatlands, over the
 420 last 6–8 thousand years, is estimated to be 0.73–1.1 t CO₂e ha⁻¹ yr⁻¹ (20–30 g C m⁻² yr⁻¹),
 421 with CO₂ sequestration rates for two peat cores in Ontario, Canada for the time interval
 422 3000–400 BP of 0.8 t ± 0.1 (SD) t CO₂e ha⁻¹ yr⁻¹ and 0.51 t ± 1.37 t CO₂e ha⁻¹ yr⁻¹. Values of

423 $< 1 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$, are typically reported for long-term peat records in northern and boreal
424 peatlands.

425 Utstøl-Klein *et al.* (2015) reported peat growth and C accumulation for 1978–1995 of
426 $8.38 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ ($230 \text{ g C m}^{-2} \text{ yr}^{-1}$) and for 1995–2012 of $13.56 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ (370 g C
427 $\text{m}^{-2} \text{ yr}^{-1}$) in *Sphagnum*-dominated boreal peatland in south-east Norway. These values are
428 similar to those reported for contemporary CO_2 sequestration in our study. Utstøl-Klein *et al.*
429 (2015) and Helfter *et al.* (2015) suggested that higher rates of C accumulation were
430 associated with increased precipitation. McNeil and Waddington (2003) concluded that
431 *Sphagnum* photosynthesis was greatest at wetter sites and that drying and wetting cycles
432 negatively affect *Sphagnum* NPP and net ecosystem CO_2 exchange.

433 **4.3 Net Primary Productivity (NPP) of *Sphagnum***

434 Fig. 5 shows that present-day mean rates of *Sphagnum* NPP for the southern moors ranged
435 from $11.8 \text{ t} \pm 0.58 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ for the aquatic species, *Sphagnum denticulatum*, to
436 $12.59 \text{ t} \pm 0.45 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ for the lawn species, *Sphagnum papillosum*, with *Sphagnum*
437 *capillifolium var. rubellum* ($12.3 \text{ t} \pm 0.61 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$) and *Sphagnum cuspidatum*
438 ($11.89 \text{ t} \pm 0.47 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$) intermediate. These rates for contemporary NPP are similar
439 to past rates of carbon accumulation occurring on site during the last 160 years. Krebs *et al.*
440 (2016) reported mean global NPP of *S. papillosum* to be $3.81 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ (204 g dry
441 $\text{weight m}^{-2} \text{ yr}^{-1}$) with a range of $0.54\text{--}9.15 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ ($29\text{--}490 \text{ g dry weight m}^{-2} \text{ yr}^{-1}$).
442 Gunnarsson (2005) suggested a mean global NPP for *Sphagnum* of $3.74\text{--}5.6 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$
443 ($2\text{--}3 \text{ t dry weight m}^{-2} \text{ yr}^{-1}$). Krebs *et al.* (2016) recorded the highest *Sphagna* productivity in
444 warm and humid peatlands in southern Georgia, Black Sea, with NPP for *S. papillosum* of
445 $5.03\text{--}10.24 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ ($269\text{--}548 \text{ g dry weight m}^{-2} \text{ yr}^{-1}$) and for *S. palustre* of 7.23--
446 $14.72 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ ($387\text{--}788 \text{ g dry weight m}^{-2} \text{ yr}^{-1}$); rates closer to our NPP values for *S.*

447 *papillosum*. Lütt (1992) reported CO₂ sequestration rates of 3.21–4.11 t CO₂e ha⁻¹ yr⁻¹ (172–
448 220 g dry weight m⁻² yr⁻¹) for *S. papillosum* in northern Germany, at similar latitudes to the
449 UK but with a less favourable continental climate. In the UK, Clymo (1970) reported values
450 of 11.4 t CO₂e ha⁻¹ yr⁻¹ (610 g dry weight m⁻² yr⁻¹) for transplanted *Sphagnum*. There is a
451 great deal of variability in the literature reflecting local growth conditions (Gunnarson, 2005;
452 Loisel *et al.* 2012; Campbell, 2014; Nijp *et al.* 2015; Krebs *et al.* 2016), the methodology
453 used and difficulty in assessing annual increases in *Sphagnum* growth (Clymo, 1970).
454 However, our mean values for *Sphagnum* NPP are over twice those of global means reported
455 by Gunnarsson (2005) and suggest that means reported from the literature may well provide
456 an underestimate of contemporary rates of carbon sequestration occurring under optimal
457 conditions in temperate peatlands. Similar values of 8.58 t CO₂e ha⁻¹ yr⁻¹ (234 g C m⁻² y⁻¹)
458 have been reported for a raised bog in New Zealand (Campbell *et al.* 2014), ascribed to the
459 mild climate and long growing season at temperate sites, showing the sensitivity of
460 ombrotrophic peat growth to climatic conditions.

461 **4.4 Net Ecosystem Carbon Balance (NECB)**

462 Mean contemporary CO₂ sequestration rates for *Sphagna* in the valley mire were calculated to
463 be 9.13 t ± 0.98 t CO₂e ha⁻¹ yr⁻¹ from the NECB model (Fig. 6). This value does not take into
464 account aerobic heterotrophic respiration. Ecosystem respiration is one of the major fluxes in
465 peatland net ecosystem CO₂ exchange (composed of autotrophic + heterotrophic respiration),
466 comprising of up to 80% of exchange (Riutta *et al.* 2007; Wilson *et al.* 2016; Kandel *et al.*
467 2018). By not accounting for the aerobic heterotrophic component of respiration in our model,
468 the calculated value of 9.13 t ± 0.98 t CO₂e ha⁻¹ yr⁻¹ is likely to be the maximum value for the
469 contribution of carbon sequestration to long-term carbon storage. Taking an upper estimate for
470 aerobic respiration from the literature of 50% of heterotrophic respiration (Riutta *et al.* 2007;

471 Laine *et al.* 2009; Minke *et al.* 2016; Wilson *et al.* 2016), it is possible that 3.65 t CO₂e ha⁻¹ yr⁻¹
472 ¹ (40% of annual NPP) could be lost from the acrotelm via aerobic heterotrophic microbial
473 decomposition. This would leave a minimum contribution of 5.48 t CO₂e ha⁻¹ yr⁻¹. However,
474 values at the lower end of the range 9.13 - 5.48 t CO₂e ha⁻¹ yr⁻¹, are unlikely in the pool and
475 lawn microforms, where levels of aerobic heterotrophic respiration will be low in the
476 permanently saturated conditions (Laine *et al.* 2009; Wilson *et al.* 2016). Wilson *et al.* (2016)
477 found considerable spatial and temporal variation in the annual NECB with the highest uptake
478 observed in *Eriophorum angustifolium* dominated intact sites in 2009 (6.25 t CO₂-eq ha⁻¹ yr⁻¹).
479 Vegetation at the Fox Tor valley mire site consisted of a mosaic of mire communities including
480 *Eriophorum* sp., other Cyperaceae and dwarf shrub species. As reported by Wilson *et al.* (2016)
481 many of these vascular plant species have higher growth rates than *Sphagna* and where present
482 with *Sphagnum* mosses are likely to lead to increased overall NPP.

483 NECB and its components in peatlands are known to vary considerably between sites
484 (Limpens *et al.* 2008; Lund *et al.* 2009), as well as inter-annually within sites. During a two-
485 year study of NECB in an intact low-lying ombrotrophic mire in Scotland, Dinsmore *et al.*
486 (2010) found that the peatland acted as a net CO₂e sink of 3.52 t CO₂e ha⁻¹ yr⁻¹. Run-off of
487 DOC was found to be the principal route for loss of carbon, accounting for 24% of the uptake
488 via NECB, with an estimated 12% evasion of carbon from the stream surface. Gaseous
489 emissions of CH₄ and N₂O combined returned 4% of CO₂e. In our study the valley mire
490 peatland acted as a carbon sink with a mean for peatland microforms of 9.13 t ± 0.98 t CO₂e
491 ha⁻¹ yr⁻¹ (Fig. 6). This value was over twice that recorded by Dinsmore *et al.* (2010) for
492 Scottish ombrotrophic mire. Our value for carbon sequestration of 9.13 t ± 0.98 t CO₂e
493 ha⁻¹ yr⁻¹ is at the upper limits of reported values, but is consistent with the figure of
494 11.26 t ± 0.64 t CO₂e ha⁻¹ yr⁻¹, derived from the analysis of dated cores at the same valley
495 mire site. This current study and that of Dinsmore *et al.* (2010) found that annual rates of

496 carbon sequestration accounted for 60-70% of NPP. As in Dinsmore *et al.* (2010) the most
497 significant loss of C from the peat body in our study occurred via the aquatic C pathway
498 (Fig.6). Export of aquatic carbon accounted for 17% of the NEE. Under base flow conditions
499 in our study, DOC and POC loads contributed equal proportions of the total organic carbon
500 load (48% and 51%, respectively). Dinsmore *et al.* (2010) and Pawson *et al.* (2008) found
501 higher losses of carbon under storm flow conditions and concluded that the release of POC
502 was episodic. Evans and Warburton (2007) found that the POC component contributed on
503 average 60% of the total organic carbon load on degraded peatland. Higher peat temperatures
504 and water table draw-down produce higher soil DOC concentrations, indicating either
505 increased biological production or increased aerobic oxidation (Fenner *et al.* 2005; Evans &
506 Warburton, 2007; Limpens *et al.* 2008).

507 In our study, variation in microform was observed with export of CO₂ as CH₄, accounting for
508 over 24% of NECB for the pool microform, 11% for the lawn microform and 2% for the
509 hummock microform (Fig. 6). This variation in CH₄ export for microforms is consistent with
510 that reported by other authors (Laine *et al.* 2009; Levy & Gray, 2015; Kendal *et al.* 2018)
511 who found that depth of water table was the key determinant of CH₄ export.

512 **4.5 Optimal conditions for *Sphagnum* growth**

513 *Sphagnum* productivity is controlled by mean annual temperature, precipitation and
514 photosynthetically active radiation (PAR) (Gunnarsson, 2005; Loisel *et al.* 2012; Nijp *et al.*
515 2015; Zhao *et al.* 2016). Dartmoor has limited seasonal variability and high precipitation,
516 providing waterlogged conditions to retard decomposition processes and giving rise to an
517 extended growing period. Lund *et al.* (2009) for northern peatland and tundra found that the
518 length of the growing season was the most important variable describing the spatial variation
519 in summertime gross primary production.

Temperate peatland carbon exchange model

520 Table 4 Changes in total seasonal precipitation from Dartmoor National Park (DNP) and
 521 Plymouth between 1961 and 2015. Values show % change from the mean, calculated by
 522 subtracting the 1961–2015 mean from the 1961 - 2015 trend (linear least squares fit). Values
 523 in brackets show the change in actual rainfall (mm). Statistically significant linear trends,
 524 using the seasonal Mann Kendall test, are denoted $**P \leq 0.01$, $*P \leq 0.05$. Data source Met
 525 Office (2016).

Location	Elevation	% change in total precipitation (mm)				
		Spring	Summer	Autumn	Winter	Annual
Plymouth Mountbatten	50 m	-5.4 (11)	13.6 (26.3)	7.7 (22.1)	5.6 (17.9)	5.2 (52.4)
Double Waters (DNP)	355 m	6 (21)	*23.2 (82.7)	**20.3 (106.3)	**20.9 (20.9)	**18.3 (208.4)
Hurston Ridge (DNP)	418 m	-1.5 (5.8)	12.6 (40.1)	10 (56.4)	13.9 (97.6)	**10.6 (208.4)
Princetown (DNP)	433 m	6.6 (26.1)	18.8 (74.5)	*14.5 (81.1)	*17.3 (106)	**14.8 (289.7)
White Ridge (DNP)	488 m	-3.6 (15.3)	13.3 (47)	8.2 (49.3)	11.3 (85.4)	7.8 (166.7)

526 Table 4 shows a significant increase in annual rainfall in three of the four Dartmoor sites. A
 527 significant seasonal increase occurred in summer, autumn and winter at the Double Waters
 528 site and autumn and winter at Princetown. Current climatic models for the UK (Murphy *et al.*
 529 2018), predict ensemble-mean reductions of 26% for summer rainfall and therefore a
 530 projected potential reduction in the size of the bioclimatic envelope for UK blanket bog
 531 (Gallego-Sala & Prentice, 2013). If such projections prove correct this may make peatlands in
 532 the southwest of the UK marginal for future peat growth (Gallego-Sala *et al.* 2010). Table 4
 533 shows a trend of increasing rainfall for all seasons apart from spring (March-May).
 534 Particularly noteworthy are the increases in summer rainfall (June-August); which is

535 significant at Double Waters, the most westerly windward upland site. Across all sites,
536 average annual rainfall for 1961–2010 was 1968 mm, compared with the mean for the study
537 period (2011–2015) of 2165 mm, an increase of 10%.

538 South west UK has an optimal climate for *Sphagnum* growth with a long growing season
539 associated with a warm, wet climate and limited seasonal variability compared with boreal
540 and continental climates (Charman *et al.* 2013). In recent decades, Dartmoor has seen an
541 increase in the length of the growing season for *Sphagnum* (number of days with minimum
542 air temperatures above freezing), an increase in total rainfall and an increase in the number of
543 contiguous days with rainfall. Krebs *et al.* (2016) modelled global biomass productivity of *S.*
544 *papillosum* and found a step change increase in carbon sequestration when the mean duration
545 of contiguous days with rain is longer than three days during the growth period.

546 **4.6 Response of modelled peatland bioclimatic envelope to climate change**

547 Many authors working with global climate models propose that there may be a decline in the
548 strength of high latitude and tropical peatland carbon sinks throughout the 21st century
549 (Friedlingstein *et al.* 2006; Canadell *et al.* 2007; Limpens *et al.* 2008; Clark *et al.* 2010;
550 House *et al.* 2010). Gallego-Sala and Prentice (2013) suggested that blanket bogs in south-
551 west UK are at the lower limit of bioclimatic space and that, when future climate change
552 scenarios were applied, a decline in the area of blanket peat was, according to their model,
553 projected under both UKCIP02 high and low emission scenarios (Hulme *et al.* 2002). These
554 modelled predictions do not appear to fit with the findings presented in this study for blanket
555 bog in South West England. Our results for contemporary rates of carbon sequestration
556 suggest that recent climate change may be having a positive effect on *Sphagnum* NPP and
557 rates of carbon sequestration in rain-fed peatlands, due to increased precipitation and an
558 extension in the length of the growing period for *Sphagnum* (Campbell *et al.* 2014; Krebs *et*

559 *al.* 2016). Contrary to the bioclimatic envelope model predictions of Clark *et al.* (2010) and
560 House *et al.* (2010), our findings suggest that blanket bogs in south-west UK may have the
561 potential to act as a significant sink for CO₂ under present upland climatic trends.

562 There is agreement amongst climate scientists that peatlands have had an important role in
563 past global cooling and that they have potential for significant negative feedbacks to the
564 climate system (Freeman *et al.*, 1993; Gorham, 1995; Fenner, 2005; Roulet *et al.* 2007;
565 Limpens *et al.* 2008; Yu *et al.* 2012; Charman *et al.* 2013). Peatland ecosystems are the most
566 efficient carbon store of all terrestrial ecosystems (Brooks & Stoneman, 1997; Worrall *et al.*
567 2003) and retaining active peatlands is one of the most cost-effective measures in achieving
568 zero net global carbon emissions (Ostle *et al.* 2009; Lindsay, 2010). Actively growing
569 peatlands are important in the global C cycle, capturing atmospheric CO₂ emissions and have
570 the potential to make a significant contribution over 100-year timescales.

571 **5.0 Conclusions and future research challenges**

572 This paper reports mean rates of CO₂ sequestration for *Sphagna* of
573 9.13 t ± 0.98 t CO₂e ha⁻¹ yr⁻¹ and carbon accumulation rates from peat cores dated to 1850 of
574 11.26 t ± 0.68 t CO₂e ha⁻¹ yr⁻¹ for valley mire and 11.77 t ± 0.88 t CO₂e ha⁻¹ yr⁻¹ for blanket
575 bog from an oceanic peatland setting in southwest England. These values are much higher
576 than the uncertainty range for rates of carbon accumulation in undrained/rewetted peatlands
577 reported in the IPCC Wetlands Supplement met-analysis (Blain *et al.* 2014). The IPCC values
578 do not incorporate local variability and are much lower than values for temperate peatlands
579 reported recently (Laine *et al.* 2009; Campbell *et al.* 2014; Wilson *et al.* 2016). Our findings,
580 together with other studies (Levy & Gray 2015; Ratcliffe *et al.* 2018), where NEE and NECB
581 models have been used to measure the strengths of carbon sinks, suggest that using past rates

582 of peat growth based on peat cores provides an underestimate of contemporary rates of CO₂
583 sequestration.

584 Recent changes in climate appear to have had no impact on the strength of peatland carbon
585 sinks in South West England. Past and contemporary peatland carbon sinks on our study sites
586 located in South West England were found to be at the upper limits of those reported in the
587 literature for temperate peatlands. This finding suggest that recent bioclimatic envelope
588 models (Clarke *et al.* 2010; House *et al.* 2010; Gallego-Saga *et al.* 2013) may underestimate
589 the potential future contribution that UK peatlands can make to carbon sequestration under
590 observed climatic trends. Temperate oceanic peatlands offer one of the more viable and
591 achievable options for long term storage of carbon fixed by photosynthesis under present
592 climate trends.

593 This study highlights how peatland carbon sinks have responded to anthropogenic climate
594 change and historic anthropogenic impacts, comparing contemporary rates of carbon
595 sequestration with past rates of carbon accumulation for the same site. Findings suggest that,
596 contrary to expectations based on bioclimatic envelope models, peatland carbon sequestration
597 rates in South West England are stable and possibly increasing, due to amongst other factors,
598 altered patterns of precipitation amount and frequency .

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