

2 **Assessing soil carbon dioxide and methane fluxes from a Scots pine raised bog-edge-**
3 **woodland**

4 Valeria Mazzola^{1,2,3}, Mike P. Perks², Jo Smith¹, Jagadeesh Yeluripati³ and Georgios Xenakis²

5 ¹Institute of Biological & Environmental Sciences, School of Biological Sciences, University of
6 Aberdeen, 23 St Machar Drive, AB24 3UU, UK. ²Forest Research, Northern Research Station, Bush Estate,
7 Roslin, EH25 9SY. ³Information and Computational Sciences Department, The James Hutton Institute,
8 Craigiebuckler, Aberdeen AB15 8QH, UK.

9 **Contact information:** Valeria Mazzola, School of Biological Sciences, University of Aberdeen, 23 St. Machar
10 Drive, AB24 3UU, UK. Email: r03vm16@abdn.ac.uk. Tel: +447538826042

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12
13 **Abstract:**

14 Scots pine bog edge woodland is a type of habitat typical on raised bogs where trees cohabit with bog
15 vegetation to form a low-density stand. Even though nowadays this habitat does not cover large areas, in a
16 future scenario it is possible that this environment will expand, either naturally (drier climate) or
17 anthropogenically, as the result of the application of new restoration strategies that could increase net landscape
18 carbon benefits from both peatland and woodland environments. This study is the first reported investigation in
19 Scotland exploring carbon flux dynamics from sparse woodlands on raised bogs. We examined how Scots pine
20 trees directly or indirectly affected soil temperature and moisture, ground vegetation, and consequently carbon
21 dioxide (CO₂) and methane (CH₄) soil fluxes. Soil CO₂ and CH₄ were measured at different distance from the
22 tree and thereafter assessed for both spatial and temporal variability. Our results showed that these low-density
23 trees were able to modify the ground vegetation composition, had no effect on soil temperature, but did affect
24 the soil moisture, with soils close to tree roots significantly drier ($0.25 \pm 0.01 \text{ m}^3 \text{ m}^{-3}$) than those on open bog
25 ($0.39 \pm 0.02 \text{ m}^3 \text{ m}^{-3}$). Soil CO₂ fluxes were significantly higher in the vicinity of trees ($34.13 \pm 3.97 \mu\text{g CO}_2 \text{ m}^{-2}$
26 s^{-1}) compared to the open bog ($24.34 \pm 2.86 \mu\text{g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). On the opposite, CH₄ effluxes were significantly
27 larger in the open bog ($0.07 \pm 0.01 \mu\text{g CH}_4 \text{ m}^{-2} \text{ s}^{-1}$) than close to the tree ($0.01 \pm 0.00 \mu\text{g CH}_4 \text{ m}^{-2} \text{ s}^{-1}$). This
28 suggests that Scots pine trees on bog edge woodland may affect soil C fluxes in their proximity primarily due to

29 the contribution of root respiration, but also as a result of their effects on soil moisture, enhancing soil CO₂
30 emissions, while reducing the CH₄ fluxes. There is, however, still uncertainty about the complete greenhouse
31 gas assessment, and further research would be needed in order to include the quantification of soil nitrous oxide
32 (N₂O) dynamics together with the analysis of complete gas exchanges at the tree-atmosphere level.

33 Keywords: raised bog, peatland-edge-woodland, Scots pine, carbon dioxide, methane, Scotland

34 **Highlights:**

- 35 • First investigation in Scotland of carbon flux dynamics from bog edge woodland
- 36 • Isolated trees modify ground vegetation and soil moisture only in their proximity
- 37 • Trees only affected soil carbon fluxes in their vicinity, not in the open bog
- 38 • Both trees and open bog may cohabitate without interfering with each other

39 **1 Introduction**

40 Peatlands cover at least 5% of the total world land surface (Yu et al., 2010), and they are estimated to
41 store more than 20% of the global soil organic carbon (C) within 3m depth (~650,000 Mt C, Leifeld and
42 Menichetti, 2018). Deep peat soils are therefore a key component of the global C cycle and a large terrestrial C
43 store. In Scotland, peatlands cover 23% of total land surface, around 1.8 Mha (Bruneau and Johnson, 2014) and
44 hold ~1620 Mt C stock (assuming an average peat depth of 2 m; Chapman, Bell, Donnelly & Lilly, 2009).
45 Around 90% of these peatlands are blanket bogs (Bruneau and Johnson, 2014; Ferretto et al., 2018), while the
46 rest can be classified as lowland wetlands. When lowland wetlands are exclusively rain-fed (ombrotrophic), they
47 are defined as raised bogs. This type of bog is mostly found in areas with topographic depressions where the
48 drainage is compromised due to either high groundwater table or low permeability of the substrate (Artz et al.,
49 2012). The constant waterlogging and the consequent slow decomposition of plant material leads to elevation of
50 the bog surface above groundwater level and creation of a typical dome shape, from which the term “raised bog”
51 is derived (Lindsey, 1995).

52 In the UK, lowland raised bogs are typically surrounded by agricultural lands or forests (Lindsey and
53 Immirzi, 1996), their peat depth can exceed 12 m and their extent can vary from a few to more than a hundred
54 hectares (Artz et al, 2012). Based on the UK Lowland Raised Bog Inventory (LRBI, 1996) and according to
55 Lindsay and Immirzi (1996), the total extent of raised bogs in UK is around 69,700 ha, of which 27,884 ha are
56 in Scotland (peat depth > 1 m). The typical raised bog surface can show a peculiar structure characterized by the

57 presence of hummocks (drier) and hollows (wetter) and dominance of peat forming *Sphagnum* spp. and
58 acidophilic plants (Lindsay, 1995).

59 When trees are found to cohabitate with this type of vegetation, naturally or as an effect of the alteration
60 of the bog's natural hydrology, they are defined as bog woodlands. In the Interpretation manual of European
61 Union Habitats (European Commission, 2007) bog woodlands are defined as “coniferous or broad-leaved
62 forests on a humid-to-wet peaty substrate, with the water level permanently high or even higher than the
63 surrounding water table” and very poor in nutrients. It further describes them as generally small and non-
64 intrusive groups of trees (typically Scots pine, birch and willow) able to co-exist with the bog habitat in a
65 relatively stable relationship, without the loss of bog species and/or perturbation of the bog hydrology (IUCN,
66 2020). Some bog woodlands are also regarded as a conservation priority habitat type (M3-91D0 type) under the
67 EU Habitats Directive (European Commission, 2007). The UK Biodiversity Action Plan (UKBAP) includes bog
68 woodlands dominated by Scots pine in the Habitat Action Plan for Wet Woodlands, specifying that they are of
69 particular importance in Scotland (English Nature, 1998), mainly in the Scottish Highlands, in the Cairngorms
70 and in the north east.

71 Bog woodland is extensive in Finland, Norway and Sweden, becoming rare through the lowlands of western
72 Europe. It may occur, however, in Germany, Poland, the Czech and Slovak republics, and in the in the pre-Alps.
73 Bog woodlands are also present In Canada and in Siberia. Even though nowadays bog woodlands dominated by
74 Scots pine do not cover large areas in Scotland (estimated around 16000 ha), there is evidence that, at one time,
75 trees were not rare on peatland environments. It is estimated that during relatively drier climatic periods,
76 occurring between 7000 and 4000 years ago (MacKenzie and Callander, 1995), this habitat covered about about
77 1.5 million ha (JNCC, 2008), as substantiated by the large number of stumps found buried in the peat (Birks,
78 1975). Godwin (1956) proposed that in Scotland, stunted Scots pine may have grown on raised bogs since their
79 formation, becoming denser during dry climatic periods and declining as wetter climate returned. In view of
80 this, in a future scenario where Scotland will be characterized by a warmer and drier climate (Scottish
81 Government, 2019), it is possible that bog woodlands would naturally expand again; this highlights the
82 importance of understanding the climate dynamics of this habitat to inform appropriate management.

83 Interest in bog woodlands has recently further increased after the publication of new restoration policies
84 by Forestry Commission Scotland (2015), which covers the development of new strategies for minimal
85 intervention to create open woodlands in previously afforested peatland locations. Forestry Commission
86 Scotland (2015) defines these low-density woodlands as “peatland edge woodlands”; the purpose of creating

87 these habitats is to combine the benefits of both woodlands and peatlands in terms of biodiversity and C storage.
88 Native woodlands and peatlands are indeed two of the largest natural climate regulating ecosystems and their
89 combination in this new restoration strategy could potentially increase net landscape C benefits from both
90 environments, without compromising one for the other (IUCN, 2020). Peatland edge woodland is the preferable
91 option where there is no intention to start a second rotation of the forest, nor restore bog function after felling
92 (Forestry Commission Scotland, 2015). The guidelines further specify that the peatland edge woodland would
93 require low-density planting (or natural regeneration), with 50% trees and 50% open bog (~500 trees/ha),
94 preferring the use of native species. This new approach would also fit the purpose of increasing the forested area
95 in order to meet the targets set by the Scottish Government (2018) which aim to increase the woodland cover
96 from around 18% to 21% of the Scottish land area by 2032.

97 It is important to note, however, that trees (especially on peat) are not passive components of the
98 ecosystem. In afforested blanket peats, evapotranspiration from densely planted Sitka spruce trees for example
99 is known to have a negative impact on the water table depth and soil moisture (Hargreaves et al., 2003). When
100 peat dries out, the waterlogged condition that ensure peat growth is missing, causing aerobic decomposition of
101 the organic matter and consequent emissions of carbon dioxide (CO₂). Many studies have suggested how trees
102 may affect soil C emissions by enhancing soil respiration (Yamulki, 2017, Liu et al., 2014; McCarthy and
103 Brown, 2006; Potts et al., 2010; Chapman, Campbell & Pury, 2003). Trees can also affect soil C dynamics and
104 the soil organic carbon pool through the input of leaf litter, lignin, decomposed roots, root exudates, and
105 dissolved organics leaching from the litter layer (D'Amore and Keane, 2016).

106 Another important aspect is the effect of tree canopies. The shade formed from the projection of the tree
107 crown above the ground may decrease the diurnal soil temperature variations and reduce irradiance on the
108 surface, consequently affecting high and low soil temperatures (Liu et al., 2014). It may also increase the
109 humidity of the area under the trees, lowering evaporation losses from the surrounding soil. Trees can also
110 intercept significant amounts of rainfall, a proportion of which is then lost to the atmosphere (Xiao et al. 2000).

111 Trees may also affect soil methane (CH₄) dynamics in their proximity. Previous studies have shown that
112 vascular bog species are able to transport CH₄ directly from the soil to the atmosphere, by root uptake and
113 transport through the aerenchyma, bypassing CH₄ oxidation (Couwenberg, 2009; Davidson et al., 2016; Findlay,
114 2020; Greenup et al., 2000; Joabsson, Christensen, & Wallén, 1999; McNamara et al., 2008; Whalen, 2005).
115 Machacova et al. (2016) provided evidence that Scots pine also has the ability to function as CH₄ conductor,
116 with CH₄ uptakes from the forest floor being correlated with high CH₄ fluxes from the tree shoots, indicating a

117 direct CH₄ pathway to the atmosphere via the tree transpiration streams, mirroring other studies for different tree
118 species and environments (Carmichael et al., 2014; Covey and Megonigal, 2019; Rusch and Rennenberg, 1998;
119 Terazawa et al., 2015; Yamulki, 2017).

120 Trees may also have an effect on peatland vegetation distribution. As reported by Peacock et al. (2018)
121 trees can modify plant composition due to the effect of their shade and evapotranspiration. In particular, they
122 noticed a decrease of Sphagnum and vascular plants, typical bog species, that usually vegetate in more open and
123 wetter environments. According to various studies, vegetation composition plays a key role in the peatlands C
124 dynamics, mainly on CH₄ fluxes (Mazzola et al., 2021; Joabsson et al., 1999; Levy et al., 2012). The
125 aerenchymatous tissues of vascular plants like Eriophorum, can transport CH₄ from the roots directly to the
126 atmosphere, bypassing the aerobic, CH₄-oxidizing peat layers (Whalen, 2005). Since the contribution of
127 vascular species to overall CH₄ emissions has been estimated to be 25-97% (Whalen, 2005), we might expect
128 higher CH₄ fluxes from areas with a higher percentage of these “methane shunt” species (Davidson et al., 2016).

129 The rarity of these habitats, in the UK, has limited research effort and there remains a lack of
130 understanding of C flux dynamics from sparse woodlands on raised bogs. To the best of our knowledge, this
131 study represents the first reported investigation in Scotland into bog-edge woodland C fluxes, providing new
132 evidence of CO₂ and CH₄ dynamics occurring between the trees and the bog. We investigate how Scots pine
133 trees directly or indirectly affect soil temperature and moisture, ground vegetation, and consequently soil CO₂
134 and CH₄ fluxes. We hypothesize that (a) single trees will influence CO₂ and CH₄ emissions and in particular will
135 result in the root zone having a lower soil temperature than the open bog, emitting more CO₂ and less CH₄, (b)
136 the open bog zone will be warmer and wetter than the root or canopy zone, providing a larger source of CH₄, (c)
137 the canopy zone will have intermediate properties between the root zone and the open bog and (d) bog
138 vegetation will influence soil emissions of both CO₂ and CH₄.

139

140 **2 Materials and method**

141 *2.1 Study area*

142 Our experiment site was located in Maud Moss (57°04'57.5"N 2°36'50.6"W, Figure 1), a raised bog of 42
143 ha, about 10 km west of Banchory (Aberdeenshire, Scotland). The area is a dystrophic basin peat, with a topsoil
144 organic C content of 51%. The Carbon and Peatland map (NatureScot, 2016), which puts together existing soil

145 and vegetation data, classifies the site as CLASS 1, which refers to nationally important C rich soils, deep peats
146 and priority peatlands habitats, considered as areas of high conservation value. The climate in Maud Moss is
147 mild, with mean precipitation of 780 mm (average 1981-2010) and a mean daily temperature of max 13.7 °C
148 and min 2.2 °C (Aboyne weather station, 57°04'37.2"N 2°50'09.6"W, 140m amsl and ~15 km from the
149 fieldsite). The wettest month is October (79 mm average), while the driest is February (53 mm average rainfall).

150 There was no recent anthropic disturbance, but the site was affected by peat extraction in the early 1900s.
151 This is substantiated by the presence of scattered small square pits throughout the area. The pits (now naturally
152 filled with water) have an average depth of 50 cm and their dimension varies across the site. Peat depth was
153 measured in early spring 2018 by using a 5m long peat probe. Peat depth was between 2 - 3 m at the edge and
154 >5m at the centre of the bog.

155 According to the classification by McHaffie et al (2002), Maud Moss is classed as a wooded bog, with
156 bog ground vegetation, scattered with mature trees of moderate height and an open canopy. The site is a Scots
157 pine (*Pinus sylvestris* L.) woodland with trees both at the edge and the centre of the bog. It is not clear whether
158 the trees were planted or resulted from natural invasion of the bog. Wood cores randomly sampled in the area,
159 showed that trees at edge of the bog are older (~80 years) than those in the centre (~20years), which suggests
160 natural invasion. Initial investigation of tree size and age suggests that trees at the edges of the area are older,
161 taller with a larger girth, while trees in the central part were younger, shorter and showed a stunted
162 growth. These two zones were connected by a third area that we called the “buffer zone”, where trees were less
163 stunted than the ones at the very centre of the bog but not as big and dense as the ones at the very edge.

164 Prior to the start of the experiment, a vegetation survey was conducted in November 2017. Vegetation
165 analysis used the same methodology as reported by Mazzola et al. (2020). The survey showed mostly common
166 cotton grass (*Eriophorum angustifolium*, Honck), ling heather (*Calluna vulgaris* (L.) Hull), cross-leaved heath
167 (*Erica tetralix*, L.), species that are suited to acidic soils in open, sunny areas. Red-stemmed feather moss
168 (*Pleurozium schreberi* (B. Mitt) was also present, occurring with ling heather and cotton grass. *Sphagnum*
169 *capillifolium* (E. Hedw) and *Sphagnum tenellum* (B. Bory) were the two sphagnum moss species found on the
170 site. *Cladonia* spp., heath plait-moss (*Hypnum jutlandicum*, Hedw) and tree fingerwort (*Ptilidium*
171 *pulcherrimum*, Weber) were also observed in the vegetation survey performed on the site.

172

173 2.2 *Experimental design*

174 To measure the direct or indirect influence of trees on soil CO₂ and CH₄ emissions, vegetation composition and
 175 environmental variables (soil temperature and moisture), we established four transects in the “buffer zone”
 176 (Table 1 and Figure 1), each one starting from a tree trunk and proceeding towards the open bog. We selected
 177 trees with similar height and diameter of the stem at 130 cm, making sure they were not too close to each other
 178 so as to ensure the results from each transect were independent. For this reason, we opted for the minimum
 179 distance between trees to be bigger than the transect length.

180 Table 1 - Maud Moss transects features (UK Grid Reference Finder, 2011). Distance between each plot was
 181 measured using the tree as a waypoint.

Transect	Grid Reference	Peat Depth(m)	Tree Height (m)	Tree Girth (cm)	Distance (tree to tree)
T1	NO 62935/99100	>5	6	55	1 ↔ 2 (20.2 m)
T2	NO 62945/99117	>5	7	55	2 ↔ 3 (17.9 m)
T3	NO 62968/99119	3.6	7	60	3 ↔ 4 (19.2 m)
T4	NO 62965/99098	4.7	6.3	75	4 ↔ 1 (29.7 m)

182



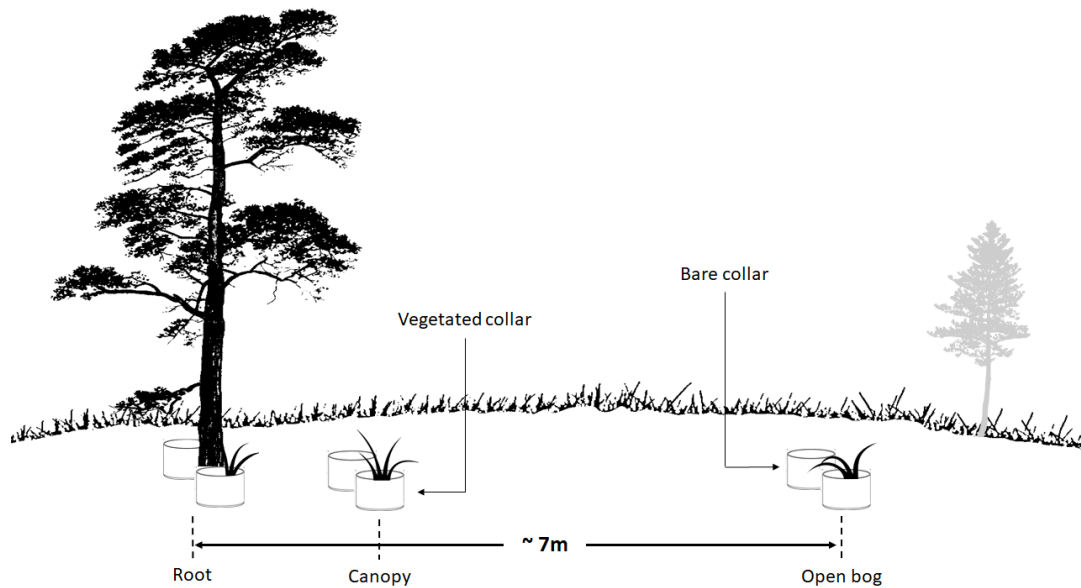


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185 Figure 1 – Aerial images of Maud Moss (A). In Figure B we identified three areas: in area a (yellow) trees were taller and
186 with a larger girth, and forest was denser; area c (green), in the centre of the bog, was characterized by presence of shorter
187 and stunted trees; b (red) is the “buffer zone”, where the white box represents the area of our study. The location of the four
188 transects is enhanced in Figure C. Figure 1D shows a view of the site from the ground.

189

190 Along each transect, we placed a total of six collars following an imaginary line (~ 7m) that went from
191 the trunk of the tree (root zone) and its canopy projection (canopy zone), to a zone that we termed “open bog”,
192 where we assumed the individual tree features had no more direct influence on soil processes. We positioned
193 two collars (collar types, one bare and one vegetated) within each zone (Figure 2), to determine how the
194 presence or absence of bog vegetation affected soil CO₂ and CH₄ fluxes. The collars were made out of polyvinyl
195 chloride (PVC), with a diameter of 10 cm and inserted 5 cm into the soil with ~2 cm left above ground. Collars
196 were maintained throughout the whole study, removing vegetation growing inside the bare collars and re-
197 inserting any that were dislodged by peat movements, occurring mainly after winter.



198

199 Figure 2 – Example of transect structure. The transect follows a line from the tree trunk to the open bog area (~7 m).
 200 On the transect are identified three zones (root, canopy and open bog), each of which contains two collars, one bare and one
 201 vegetated.

202

203 2.3 Carbon dioxide and methane flux measurements

204 Soil CO₂ and CH₄ fluxes were measured between December 2017 and September 2018 at irregular
 205 intervals for a total of 9 sampling dates. Measurements were done using an Ultra-Portable Greenhouse Gas
 206 analyser (UGGA, Los Gatos Inc., San Jose, CA) with a Licor-6400-09 soil chamber (Li-Cor Inc., Lincoln, NE)
 207 connected to the UGGA through Bev-a-line tubing with return connection. The Li-6400-09 was a dark chamber
 208 and therefore we measured CO₂ fluxes in the form of ecosystem respiration, which includes both autotrophic
 209 and heterotrophic respiration (hereafter referred to as CO₂ flux). During measurements, the chamber (area =
 210 71.6 cm², volume = 991 cm³) was placed on the PVC collar for three minutes and an extra 20 seconds (to enable
 211 initial disturbance and pressure fluctuations to stabilize), with the intention to reach a stable increase in both
 212 CO₂ and CH₄ concentrations within the chamber headspace. After every measurement and before placing the
 213 chamber on the next collar, we allowed ambient air to flow in the chamber for two minutes in order to re-
 214 establish ambient gas concentrations in the analyser. The UGGA pump which ensured a constant flow rate and
 215 good air circulation in the system, together with the action of the perforated manifold inside the chamber which
 216 provided a homogeneous air mix, prevented the formation of potential localized pressure within the chamber
 217 headspace.

218 Fluxes were calculated using the linear slope fitting technique based on changes in CO₂ and CH₄
219 concentration in the chamber headspace over time:

$$F = \frac{\delta v \times P \times V}{R \times (273 + T) \times t \times A} \quad (1)$$

220 where F is the CH₄ or CO₂ flux ($\mu\text{mol m}^{-2} \text{s}^{-1}$), δv is the change in gas concentration (slope) in the chamber
221 headspace over the closure time ($\mu\text{mol mol}^{-1}$), P is the atmospheric pressure (atm), V is the total volume of the
222 chamber (m^3), R is the gas constant ($\text{atm K}^{-1} \text{mol}^{-1}$), T is the temperature in the chamber ($^{\circ}\text{C}$), t the enclosure
223 time (s) and A is the chamber area (m^2). Only fluxes based on regressions with a p-value < 0.05 were
224 considered as robust estimates, and kept for further analysis. This led to the rejection of 1% of CO₂ fluxes and
225 11% of CH₄ fluxes. Potential outliers were removed before calculation of the means, using the interquartile
226 range criterion (IQR), where all the observation above $Q3 + 1.5 \times \text{IQR}$ or below $Q1 - 1.5 \times \text{IQR}$ (where $Q1$ and $Q3$
227 correspond to first and third quartile respectively) were considered potential outliers (Tukey, 1977; Schwertman
228 et al., 2004). This led to rejection of 4.5% of fluxes for CH₄ and 1.8% for CO₂. Fluxes in $\mu\text{mol m}^{-2} \text{s}^{-1}$ were then
229 converted in $\mu\text{g m}^{-2} \text{s}^{-1}$ by multiplying the flux by the molar mass of the respective gas ($16.04 \mu\text{g } \mu\text{mol}^{-1}$ for
230 CH₄, $44.01 \mu\text{g } \mu\text{mol}^{-1}$ for CO₂). We report CH₄ fluxes in CO₂ equivalents (CO₂eq) when investigating the C
231 balance, estimating a global warming potential for CH₄ of 28 CO₂eq over 100 years with no feedbacks (Myhre
232 et al., 2013).

233 Collars were allocated to the vegetation type according to the most dominant species growing inside the
234 collar. We initially gave a specific percentage (%) cover in relation to the area covered by each species inside
235 the collar. The result was a total % coverage (sum of all species) that most of the time exceeded the 100%. We
236 then normalized the results, obtaining a normalized covered area for every species in the collar. For example, a
237 collar might present a 100% of the area covered by *Sphagnum* (layer 1), with presence of 5% of *Calluna* (layer
238 2), with a total of 105%. Normalising the data, the % area covered by the species became 95% for *Sphagnum*
239 and 5% for *Calluna*. Collars containing *Eriophorum* were treated differently since this vascular species is able to
240 transport CH₄ directly and in larger quantities from the soil to the atmosphere. *Eriophorum* was attributed to the
241 relative collar according to presence/absence (even if not abundant). For example, a collar where 10% was
242 covered with *Eriophorum* was automatically considered an “*Eriophorum* collar”. This is because even a small
243 amount of this species can lead to significantly high CH₄ fluxes (Whalen et al., 2005).

244 Lastly, we estimated the total C efflux by summing the average CO₂ and CH₄ fluxes (in CO₂eq) over the
245 entire study period for each zone and collar type.

246 2.4 *Environmental monitoring*

247 Ancillary measurements of soil temperature were taken at 2 cm (Ts2) and 10 cm (Ts10) below the soil
248 surface and soil moisture (θ) at 6 cm depth (ML3 Tetha probe, Delta-T Devices Ltd). These were collected
249 outside each collar and immediately after gas measurements to minimize disturbance while sampling. Winter
250 (December 2017 – January 2018) collection of soil temperature and moisture were not possible for some
251 sampling dates due to frosts, leading to gaps in the environmental variables.

252 2.5 *Statistical analysis*

253 Data analysis was undertaken in R Core Team (2020). The p-values were used to determine statistically
254 significant differences and correlations. We assumed strong evidence against the null hypothesis (no
255 difference/correlation) when the p-value was less than or equal to 0.05, therefore allowing the null hypothesis to
256 be rejected in favour of the alternative hypothesis. We tested the significance of the differences in the gas fluxes
257 (CO₂ and CH₄) and environmental variables (Ts2, Ts10 and θ) between different zones, collar types, transects
258 and vegetation types (including bare collars) by performing an analysis of variance (ANOVA, Tukey's range
259 test with pairwise comparison). We tested correlations between CO₂ and CH₄ fluxes and environmental
260 variables for different collar types, zones and transects.

261 For data analysis, both CO₂ and CH₄ data were log₁₀ transformed, because they did not meet normality
262 of distribution. No transformation was needed for Ts2, Ts10 and θ , because they met normality of distribution.
263 We used a linear mixed-effect model (LMM, *nlme* package, Pinheiro et al., 2020) to determine whether soil
264 fluxes could be explained by climatic factors (soil temperature and moisture), presence of vegetation and
265 relative species (vegetation), distance from the tree (zones), transect number and date of sampling (time point).
266 We first built the more complex model, taking into account all the variables we wanted to test. Goodness of
267 model fit was assessed estimating the Akaike's Information Criterion (AICc). We compared the AICc of the
268 different models and the model with lowest AICc was selected as the most probable model (Burnham and
269 Anderson, 2002). Whenever we found models with delta (Δ) AICc of less than 2, we considered them to be as
270 good as the most probable model. The final model chosen was then the one with the highest "weight" (a
271 parameter obtained using the "model.sel" function from *MuMIn* package, Barton, 2020). Weight varies from 0
272 to 1, where 1 means there is 100% chance that the model is the best approximation among the models that we

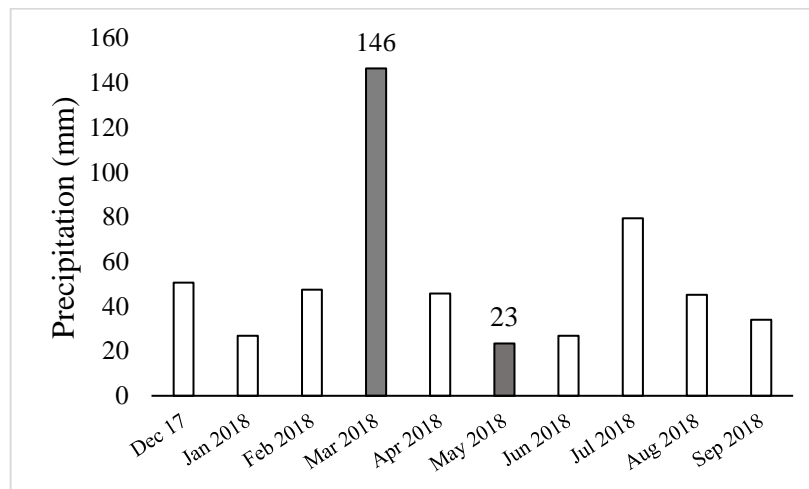
273 considered. In this study, the best model was determined by combining both the lowest AICc and the highest
274 weight. Lastly, the “step” function dropped from the candidate model the factors that had no predictive value.
275 We tested the models for multicollinearity, by calculating the variance inflation factor (VIF) using the
276 *performance* package. We assumed absence of collinearity for $VIF = 1$, low collinearity for $VIF < 5$, moderate
277 collinearity for $5 < VIF < 10$ and high collinearity for $VIF > 10$. We only considered models where
278 multicollinearity was absent, low or moderate. Lastly, we used the *r.squaredGLMM* function from the
279 *piecewiseSEM* package (Lefcheck, 2016) to calculate the proportion of the variance described respectively by
280 the fixed factors only (marginal R^2) and by both fixed and random factors altogether (conditional R^2).

281 3 Results

282 3.1 Climate and environmental variables

283 Figure 3 shows monthly precipitation between December 2017 and September 2018 from the Westhill
284 weather station (SEPA, 2020) located 28 km from the site. Monthly rainfall during the study period showed
285 highest rainfalls in March, lowest in May.

286



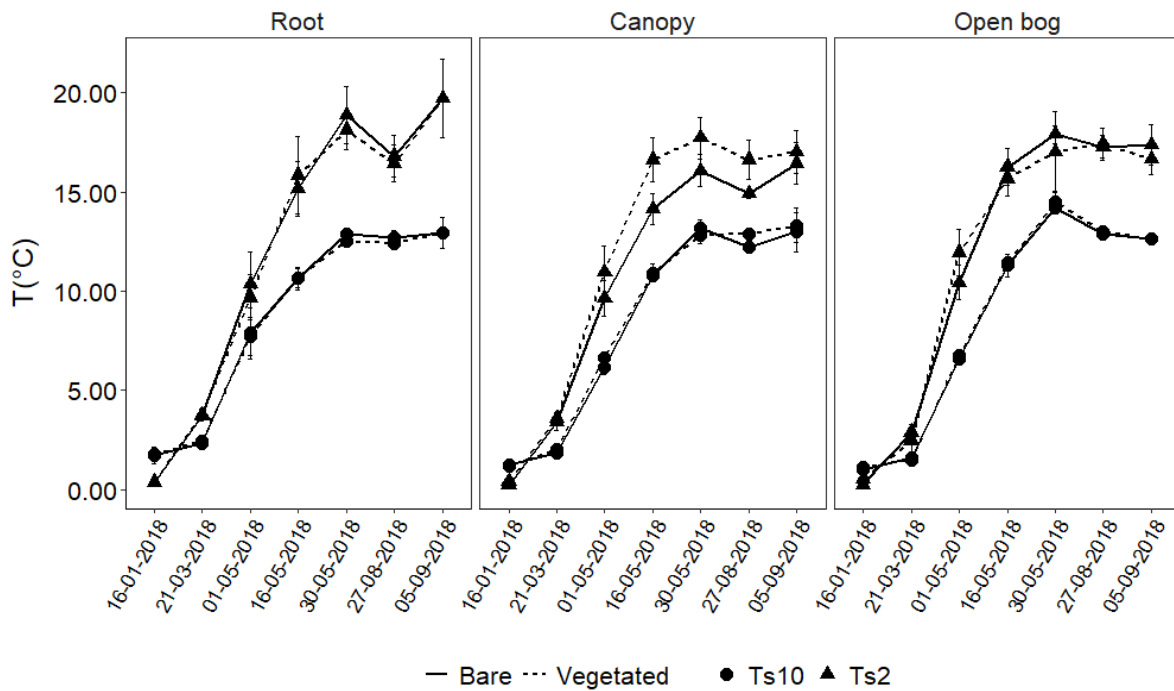
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288 Figure 3 –Monthly precipitation (bars) for Westhill (SEPA, 2020) in the period December 2017 – September 2018. Filled
289 bars indicate maximum and minimum precipitation values.

290 On average, soil temperature at 10 cm (Ts10) depth were lower compared to those closer to the soil
291 surface, at 2cm depth (Ts2), but there was no statistical difference with zones and collars type (Figure 4).
292 Generally, both Ts2 and Ts10 increased from January to the end of May, decreasing at the end of August and
293 then increasing again in September (with the exception on Ts2 on vegetated collars and Ts10 in the open bog).

294 In January 2018 Ts2 never exceeded 0.5 °C and the absolute lowest temperature was in the same month for bare
 295 collars under canopy (0.2 ± 0.1 °C). Soil temperatures at 10 cm were warmer during winter for every zone type,
 296 but remained colder during spring and summer. During our study, the highest soil temperature recorded (Ts2)
 297 was in September (19.7 ± 1.9 °C) for bare collars in the root zone.

298



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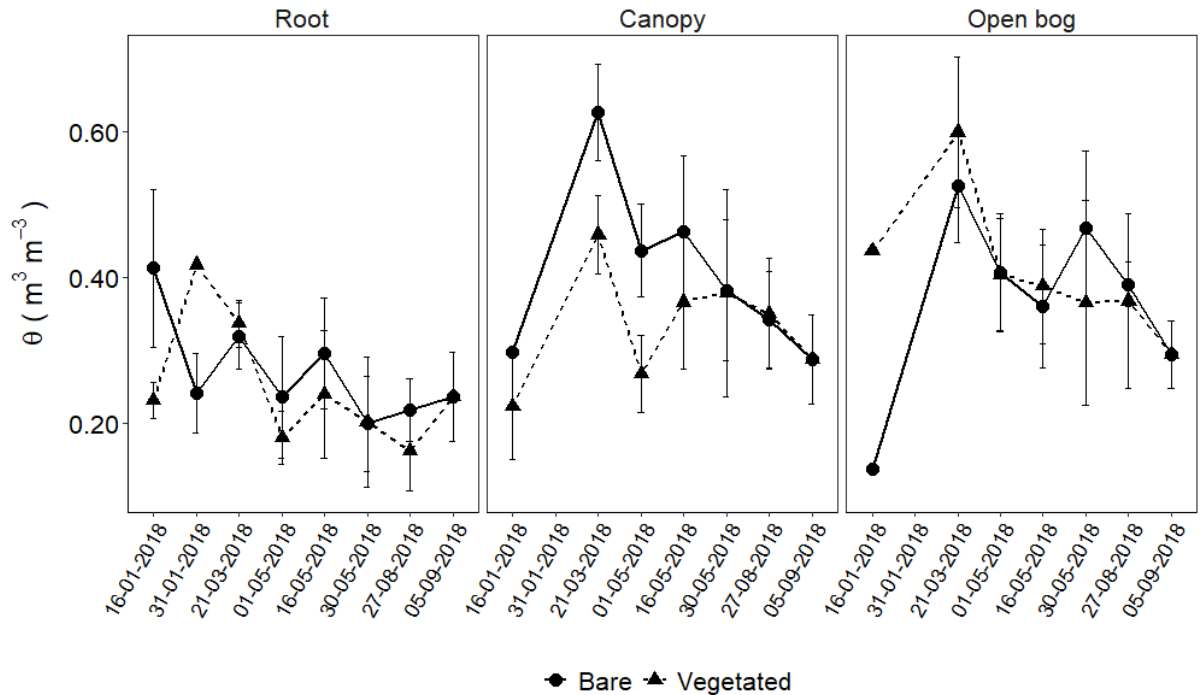
300 Figure 4 – Soil temperature at 2 cm (Ts2, solid triangles) and 10cm (Ts10, solid circles) below the soil surface in different
 301 zones and collar types, sampled between January and September 2018. Solid lines represent bare soils, while dashed lines
 302 symbolize vegetated soils. The error bars represent the standard errors.

303

304 Soil moisture was significantly different between zones ($p < 0.001$, $Df=2$, $F\text{-value}=13.56$, specifically
 305 between root and canopy and root and open bog zone) but not between collar types. Figure 5 shows that the
 306 open bog was, on average, the wettest zone (0.39 ± 0.02 $\text{m}^3 \text{m}^{-3}$), followed by the canopy (0.37 ± 0.02 $\text{m}^3 \text{m}^{-3}$)
 307 and the root zones (0.25 ± 0.01 $\text{m}^3 \text{m}^{-3}$). Soil moisture under the canopy and in the open bog followed the
 308 rainfall seasonality, while moisture under roots followed a decreasing pattern from winter (wetter values) to
 309 September. The noticeable moisture peaks in March relative to canopy and open bog correspond to the rainfall
 310 peak for the same month. The highest soil moisture value recorded was for bare collars under the canopy ($0.62 \pm$
 311 0.07 $\text{m}^3 \text{m}^{-3}$) and for vegetated (0.60 ± 0.10 $\text{m}^3 \text{m}^{-3}$) and bare (0.53 ± 0.08 $\text{m}^3 \text{m}^{-3}$) collars on open bog. The

312 lowest moisture was recorded in August for vegetated collars on roots ($0.16 \pm 0.05 \text{ m}^3 \text{ m}^{-3}$). On the 16th of
 313 January we recorded another extremely low value for soil moisture ($0.14 \pm 0.01 \text{ m}^3 \text{ m}^{-3}$) from bare collars on
 314 open bog.

315



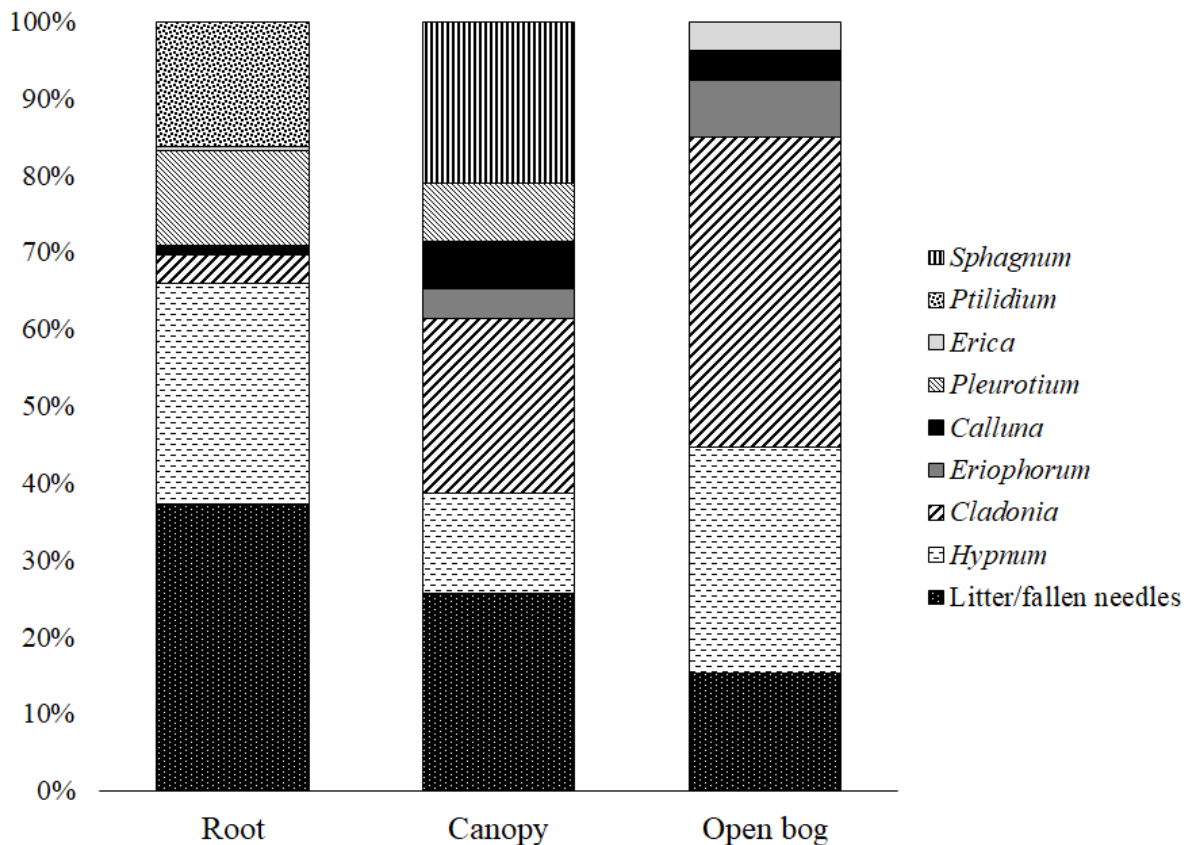
316

317

318 Figure 5 – Mean soil moisture (θ) in different zones and collar types, sampled between January and September 2018.
 319 Solid lines represent bare soils, while dashed lines symbolize vegetated soils. The error bars represent the standard errors.

320 3.2 Vegetation composition

321 We identified eight species in our transects and, on average, *Hypnum jutlandicum* and *Cladonia* spp,
 322 were the most abundant (Figure 6). *Cladonia* was mostly found on collars on open bog, while *Hypnum* was
 323 present in all three different zones. *Sphagnum* was only found on collars under the tree canopy, but not in the
 324 root or in the open bog zones. *Sphagnum* was in general present in the open bog area, but missing in the sampled
 325 collars. *Eriophorum* was more abundant on the open bog and under canopy but absent in the root zone.
 326 *Ptilidium pulcherrimum*, commonly found on wetlands and the base of coniferous trees, was solely found on
 327 collars in the root zone. We also assessed the amount of fallen needles per collar and, according to our
 328 expectations, it was higher on collars in the root and canopy zone (directly under the tree) and lower on the open
 329 bog (where needles must have been blown into the collars by the wind).

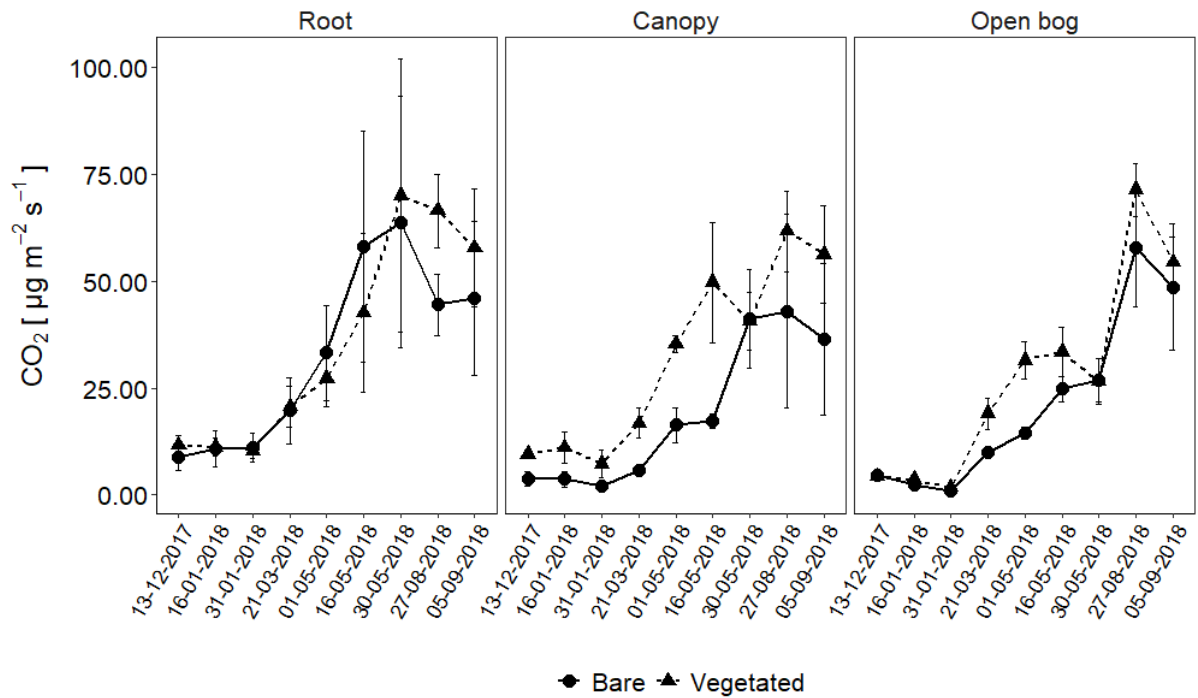


331

332 Figure 6 - Distribution of species in the three different zones (%) identified during the vegetation survey in November 2017.

333 3.3 Carbon dioxide fluxes

334 Overall collars from the root zone emitted more CO₂ ($34.13 \pm 3.97 \mu\text{g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), followed by collars
 335 under canopy ($26.41 \pm 3.04 \mu\text{g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and open bog ($24.34 \pm 2.86 \mu\text{g CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). These differences were
 336 significant between root and open bog ($p < 0.05$, Df=2, F-value=4.5). We also found significant differences
 337 between transects ($p < 0.05$). The CO₂ emissions from both bare and vegetated collars increased during the
 338 growing season (in comparison to winter months) for every zone type (Figure 7). Vegetated collars in the
 339 canopy and open bog zones followed a similar pattern, with fluxes showing two peaks in mid-May and the end
 340 of August, followed by two dips at the end of May and the beginning of September. By contrast, bare soils
 341 showed a constant increase in CO₂ fluxes, until they reached a peak in August, followed by a decrease in
 342 September. Carbon dioxide emissions from collars on roots (both bare and vegetated) peaked at the end of May,
 343 before decreasing in August.



344

345 Figure 7 - Average carbon dioxide (CO₂) flux over the assessment period (December 2017 – September 2018) for each of
 346 the three zones (root, canopy and open bog) and collar type. Solid line and closed circles are for bare, dashed line and closed
 347 triangles are for vegetated collars. Error bars show the standard error around the mean.

348

349 Two linear mixed effect candidate models were identified with $\Delta AICc < 2$ (Table 2). Model M₁-CO₂ had the
 350 higher weight and it was selected as the most probable.

351

352 Table 2 - Summary of the two linear mixed effect models for CO₂ flux with $\Delta AICc < 2$. Df is the degrees of freedom,
 353 LogLik is the log likelihood and AICc is the Akaike's Information Criterion.

Candidate models	Df	LogLik	AICc	$\Delta AICc$	Weight
M ₁ -CO ₂ : $\log_{10}(\text{CO}_2) \sim \text{Ts}_2 + (1 \mid \text{Time point}) + (1 \mid \text{Vegetation})$	9	-11.61	42.52	0.00	0.52
M ₂ -CO ₂ : $\log_{10}(\text{CO}_2) \sim \text{Ts}_2 + (1 \mid \text{Transect}) + (1 \mid \text{Vegetation})$	9	-12.28	43.85	1.33	0.27

354

355

356 Total CO₂ emissions were best explained with a combination of soil temperature at 2 cm as a fixed effect
 357 and the time point and vegetation as random effects (Table 3). According to model M₁, the increase of marginal

358 R² by 0.09 was almost equally explained by both time point and vegetation, where time point explained 12% of
 359 the variance not explained by Ts2, while vegetation explained 9%.

360 Table 3 - Parameters of the linear mixed model found for soil CO₂ emissions.

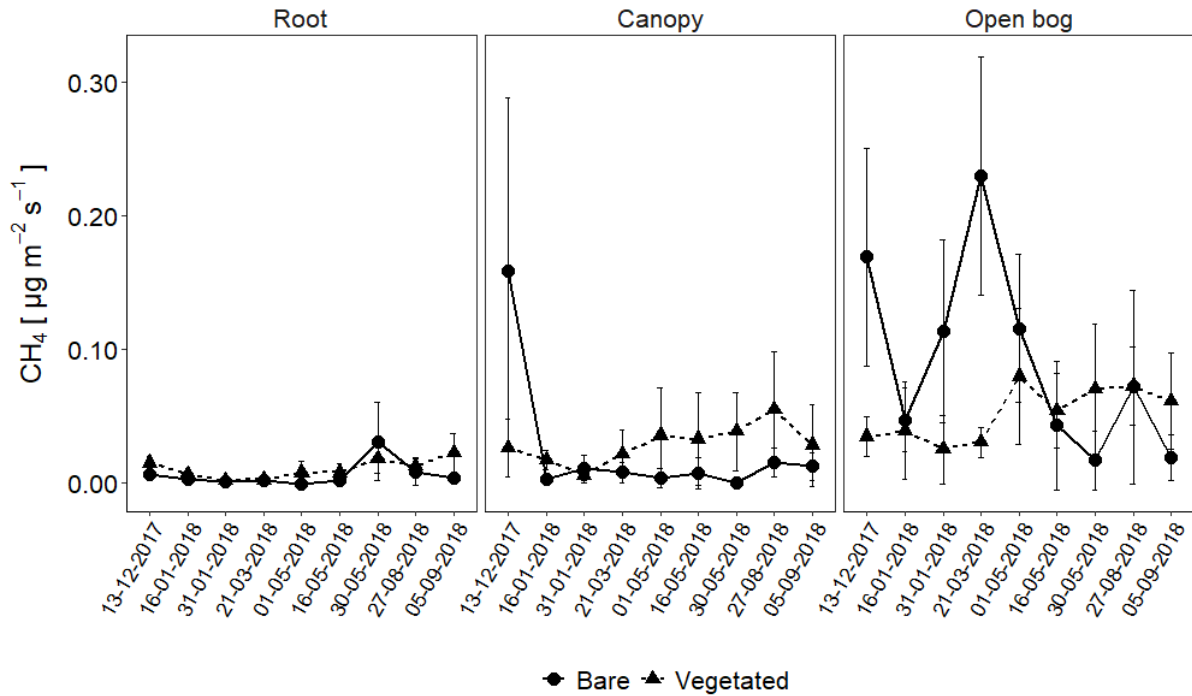
CO₂ model					
<i>Random effects</i>	<i>Variance</i>	<i>Std. Dev</i>	<i>Pr (>χ²)</i>	<i>% variance explained</i>	
Time point (Intercept)	0.01	0.09	0.10	11.58	
Vegetation (Intercept)	0.01	0.08	< 0.001	9.81	
Residuals	0.06	0.25			
<i>Fixed effects</i>	<i>Estimate</i>	<i>Std. Error</i>	<i>df</i>	<i>t value</i>	<i>Pr(> t)</i>
Intercept	-0.71	0.08	10.49	-0.73	< 0.001
Ts2	0.04	0.01	9.48	8.27	< 0.001
Marginal R ² :	0.52				
Conditional R ² :	0.61				

361

362 3.4 Methane fluxes

363 Soil methane fluxes were significantly different between open bog and root zone and between open bog
 364 and canopy zone (p<0.001, Df=2, F-value=19), with the highest efflux from the open bog zone (0.07 ± 0.01 μg
 365 CH₄ m⁻² s⁻¹, total average of bare and vegetated collars), followed by canopy (0.03 ± 0.01 μg CH₄ m⁻² s⁻¹) and
 366 root zones (0.01 ± 0.00 μg CH₄ m⁻² s⁻¹). We observed higher fluxes of CH₄ from vegetated collars during the
 367 growing season (March – September 2018, Figure 8). By contrast, bare collars emitted more CH₄ during the
 368 winter months and early spring, specifically in December, mid-January and March. The highest efflux of CH₄
 369 was observed for bare collars on open bog (average of 0.09 ± 0.02 μg CH₄ m⁻² s⁻¹). Vegetated collars on root
 370 and canopy emitted on average more CH₄ than the bare collars on the same zone, while in the open bog it was
 371 the opposite. We found significant differences between transects (p < 0.01, Df=3, F-value=5.1).

372

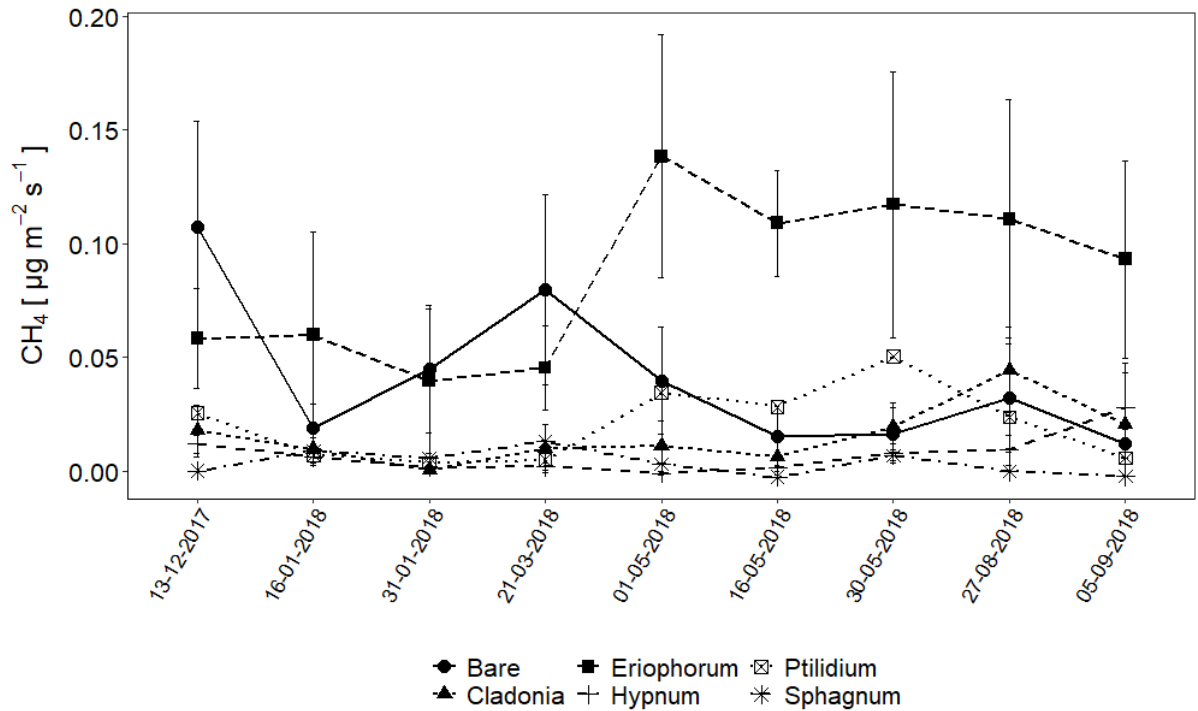


373

374 Figure 8 - Average contribution of methane (CH₄) flux over the assessment period (December 2017 – September 2018) for
 375 each of the three zones (root, canopy and open bog) and collar types. Error bars show the standard error around the mean.

376

377 We also found statistically significantly different fluxes between vegetation types ($p < 0.001$, $Df=5$, F -
 378 value=5.6), with the highest flux coming from collars with *Eriophorum* ($0.09 \pm 0.01 \mu\text{g CH}_4 \text{ m}^{-2} \text{ s}^{-1}$) and the
 379 lowest from *Sphagnum* ($0.003 \pm 0.001 \mu\text{g CH}_4 \text{ m}^{-2} \text{ s}^{-1}$, Figure 9).



380

381 Figure 9 – Vegetation species (including bare collars) CH₄ efflux over the assessment period (December 2017 – September
382 2018). The error bars show the standard error of the mean.

383

384 We found two candidate models with an $\Delta AICc$ of less than 2 and they were both good in explaining the
385 variance in the CH₄ fluxes (Table 4). The M₁-CH₄ showed a higher weight, so this is the model we used.

386

387 Table 4 - Summary of the two linear mixed effect models for CH₄ flux with $\Delta AICc < 2$. Df is the degrees of

Candidate models	Df	LogLik	AICc	$\Delta AICc$	Weight
M ₁ -CH ₄ : $\log_{10}(\text{CH}_4) \sim \text{Ts}_{10} + \text{Zone} + \text{Time point} + (1 \text{Transect}) + (1 \text{Vegetation})$	10	-113.11	248.67	0.00	0.61
M ₂ -CH ₄ : $\log_{10}(\text{CH}_4) \sim \text{Zone} + (1 \text{Time point}) + (1 \text{Transect}) + (1 \text{Vegetation})$	10	-114.01	250.45	1.81	0.25

388 freedom, LogLik is the log likelihood and AICc is the Akaike's Information Criterion.

389

390 Total CH₄ emissions were best explained with a combination of soil temperature at 10 cm, zone and time
391 point as fixed effects and transect and vegetation as random effects (Table 5). Random effects increased the
392 marginal R² by 0.15 with the transect explaining 15% and vegetation 9% of the variance not explained by the

393 fixed effects. The model did not show high collinearity between parameters (VIF index of 1.01, 5.76 and 5.77
 394 respectively for zone, Ts10 and time point).

395

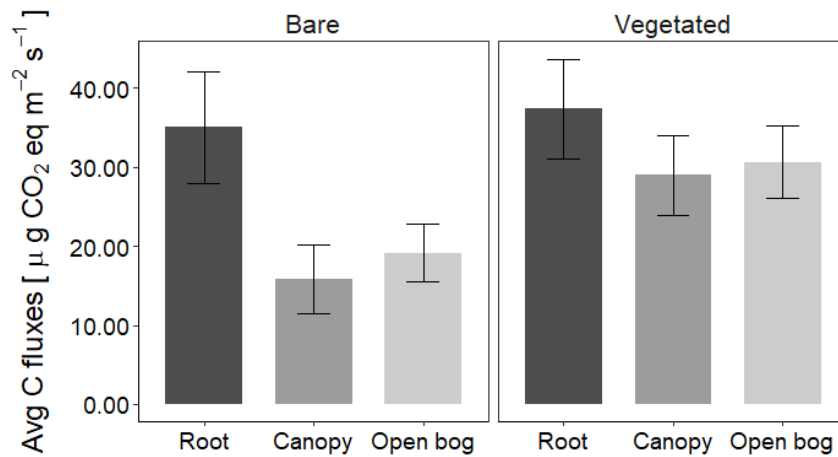
396 Table 5 – Summary table of the parameters of the best fit linear mixed effect model for CH₄ fluxes.

M₁-CH₄ model					
<i>Random effects</i>	<i>Variance</i>	<i>Std. Dev</i>	<i>Pr(>χ²)</i>	<i>% variance explained</i>	
Transect (Intercept)	0.07	0.27	< 0.01**	14.58	
Vegetation (Intercept)	0.04	0.20	0.18	9.24	
Residuals	0.42	0.25			
<i>Fixed effects</i>	<i>Estimate</i>	<i>Std. Error</i>	<i>df</i>	<i>t value</i>	<i>Pr(> t)</i>
Intercept	-2.30	0.24	15.54	-9.57	< 0.001***
Ts10	-0.06	0.03	97.10	-2.05	< 0.05*
Zone - Canopy	0.27	0.18	54.20	1.50	0.14
Zone - Open bog	0.96	0.18	42.26	5.34	< 0.001***
Time point	0.17	0.07	96.32	2.43	< 0.05*
Marginal R ² :	0.28				
Conditional R ² :	0.43				

397

398 3.5 Total C fluxes

399 Our results (Figure 10) showed that vegetated collars emitted more C as respiration than bare collars and
 400 that C effluxes from root zones were higher in comparison to canopy and open bog, following a similar pattern
 401 reported by the CO₂ fluxes. Contribution of CH₄ to the total C efflux was very small.



402

403 Figure 10 – Average C efflux (Avg C fluxes) relative to different zones and collar types in the period December 2017 –
 404 September 2018.

405

406 3.6 Flux response to environmental variables

407 Correlation of both CO₂ and CH₄ fluxes against environmental variables (Ts2, Ts10 and θ) was tested for
 408 each collar type, zone and transect (table 6a, 6b, 6c). The CO₂ fluxes were always strongly and significantly
 409 correlated with soil temperature in all categories, while soil moisture was not correlated in some of the zones
 410 and transects. The CH₄ fluxes did not show any significant correlations with soil temperature at either depth,
 411 except for a negative one (Ts10) for collars on open bog. There were, however, some moderate significant
 412 correlations with soil moisture.

413 Table 6 – Correlations between CO₂ and CH₄ fluxes and environmental variables for different groups (a,b,c) in the period
 414 December 2017-September 2018. Soil temperature at 2 cm (Ts2) and 10 cm (Ts10) depth are expressed in °C, while soil
 415 moisture (θ) in m³ m⁻³. Significant correlations are indicated with asterisks, where P < .001(***), P < .01 (**) and P < .05(*).

(a) Collar type

	CO ₂		CH ₄	
	bare	vegetated	bare	vegetated
Ts2	0.57***	0.68***	-0.16	0.15
Ts10	0.51***	0.59***	-0.19	0.11
θ	-0.29*	-0.24*	0.32**	0.07

416

(b) Zone

	CO ₂			CH ₄		
	Root	Canopy	Open bog	Root	Canopy	Open bog
Ts2	0.63***	0.60***	0.66***	0.20	0.20	-0.18
Ts10	0.57***	0.55***	0.58***	0.23	0.10	-0.31*
θ	-0.44***	-0.25	-0.07	-0.10	-0.29*	0.34*

417

(c) Transect

	CO ₂				CH ₄			
	T1	T2	T3	T4	T1	T2	T3	T4
Ts2	0.56***	0.65***	0.63***	0.76***	-0.01	-0.17	0.061	-0.19
Ts10	0.62***	0.51***	0.59***	0.68***	-0.01	-0.25	-0.04	-0.29
θ	0.076	-0.3	-0.55***	-0.14	0.32*	0.16	0.13	0.26

418

419

420 **4 Discussion**

421 *4.1 Effect of trees on soil temperature, soil moisture and bog vegetation*

422 Soil temperature at both 2 and 10 cm showed a clear temporal variability, but contrary to our
423 expectations we found no significant differences between different zones of the transects. This may be due to
424 the stunted appearance of the canopy of the trees, which was probably not thick enough to filter the incoming
425 solar radiation and so to create a significant temperature drop in collars under the canopy and on roots (Tanaka
426 and Hashimoto, 2006). A similar pattern was observed in a study by Von Arx et al. (2012), where higher
427 temperatures were measured under some pine canopies than in open land; this was explained by needles of some
428 pine species growing in all directions, allowing more light to penetrate the canopy. By contrast, soil moisture
429 showed significant differences between the zones, with lower values in the root zone, gradually decreasing from
430 January (and the beginning of the growing season) until end of August.

431 The constant decline in soil water content could have been the result of the concomitant effects of water
432 uptake by tree roots (Lee, 2018; Sarkkola et al., 2010, Hokka et al., 2008) and rainfall interception by the tree
433 canopy, stems and branches. Interception of rainfall by different tree species and in different environments has
434 been widely reported in the literature (Yang et al., 2019; Dunkerley and Booth, 1999; Gavazzi et al., 2016;
435 Carlyle-Moses and Gash, 2011; Haria and Price, 2000; Roth et al., 2007). Ahmad-Sha and Rieley (1989)
436 measured the quantity of rainfall reaching the surface of a mire in Staffordshire (UK) under different types of
437 canopies (open mire, mixed woodland, fen woodland and pine woodland) over a two years period. Their results
438 showed that a Scots pine canopy intercepted approximately 32% of the total rainfall, while broadleaved
439 woodland intercepted only 20%, mainly due to presence of needles all year round. Soil moisture on open bog
440 and canopy collars were more affected by rainfall events and in March (the wettest month of the study period)
441 we measured two moisture peaks for both zones.

442 The presence of trees in Maud Moss may have also contributed to the different bog species distribution
443 across the raised bog, mainly as a secondary effect due to the spatial variability of soil moisture induced by
444 trees. The species found in Maud Moss were all typical of raised bogs, but species such as the lichen *Cladonia*
445 and the moss *Hypnum jutlandicum* (McHaffie et al., 2002) indicate that the bog is experiencing a drying trend.
446 *Pleurozium shreberi*, a moss important for survival of seedlings of Scots pine (Gunnarsson and Rydin, 1998)
447 was mainly found on collars in root and canopy zones, but was absent on collars in open bog. This species
448 usually vegetates well in dry and shaded soils (Scandrett and Gimingham, 1989); this is similarly the case for

449 *Hypnum jutlandicum*. The latter usually dominates, as shown in our results, at least in collars on roots.
450 *Eriophorum* spp, a typical bog species that indicates higher water tables (McHaffie et al., 2002) was mainly
451 found in the open bog and canopy zones. *Sphagnum* was only found on collars in the canopy zone.

452 4.2 Temporal and spatial variation in soil carbon dioxide fluxes

453 Our results showed a significant temporal variation in soil temperature and CO₂ emissions, with fluxes
454 increasing from winter throughout the growing season. A number of other studies in the field (Bubier et al.,
455 1998; Silvola et al., 1996) and in the laboratory (Scanlon and Moore, 2000; Yavitt et al., 1997; Moore and
456 Dalva, 1993, Updegraff et al., 2001) have shown that CO₂ production and emissions are positively correlated
457 with soil temperature. In a study by Lee (2018), soil respiration showed clear seasonal variations and high
458 exponential correlation with increasing soil temperatures associated with distance from maple trees. The
459 relationship between soil temperature and stage in the season also emerged from our analysis, in which CO₂
460 fluxes were best predicted by temperature at 2 cm depth as a fixed effect with time as a random intercept. Soil
461 temperature alone explained 52% of the variability of CO₂ (marginal R²) and was also statistically and highly
462 correlated with CO₂ fluxes.

463 Because soil temperatures did not differ significantly between zones, we can assume that trees did not
464 cause a change in the temperature-related CO₂ dynamics between zones. However, trees might still have
465 influenced CO₂ emissions in their proximity in other ways. Spatial variability of CO₂ fluxes has been studied by
466 Anderson et al. (2005) who highlighted the importance of factors including root respiration, heterotrophic
467 respiration, heterogeneity of vegetation cover and microclimatic conditions in determining variation of CO₂ at
468 different distances from trees. Root respiration, which can constitute 40 – 70% of total soil respiration, could
469 have driven soil CO₂ emissions in the root zone (Kucera and Kirkham, 1971; Chapman, 1979; Wang et al.,
470 2009, Crow and Wieder, 2005; Ohashi et al., 2000), especially during the growing season.

471 Trees may also have influenced soil respiration by affecting soil moisture (Tang and Baldocchi, 2005),
472 which was significantly lower and negatively correlated with CO₂ fluxes in the root zone. Other studies showed
473 a similar pattern (Lee, 2018) in relation to the ability of trees to dry the surrounding area through
474 evapotranspiration streams (Sarkkola et al., 2010; Hokka et al., 2008). Our measurements indicated that soil
475 moisture levels were significantly reduced in the root zone in both bare and vegetated collars during the growing
476 season. The drying of saturated anaerobic soils could result in increased aerobic decomposition of organic
477 matter (Wang et al., 2016) and therefore increased release of CO₂. Lee (2018) showed that the rate of soil

478 respiration was highly correlated to root biomass and that the latter was also correlated with soil moisture,
479 noting that as distance from the tree increased, root biomass and soil respiration strongly and exponentially
480 decreased.

481 In addition, CH₄ oxidation, carried out by methanotrophs, could have increased CO₂ emissions in the
482 drier root zone. Methanotrophic activity is related to soil water content and oxygen availability. It increases as
483 the soil approaches field capacity and then decreases as the water content increases further (Le Mer and Rogers,
484 2001). Methane oxidation may also increase close to the root zone of vascular plants, where it is likely that roots
485 would favour diffusion of oxygen from the atmosphere into the soil (Armstrong, 1979). As a result, the
486 methanotrophic bacteria living in the root zone can oxidise CH₄ before it is emitted into the atmosphere, causing
487 an increase in soil CO₂ efflux.

488 Unfortunately, we cannot distinguish, using these measurements alone, between these three possible
489 sources of additional CO₂ flux, but if a significant proportion originates from increased heterotrophic respiration
490 associated with the observed drying of the soil, the presence of trees could result in net loss of stored C from the
491 bog. This could be amplified in the case of biomass gain by trees. If trees increase in biomass, drier climatic
492 conditions could be established due to increased evapotranspiration and root respiration. This would eventually
493 lead to an increase in soil CO₂ effluxes, not only linked to increased root respiration but also to the increased
494 amount of dead fine roots (turnover) that will eventually decompose.

495 4.3 *Temporal and spatial variation in soil methane fluxes*

496 We observed different temporal patterns of CH₄ emissions between bare and vegetated collars. The CH₄
497 fluxes from bare collars on different zones showed no relationship with time, but instead followed a seasonal
498 pattern associated with the soil temperature at 10 cm, which had a significant fixed effect in the derived model
499 of CH₄ emissions. In other studies in temperate or cold regions, seasonal variations of CH₄ emission have
500 similarly been correlated with soil temperature (Klinger et al., 1994). Bare collars on the open bog also showed
501 a strong relationship to rainfall, with peaks in CH₄ emissions corresponding to the period with the most
502 precipitation and peaks in soil moisture (in March and after July). The CH₄ efflux from soil is a result of CH₄
503 production, consumption and transport processes (Couwenberg, 2009; Van den Pol-van Dasselaar et al., 1999).
504 Production of CH₄ is a process carried out by methanogenic micro-organisms in strictly anaerobic environments.
505 It is mainly influenced by soil aeration, presence (and population size) of methanogenic micro-organisms and
506 occurrence of available organic matter (above and below ground; Segers, 1998). The high emissions from the

507 bare collars on open bog in March and August might be explained by larger production of CH₄ in these collars
508 due to the absence of a tree canopy intercepting the rainfall and lack of active vegetation roots taking up water,
509 which could have led to the accumulation of water in these collars and saturated conditions within the soil. The
510 anaerobic environment would enhance CH₄ production, which would later be released to the atmosphere
511 through diffusion (Bian et al., 2018) or transport through roots remaining after vegetation removal (King et al.,
512 1999).

513 By contrast, vegetated collars followed a more seasonal trend, with fluxes increasing from the end of
514 winter throughout the growing season, and then decreasing again in September. We observed this same pattern
515 in all three different zones (Figure 7). These CH₄ emissions are likely to be related to vegetation and in
516 particular to plant transport (Davidson et al., 2016). Higher CH₄ emission from vegetated collars were measured
517 from canopy and open bog zone, and this is likely to be because, in these areas, *Eriophorum* (known for being a
518 CH₄ shunt species) was more abundant, whereas it was absent in the root zone. These zones might also have
519 been characterized by a higher CH₄ production, enhanced by the availability of fresh substrate originating from
520 vegetation inside the collar (Van den Pol-van Dasselaar et al., 1999). Our model captured both the temporal
521 variability (including time points and Ts10 as fixed effects) and the effect of vegetation. Soil temperature at 10
522 cm depth, seasonality and vegetation best explained the CH₄ dynamics.

523 Spatial variability of CH₄ emissions has been widely assessed in literature. Methane fluxes can vary
524 between sites, but also between areas within sites and within a range of less than 2m (Van den Pol-van
525 Dasselaar et al., 1999). Differences can also be detected in different microtopographies, for example in natural
526 hummocks and hollows (Frenzel and Karofeld, 2000; Lai, 2009; Waddington and Roulet, 1996; Bubier, 1993)
527 or in forestry derived microforms (Cresto-Aleina et al., 2015; Hermans, 2018; Mazzola et al., 2020). In Maud
528 Moss, spatial variability was also captured by our model, where different transects (as a significant random
529 factor) were able to explain almost 15% of the difference between conditional and marginal R² of the model. In
530 a peatland edge woodland, this spatial variability can be very complex, because the trees can alter soil
531 temperature and moisture balances and so also CH₄ emissions.

532 According to our measurements, the root zone was the driest area and was also the smallest source of
533 CH₄ due to the presence of a thicker oxic zone. Trees (and in particular Scots pine) might have also been able to
534 capture the CH₄ dissolved in soil water close to their roots and emit it to the atmosphere through stem and
535 shoots. Machacova et al. (2016) measured CH₄ fluxes simultaneously from tree shoots, stems and forest floor
536 and observed that whereas trees were a source of CH₄, the forest floor was a sink. Smaller CH₄ fluxes detected

537 in the root zone might have also been the result of CH₄ oxidation mediated by trees. Along with transporting
538 soil-produced CH₄, trees can regulate soil CH₄ fluxes through plant–soil–microbe interactions around the roots
539 (Covey and Megonigal, 2018), in which aerobic methanotrophic bacteria consume CH₄ when oxygen is
540 available (Couwenberg and Fritz, 2012). In wetlands, Denier van der Gon & Neue (1996) observed that this
541 process takes place where ever the soil is not saturated; at the soil surface above the water table, or around roots
542 where oxygen transported by plants is diffused into the soil.

543

544 4.4 Total CO₂eq efflux and knowledge gaps

545 Our results (Figure 10) showed that the root zone emitted more CO₂eq, compared to canopy and open
546 bog. This may in part have been due to autotrophic respiration from the tree roots, which could not be removed,
547 even in the bare collars. Carbon dioxide played an important role as a primary component of C fluxes from the
548 system. It was responsible for almost 99% of the emissions from collars on roots, 97% for collars on canopy,
549 showing the smallest percentage of 88% for collars on open bog. These results are, however, incomplete in the
550 bigger picture of a greenhouse balance assessment, which would also include the quantification of soil nitrous
551 oxide (N₂O) emissions and the greenhouse gas dynamics associated with trees in the form of tree CO₂ uptake
552 and tree-mediated CH₄ exchange. We expect N₂O to be a significant portion of the overall GHG emissions, due
553 to a possible nitrogen (N) deposition enhanced by the proximity of the study site to crops and grasslands.

554 5 Conclusions

555 Interest in peatland edge woodlands has increased since the publication of new restoration policy
556 guidelines by Forestry Commission Scotland (2015), which promotes the creation of low-density forests using
557 native tree species on peatlands to combine the best C benefits from both forests and bogs (Payne and Jessop,
558 2018). Moreover, in a future scenario where Scotland will be characterized by a warmer and drier climate and
559 where bog woodlands could naturally expand again, the assessment of the C dynamics of this habitat will be
560 needed in order to inform their appropriate management. There is, however, still a lack of knowledge regarding
561 this habitat in Scotland, especially in relation to soil C flux dynamics. Our study provides the first evidence to
562 fill this gap and gives unique data relating to the influence of scattered trees (Scots pine) on a raised bog,
563 focusing on their effects on soil environmental variables, bog vegetation and therefore also soil CO₂ and CH₄
564 fluxes. Our results showed that these low-density trees have no significant effect on soil temperature, but they
565 do affect the soil moisture, with soils close to tree roots significantly drier than those on open bog and under the

566 canopy. Fluxes of CO₂ showed a strong temporal variability and significant correlation with soil temperature.
567 Soil CH₄ fluxes showed significantly lower emissions in proximity of the trees. Scots pine trees on peatland
568 edge woodland may have affected soil CH₄ fluxes primarily due to their effects on soil moisture, reducing the
569 CH₄ fluxes in proximity with the root zone compared to open bog areas, while they may have influenced soil CO₂
570 emissions in their vicinity mainly due to the contribution of root respiration. There is, however, still uncertainty
571 about the effect of scattered trees on bogs in relation to a complete greenhouse gas assessment, and further
572 research would be needed in order to include the quantification of soil N₂O dynamics together with the analysis
573 of complete gas exchanges at the tree-atmosphere level.

574

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586 **8 Data sharing and data accessibility request:**

587 The data that support the findings of this study are available from the corresponding author upon
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589 **9 Conflict of interest**

590 The authors declare that they have no conflict of interest.

591 **10 Authorship**

592 Study concept and design: V. Mazzola, M.P. Perks, G. Xenakis J. Smith and J. Yeluripati. Collection of
593 data: V. Mazzola. Analysis and interpretation of data: V. Mazzola, G. Xenakis, J. Smith. Drafting of the
594 manuscript: V. Mazzola. Critical revision of the manuscript for important intellectual content: G. Xenakis, J.
595 Smith, M.P. Perks and J. Yeluripati. Statistical analysis: V. Mazzola and G. Xenakis. Study supervision: G.
596 Xenakis, J. Smith, M. P. Perks and J. Yeluripati.

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