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1 **Title:** The effect of buffer strip width and selective logging on riparian forest
2 microclimate

3

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12 **Declarations of interest:** none

13

14 **Abstract**

15 Riparian forests have cool and humid microclimates, and one aim of leaving forested buffer strips
16 between clear-cut areas and streams is to conserve these microclimatic conditions. We used an
17 experimental study set up of 35 streamside sites to study the impacts of buffer strip width (15 or 30
18 meters) and selective logging within the buffer strips on summer-time air temperature, relative air
19 humidity and canopy openness 12 years after logging. The buffer strip treatments were compared to
20 unlogged control sites. We found that 15-meter buffer strips with or without selective logging and
21 30-meter buffer strips with selective logging were insufficient in maintaining temperature, relative
22 humidity and canopy openness at similar levels than they were in control sites. In contrast, 30-meter
23 buffer strips differed only little from control sites, but they did have significantly lower mean air
24 humidity. Microclimatic changes were increased by southern or southwestern aspect of the clear-
25 cut, and by logging on the opposite side of the stream. We also tested how the cover of three
26 indicator mosses (*Hylocomium splendens*, *Pseudobryum cinclidioides* and *Polytrichum commune*) had
27 changed (from pre-logging to 12 years post-logging) in relation to post-logging air temperature,
28 relative air humidity and canopy openness. We found that each of the species responded to at least
29 one of these physical conditions. Air humidity was the most significant variable for explaining
30 changes in the cover of the indicator moss species, suggesting that the changes in this microclimatic
31 component has biological impacts. We conclude that to preserve riparian microclimatic conditions
32 and species dependent on those, buffer strips should exceed 30 meters in width, and not be
33 selectively logged. Wider buffer strips are required if the clear-cut is towards south or southwest, or
34 if the two sides of the stream are logged at the same time or during subsequent years.

35 **Keywords**

36 Canopy openness; moss; partial harvesting; refugia; relative humidity; selective logging; streamside;
37 temperature; continuous cover forestry

38

39

40

41 1 Introduction

42 Streamside riparian zones consist of the ecotone between the stream and upland forest. They host
43 high biodiversity due to the complexity in soil conditions, topography and microclimate (Hylander et
44 al., 2005; Naiman and Décamps, 1997). In addition to many species typical to upland forests, the
45 riparian zones host species that are adapted to moist soil and flooding (MacDonald et al., 2014;
46 Naiman and Décamps, 1997). Although the area of riparian forests is small in the boreal landscape (a
47 few percent), they form a habitat network of high connectivity, which may enhance the dispersal of
48 organisms (Johansson et al., 1996; Naiman and Décamps, 1997). Thus, protecting the integrity of the
49 riparian forests surrounding watercourses should be a high priority of biodiversity conservation in
50 managed forest landscapes (Fries' et al., 1998; Naiman et al., 1993). However, riparian forests and
51 their biodiversity are threatened by intensive forestry, and in North America and Europe more than
52 80 % of riparian corridors have already been disturbed or destroyed (Naiman et al., 1993).
53 Nowadays, buffer strips are left between streams and clear-cuts, but it is still uncertain what width is
54 enough to conserve the microclimatic conditions and species in the riparian zones (e.g Hylander,
55 2014; Moore et al., 2005; Selonen and Kotiaho, 2013; Sweeney and Newbold, 2014).

56 Compared to intact forest, the forest edge adjacent to a clear-cut has higher daytime temperatures
57 (but slightly lower at night), lower daytime relative air humidity, higher soil temperature, higher
58 wind speed and more solar radiation (Chen et al., 1995; Moore et al., 2005). In upland forests, solar
59 radiation and soil temperature acclimate to interior forest levels at about the distance of one tree
60 length, while it takes a longer distance for air temperature, wind speed and, especially, relative air
61 humidity (Chen et al., 1995; Moore et al., 2005). The depth of the edge effects is affected by several
62 factors, with aspect being of large importance: in the northern hemisphere, edge effects are largest
63 and deepest on south- or southwest-facing edges (Chen et al., 1995; Heithecker and Halpern, 2007;
64 Moore et al., 2005). It is not well known how the edge effect is affected if the retained forest is
65 selectively logged. When the canopy becomes less dense, it results in a longer, less steep edge effect
66 (Heithecker and Halpern, 2007). On the other hand, it has been suggested that a feathered edge
67 with a dense understory is more resistant to physical edge effects (Chen et al., 1995), and better
68 mimics the edges created by *e.g.* wildfires (Braithwaite and Mallik, 2012).

69 Results on the depth of the edge effect in upland forests do not necessarily apply in riparian forests,
70 where logging may have smaller effects on the microclimate and communities because the naturally
71 moister and cooler microclimate may buffer against the changes (Dynesius et al., 2009; MacDonald
72 et al., 2014; Rykken et al., 2007). The study of Brososke et al. (1997) suggested that buffer strips
73 should be at least 45 meters wide to protect the natural riparian microclimate, while in the study of
74 Rykken et al. (2007) buffer strips of 30 meters were sufficient. In terms of species, the buffer width
75 should be at least 30 meters in order to protect communities of vascular plants and mosses that
76 grow in the riparian habitat next to the stream (Elliott and Vose, 2016; Oldén et al., 2019; Selonen
77 and Kotiaho, 2013) as well as aquatic species (Sweeney and Newbold, 2014). Selective logging in the
78 buffer strip increases the density of stream macroinvertebrates (Carlson et al., 1990), increases the
79 regeneration of saplings in the buffer (Mallik et al., 2014; Zenner et al., 2012), and decreases the
80 amount of decaying wood in the long-term (Lundström et al., 2018). It also causes changes in moss
81 communities in 15-meter wide buffers but not in 30-meter wide buffers (Oldén et al., 2019).
82 However, studies on the effects of selective logging on riparian microclimate are lacking.

83 Bryophytes (mosses and liverworts) are excellent bioindicators for studying the possible responses
84 of species to changed microclimatic conditions in riparian buffer strips (Hylander et al., 2005, 2002;
85 Stewart and Mallik, 2006). They are poikilohydric, *i.e.* they cannot regulate their water loss and are
86 dependent on moisture from the soil and air to retain growth (Proctor, 1990). Many species,
87 especially those adapted to grow under forest canopy, are very sensitive to logging-induced changes
88 in moisture and light conditions (Busby et al., 1978; Dynesius and Hylander, 2007; Hylander et al.,

89 2005, 2002; Stewart and Mallik, 2006). Studies have shown that bryophyte growth, cover, species
90 richness and community composition change soon after clearcutting or logging with narrow buffers,
91 indicating low resistance to change (Hylander et al., 2005, 2002; MacDonald et al., 2014; Oldén et
92 al., 2019; Stewart and Mallik, 2006). Small populations may survive in microclimatic refugia on the
93 northern side of objects, such as boulders or stumps (Schmalholz and Hylander, 2011).

94 In Finland, those riparian streamside habitats that are in natural or nearly natural condition are
95 protected by law, the Forest Act. The Act states that it is not allowed to alter their characteristic
96 features, which are specified as the special growing conditions and microclimate that result from the
97 proximity of water and the tree and shrub layers (Forest Act, 2013). However, the width of buffer
98 strips has been on average 15 meters in streamside classified as Forest Act Habitats (Ahonen,
99 2017), while the latest recommendation is that the buffer width should equal the average length of
100 the trees (Metsäkeskus, 2018), *i.e.* around 20 meters, which is probably also insufficient to conserve
101 the microclimate and growing conditions. Thus, there is a contrast between the >30 meters
102 suggested by earlier studies, the reality in the field, and the law.

103 In this paper, we study the impact of buffer strip width (15 or 30 meters) and selective logging (30 %
104 of tree basal area removed from the buffer or not) on summer-time microclimatic conditions and
105 canopy openness in streamside. We compare the conditions in the logged sites to unlogged control
106 sites 12 years after the logging treatments in order to answer the following questions: 1. What kind
107 of buffer strips in our set up, if any, are able to maintain relative air humidity, air temperature and
108 canopy openness at similar levels than in unlogged sites? 2. How are air humidity and temperature
109 affected by buffer width, selective logging and the aspect of the clear-cut? 3. Are the differences in
110 humidity and temperature smaller on the northern side of a tree than on the southern side, *i.e.* can
111 objects like trees create small microclimatic refugia? In addition, we compare the effects of air
112 humidity, air temperature and canopy openness on the changes that have happened in the cover of
113 three common indicator moss species between pre-logging and 12 years post-logging in order to
114 answer the question: 4. Which physical conditions drive the changes in the cover of the three
115 mosses?

116

117 **2 Material and methods**

118 *2.1 Study sites*

119 The study area is located in Central and Eastern Finland, on southern and middle boreal vegetation
120 zones (Ahti et al., 1968). The mean annual air temperature in the area is 2-4 °C and precipitation
121 600-700 mm year⁻¹ (average from 1981-2010) (Pirinen et al., 2012). We studied 35 streamside sites
122 in the area (Table 1). Each site was located on a separate stream. Before the logging treatments, all
123 study sites were dominated by even-aged spruce (*Picea abies* (L.) H. Karst.), and the dominant trees
124 were at least 80 years old. The sites were completely forested, *i.e.* spruce trees grew close to the
125 stream and there were no extensive treeless riparian zones. The water channels were small streams
126 or rivulets with regular, year-round flow. The width of the water channels varied from 0.2 to 3.2
127 meters (Table 1). The sites did not have extensive regular flooding, but occasional flooding could
128 occur especially near the stream. All of the sites had been classified as Forest Act Habitats by Finnish
129 forest authorities.

130 Table 1. The study sites: Municipality of the location, North and East coordinates in decimal degrees,
131 width of the stream and the total basal area of trees before logging treatments. The sites are
132 listed based on their treatments.

Site ID	Municipality	N	E	Stream width (m)	Tree basal area (m ² /ha)
Control					
6	Vieremä	63.94052	26.66638	1.0	36
21	Lieksa	63.23884	30.75467	1.6	32
27	Leivonmäki	61.90145	25.92199	1.5	27
28	Leivonmäki	62.02793	26.18217	0.6	24
31	Kuhmoinen	61.71589	24.93035	0.4	13
35	Sotkamo	63.93125	28.22158	3.2	32
45	Rautavaara	63.59531	28.48888	2.1	26
47	Rautavaara	63.63822	28.44861	0.8	32
30 m without selective logging					
4	Vieremä	63.98945	26.8938	0.3	35
16	Lieksa	63.46902	29.8989	0.5	25
25	Kivijärvi	63.20412	24.90234	1.9	27
34	Uurainen	62.54641	25.48799	2.5	25
40	Rautavaara	63.66626	28.57471	0.2	27
30 m with selective logging					
15	Kaavi	63.11614	28.73192	0.6	37
18	Lieksa	63.46808	29.94605	0.3	37
23	Äänekoski	62.56329	25.51531	1.2	23
26	Korpilahti	62.04014	25.42641	1.1	31
33	Karstula	62.97202	24.97654	1.7	22
39	Rautavaara	63.67432	28.56051	0.4	30
42	Nurmes	63.56566	29.33364	0.6	29
43	Nurmes	63.57713	29.50002	0.3	26
15 m without selective logging					
1	Vieremä	63.83188	26.94863	0.3	37
2	Pieksämäki	62.39258	26.93276	1.5	33
29	Korpilahti	62.21604	25.39608	0.8	31
32	Orivesi	61.6162	24.20887	0.6	23
38	Rautavaara	63.40632	28.20288	0.7	32
15 m with selective logging					
3	Vieremä	63.98682	26.90886	0.5	40
8	Pielavesi	63.39579	26.39757	0.2	37
17	Lieksa	63.46600	29.89691	1.6	33
20	Lieksa	63.28729	30.34200	1.1	36
22	Lieksa	63.21131	30.22918	0.4	37
24	Pihtipudas	63.41049	26.05685	0.8	34
48	Rautavaara	63.59369	28.45654	0.7	36
49	Nurmes	63.78579	29.35355	0.7	38
56	Pieksämäki	62.26919	26.99563	2.2	46

133

134 2.2 Treatments

135 During the winter 2005-2006, logging treatments were applied on 27 of the sites, while 8 sites were
136 left as unlogged controls. The logging treatments included clear-cutting in the upland forest, and one
137 of the following types of buffer strips next to the stream:

- 138 1. 30-meter wide buffer strip without selective logging (5 sites),
- 139 2. 30-meter wide buffer strip with selective logging (8 sites),
- 140 3. 15-meter wide buffer strip without selective logging (5 sites),
- 141 4. 15-meter wide buffer strip with selective logging (9 sites).

142 In the selective logging, 30 % of the basal area of trees was logged from the buffer strip, focusing on
143 the largest trees of the stand. Trees were logged within the whole width of the buffer. Additional
144 information on the treatments can be found in Oldén et al. (2019). The treatments were allocated
145 randomly to the sites.

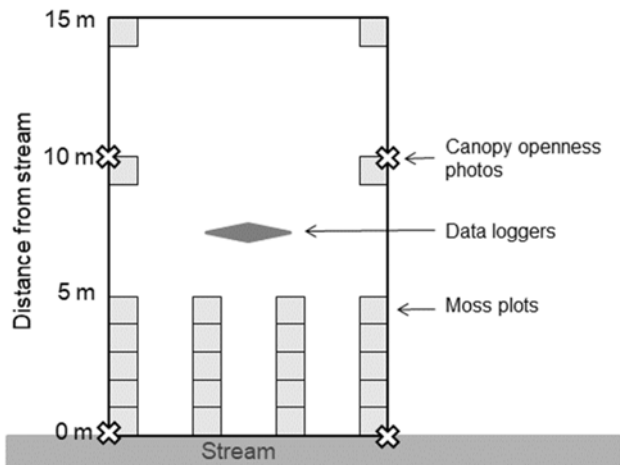
146 Originally, the logging treatment was performed on only one side of the stream, and mature forest
147 was left standing on the opposite side. If by the year 2017 logging had also happened on the
148 opposite side of the stream, we measured the distance from the stream to the edge of the clear cut,
149 and sites where the distance was less than 40 meters were recorded as logged on the opposite side.
150 In these 15 sites the opposite buffers had not been selectively logged, but the buffer width varied
151 both within sites and between sites from about 10 to 40 meters (mean of site means was 23
152 meters). In the 20 unlogged sites there were no buffer strip loggings within 50 meter distance from
153 the study area, but in some of them there were clear-cuts further than 50 meters away. Since these
154 clear-cuts were mostly tens or hundreds of meters away, it was considered that they did not impact
155 the microclimate of the study area considerably.

156 *2.3 Data collection: Microclimate and canopy openness*

157 On each study site there was a rectangular 10 m * 15 m study area next to the stream. One of the
158 10-meter sides of the study area followed the stream shoreline. The study area was placed in the
159 center of the treatment area, *i.e.* the logged area was on the same side of the stream.

160 We used data loggers (Lascar EL-USB-2) to measure relative humidity and air temperature at 5-
161 minute time intervals for a month between 18th of July and 18th of August 2017. Each data logger
162 contains one sensor for relative humidity (accuracy 2.25%) and temperature (accuracy 0.55°C). Two
163 data loggers were placed on a trunk of a mature spruce tree located at a distance of about 7.5
164 meters from the stream, and as near to the center of the 10-meter wide study area as possible
165 (Figure 1). The loggers were placed at 50 cm height from the ground, on the opposite sides, south
166 and north, of the tree. From the data of each logger, we calculated the following values: the mean
167 relative air humidity (%), the mean of daily minimum relative air humidities (%), the standard
168 deviation (SD) of all of the relative air humidity values, the mean air temperature (°C), the mean of
169 daily maximum air temperatures (°C), and the standard deviation of all of the temperature values.

170 To measure canopy openness in 2017, we took fisheye-photos and calculated the proportion of
171 visible sky from the pixels. Four photos were taken (one towards each cardinal direction) at both of
172 the lowest corners of the study area at the shoreline (Figure 1). The average proportion of visible sky
173 in these eight photos was used to approximate the openness at 0-meter distance from the stream.
174 Similarly, four photos were taken at a distance of 10 meters from the stream, along both of the
175 edges of the study area, and these eight photos were used to approximate the openness at 10-
176 meter distance. The photos were taken with a digital camera and a fish-eye converter that allows for
177 photos with 120 degrees angle of view. For each photo, the camera was held vertically so that the
178 upper edge was upright. The proportion of sky pixels out of all pixels in the photo was calculated
179 with ImageJ 1.45s (a more detailed description of the method given in Oldén et al., 2017).



180

181 Figure 1. The location of canopy openness photos, data loggers and moss plots within the study area
 182 next to the stream.

183 2.4 Data collection: Mosses

184 2.4.1 Indicator mosses

185 In order to test for the ecological significance of the physical conditions (humidity, temperature and
 186 canopy openness), we followed the change in the cover of three common indicator moss species.
 187 *Hylocomium splendens* (Hedw.) Schimp., *Pseudobryum cinclidioides* (Huebener) T.J.Kop., and
 188 *Polytrichum commune* Hedw. differ in their ecology from each other, but are known to require moist
 189 microhabitats and to respond to microclimatic changes:

- 190 1. *H. splendens* is a feather moss that forms loose wefts (intertwining branched layers) on
 191 boreal forest floors. *H. splendens* dries out quickly in dry conditions, so it thrives in relatively
 192 constant, shaded habitat conditions, where trees provide high humidity and low
 193 temperatures (Callaghan et al., 1978). The growth of *H. splendens* has been shown to
 194 decrease due to logging-induced microclimatic edge effects (Caners et al., 2013; Hylander,
 195 2005; Stewart and Mallik, 2006).
- 196 2. *P. cinclidioides* is a large-leaved moss that grows as turf (vertical stems with little or no
 197 branching). It grows on mesotrophic, waterlogged soil in springs, swamps, flooded mires,
 198 flood meadows and stream banks (Darell and Cronberg, 2011; Ulvinen et al., 2002). *P.*
 199 *cinclidioides* has been observed to decrease in retention patches after the surrounding
 200 forest is logged (Perhans et al., 2009).
- 201 3. *P. commune* is a tall turf moss that grows commonly on peat in mires and in paludified spots
 202 in forests (Ulvinen et al., 2002). It has an underground stem, internal water-conducting
 203 tissues and complex leaves that are resistant to water loss (Bayfield, 1973). Due to these
 204 properties *P. commune* is able to grow also in periodically dry and exposed conditions
 205 (Callaghan et al., 1978).

206 2.4.2 Cover change

207 The percentage cover of each of the three study species was estimated (by eye estimation) in 2004
 208 (before logging) and in 2017 (12 years after logging) on 1 m² plots within the study area. Twenty
 209 plots were located within the first five meters from the stream (distance 0-5 meters) and four
 210 additional plots were located at 10 and 15 meters from the stream (Figure 1). The sampling was
 211 focused on the first five meters from the stream because the primary aim of leaving buffer strips is
 212 to conserve the species growing in the immediate vicinity of the stream.

213 In 2017, several plots were discarded on many of the sites due to the following reasons: 1) the plot
214 markings had been lost and the plot could not be placed with certainty in the same place than in
215 2004, 2) the microhabitats in the plot had changed substantially due to windfalls (there was a root
216 mound, a log or a pile of branches on the plot), or 3) the stream had meandered and the shoreline
217 had moved. These plots were not included in the data of either year.

218 For each species, we calculated the mean cover on the studied plots in 2004 and in 2017, and then
219 calculated the relative change in the cover as $(Cover_{2017} - Cover_{2004}) / (Cover_{2004} + Cover_{2017})$. When
220 the change in the cover is divided by the sum, the relative change gets a maximum value of 1
221 (colonization) and a minimum value of -1 (extinction).

222 *2.5 Statistical analyses*

223 We used Multivariate Analysis of Variance (MANOVA) to analyse the data where several response
224 variables were affected at the same time and were correlated with each other. MANOVA is used to
225 test whether the explanatory variables affect the response variables simultaneously in their global
226 model. All analyses were performed in R (R Core Team, 2017). Function `lm` was used to build the
227 separate linear models for each response variable, and function `Anova` from package “`car`” (Fox and
228 Weisberg, 2011) was used to perform the Analysis of Variance with type III sums of squares (suitable
229 for unbalanced designs).

230 The response variables in the models were

- 231 1) Relative humidity: mean humidity, mean daily minimum humidity and the standard
232 deviation of humidity (mean values from the two data loggers on a site),
- 233 2) Temperature: mean temperature, mean daily maximum temperature and the standard
234 deviation of temperature (mean values from the two data loggers on a site),
- 235 3) Canopy openness: canopy openness at 0 meters from stream and canopy openness at 10
236 meters from stream (means of the eight canopy openness photos taken at that distance in a
237 site).

238 First, we tested how each of the four different kinds of buffer strips (the treatments) differed from
239 the unlogged controls, i.e. whether one or more of the buffer strip types could provide similar
240 microclimatic conditions as unlogged sites. We used three MANOVAs, one for the humidity
241 variables, one for the temperature variables and one for the canopy openness variables. Prior to
242 analysis, both of the canopy openness values were log₁₀-transformed to improve the model fit. In
243 each model, the explanatory variables were the treatment (controls compared to the four buffer
244 treatments: 30 m without selective logging, 30 m with selective logging, 15 m without selective
245 logging, and 15 m with selective logging), logging on the opposite side of the stream (yes or no), and
246 east coordinates of the geographic location. North coordinates could not be added in the model
247 because they correlated with logging on the opposite side (more sites had been logged in south than
248 north of the geographic area) and with east coordinates (the sites were located within the
249 geographic area so that those that were more in north also tended to be more in east).

250 Second, we used four MANOVAs to test how relative humidity and temperature were affected by
251 buffer width, selective logging and southern or southwestern aspect in the buffer strip treatment
252 sites. Control sites were not included in these analyses as aspect is not relevant without a clear-cut,
253 and there was no buffer width or selective logging in the controls. The compass point of the
254 treatment clear-cut from the stream was transformed into an index of southern aspect, which has a
255 value of 180 if the clear-cut is towards south, decreases continuously through 90 in east and west,
256 and is 0 if the clear-cut is towards north. Similarly, southwestern aspect is 180 if the clear-cut is
257 towards southwest, and 0 if the clear-cut is towards northeast. Separate models were built for
258 southern and southwestern aspects. Each model included the following explanatory variables: Buffer

259 width (15 or 30), selective logging (yes or no), southern or southwestern aspect (0-180), logging on
260 the opposite side of the stream (yes or no) and east coordinates. We also included the interactions
261 buffer width * selective logging and buffer width * southern/southwestern aspect, but these did not
262 have significant impacts in any of the models, and we excluded them from the final models.

263 Third, to test whether microclimatic changes are smaller on the northern side of a tree than on the
264 southern side of the tree, we built two similar MANOVAs separately for the south- and north-facing
265 data loggers. Separate models were built for relative humidity and temperature. Only the logging
266 treatment was included as an explanatory variable in these MANOVAs, and we compared the
267 strength of the treatment effects on the models of south-facing loggers and north-facing loggers.

268 Fourth, we used three MANOVAs to test for the effect of humidity, temperature and canopy
269 openness on the changes in the cover of the three moss species. In all of the three models, the
270 response variables were the same: the relative change in *H. splendens*, relative change in *P.*
271 *cinclidioides* and relative change in *P. commune*. In the humidity model, the explanatory variable was
272 mean humidity, and in the temperature model, it was mean temperature (means of the two loggers
273 on the site). In the canopy openness model, the explanatory variable was the mean of the canopy
274 openness values at 0 and 10 meters.

275 For those readers who are interested in the impacts of the treatments, buffer width, selective
276 logging and logging on the opposite side of the stream on the relative changes of the three indicator
277 mosses, we provide these analyses in Appendix A.

278

279 **3 Results**

280 *3.1 Impact of logging on physical conditions*

281 The treatments had a strong impact on the humidity variables, and logging on the opposite side and
282 the east coordinate also had an impact in the global MANOVA model (Table 2). When compared to
283 the control sites, all of the four types of buffer strips had lower mean humidity (Figure 2 A), and
284 mean humidity was also lowered by logging on the opposite side of the stream (Table 3). In terms of
285 the mean daily minimum humidity, the 30-meter buffers without selective logging did not differ
286 significantly from control sites, while all other treatments had significantly lower values (Figure 2 B),
287 and the minimum humidity values were also lowered by logging on the opposite side of the stream
288 (Table 3). All buffer strips, except for the 30-meter buffers without selective logging, had higher
289 variation (standard deviation) in humidity (Figure 2 C). The standard deviation was also increased by
290 logging on the opposite side and by an eastern location in the geographic area (Table 3).

291 The treatments and logging on the opposite side had significant impacts on the temperature values
292 in their global model, but east coordinate did not (Table 2). Mean temperature was increased on the
293 logged treatments, but only the 15-meter buffer strips (with or without selective logging) differed
294 significantly from controls (Figure 2 D). Mean temperature was also increased by logging on the
295 opposite side of the stream (Table 3). In terms of the mean daily maximum temperature and the
296 standard deviation of temperature, all treatments except the 30-meter buffers without selective
297 logging had significantly higher values than the controls (Figure 2 E and F). In addition, logging on the
298 opposite side also increased the daily maximum and the standard deviation of temperature (Table
299 3).

300 Canopy openness was affected by both the treatments and by the logging on the opposite side, but
301 not by the east coordinate (Table 2). At the stream shoreline, only the 15-meter buffer strips with
302 selective logging had significantly higher canopy openness than control sites (Figure 2 G). Logging on
303 the opposite side increased canopy openness at stream shoreline (Table 3). At the distance of 10

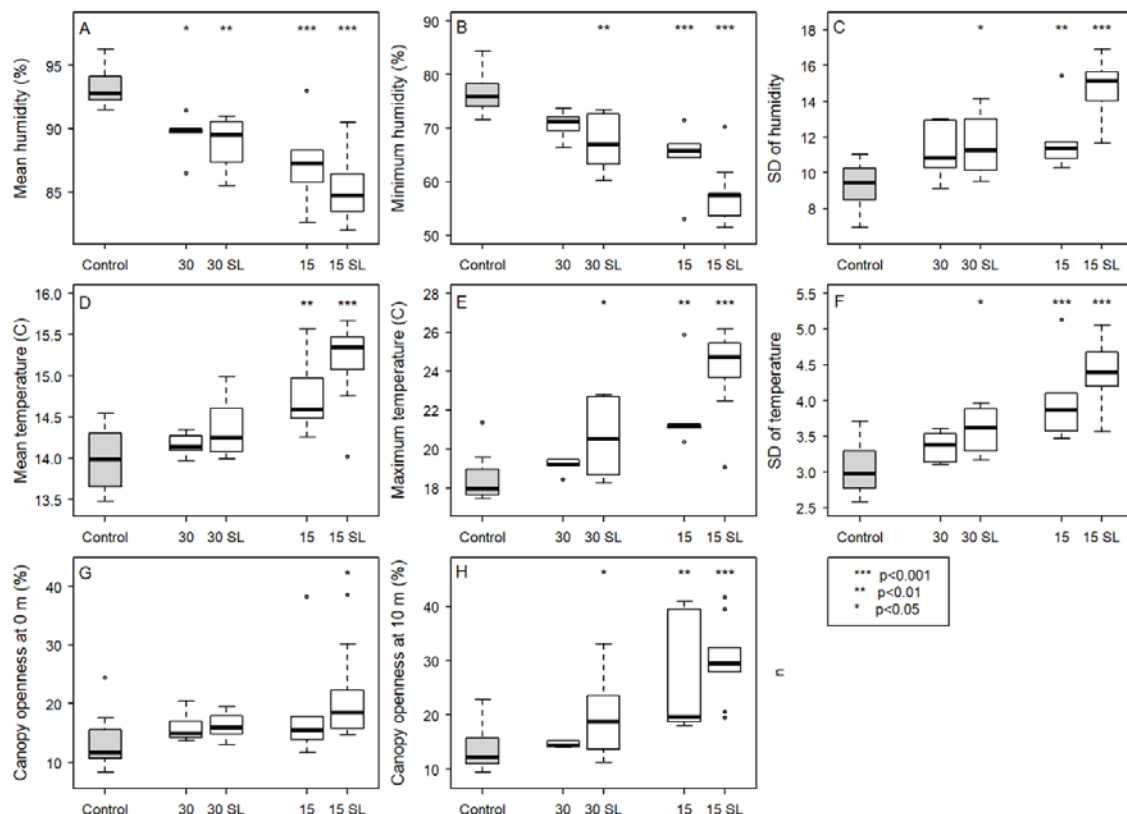
304 meters, all buffer strips, except for the 30-meter buffers without selective logging, had significantly
 305 higher canopy openness than control sites (Figure 2 H). Logging on the opposite side increased
 306 canopy openness as well (Table 3).

307 Table 2. Results from the three MANOVAs on the impact of treatments (unlogged control vs. buffer
 308 strip treatments), logging on the opposite side and east coordinate on relative air humidity
 309 (mean, daily minimum and standard deviation), temperature (mean, daily maximum and
 310 standard deviation) and canopy openness (at 0 and 10 meters from stream). The three
 311 separate MANOVAs are separated by horizontal lines. Pillai test statistic, approximate F-
 312 statistic, hypothesis and error degrees of freedom, and p-value.

Response	Explanatory	Pillai	F	Hypoth. df	Error df	p	Sign.
Humidity	Treatment logging	0.94	3.2	12	84	0.001	***
	Opposite logging	0.26	3.1	3	26	0.043	*
	East coordinate	0.29	3.5	3	26	0.029	*
Temperature	Treatment logging	0.82	2.6	12	84	0.005	**
	Opposite logging	0.30	3.8	3	26	0.022	*
	East coordinate	0.19	2.1	3	26	0.129	
Canopy openness	Treatment logging	0.59	3.0	8	56	0.008	**
	Opposite logging	0.37	8.1	2	27	0.002	**
	East coordinate	0.11	1.6	2	27	0.213	

Significance: *** $p < 0.001$, ** $0.001 < p < 0.1$, * $0.1 < p < 0.05$, . $0.05 < p < 0.1$

313



314

315 Figure 2. The differences between unlogged control sites and the sites with buffer strips (30-meter
 316 without or with selective logging [SL] and 15-meter without or with selective logging) in their

317 physical conditions: A) mean relative humidity, B) mean daily minimum humidity, C) standard
 318 deviation of humidity, D) mean temperature, E) mean daily maximum temperature, F)
 319 standard deviation of temperature, G) canopy openness at stream shoreline, an H) canopy
 320 openness at 10-meter distance from stream.

321 Table 3. Results from the eight linear models on the effects of logging on the opposite side of the
 322 stream and east coordinate on the humidity, temperature and canopy openness variables.
 323 Opposite logging and east coordinates were modelled together with the effects of treatment
 324 loggings (results in Figure 2).

Response	Explanatory					
	Logging on opposite side			East coordinate		
	Estimate	p	Sign.	Estimate	p	Sign.
Mean humidity	-2.47	0.012	*	-9.6E-06	0.066	.
Minimum humidity	-5.80	0.005	**	-2.1E-05	0.054	.
SD of humidity	1.87	0.004	**	1.0E-05	0.005	**
Mean temperature	0.36	0.037	*	7.0E-07	0.440	
Maximum temperature	1.85	0.014	*	4.4E-06	0.264	
SD of temperature	0.54	0.002	**	1.9E-06	0.033	*
Canopy openness at 0 m	0.17	<0.001	***	4.6E-07	0.079	.
Canopy openness at 10 m	0.12	0.024	*	1.9E-07	0.490	

Significance: *** p<0.001, ** 0.001<p<0.1, * 0.1<p<0.05, . 0.05<p<0.1

325

326 3.2 Impact of buffer width, selective logging and aspect on microclimate

327 Buffer width (15 or 30 meters) had significant impacts on the humidity and temperature variables
 328 (Table 4). Selective logging (yes or no) did not have significant impacts, although it did have a nearly
 329 significant impact on humidity when modelled together with southern aspect (Table 4). Both
 330 southern and southwestern aspects impacted the humidity variables significantly, but the
 331 temperature variables were not affected by southwestern aspect and southern aspect had a nearly
 332 significant impact (Table 4).

333 Table 4. Results from four MANOVAs on the effects of buffer width, selective logging and aspect
 334 (southern or southwestern) on the humidity (mean, SD and mean daily minimum) and
 335 temperature (mean, SD and mean daily maximum) on sites with buffer strips. Logging on the
 336 opposite side of the stream and east coordinates were also included as additional explanatory
 337 variables. The four separate MANOVAs are separated by horizontal lines. Pillai test statistic,
 338 approximate F-statistic, hypothesis and error degrees of freedom, and p-value.

Response	Explanatory	Pillai	F	Hypoth. df	Error df	p	Sign.
Humidity	Buffer width	0.49	6.0	3	19	0.005	**
	Selective logging	0.30	2.8	3	19	0.071	.
	Southern aspect	0.46	5.4	3	19	0.008	**
	Logging on opposite side	0.38	3.9	3	19	0.026	*
	East coordinate	0.45	5.1	3	19	0.009	**
Temperature	Buffer width	0.46	5.3	3	19	0.008	**
	Selective logging	0.25	2.1	3	19	0.136	
	Southwestern aspect	0.33	3.2	3	19	0.049	*
	Logging on opposite side	0.23	1.9	3	19	0.161	
	East coordinate	0.28	2.4	3	19	0.099	.

Temperature	Buffer width	0.58	8.7	3	19	0.001	***
	Selective logging	0.27	2.3	3	19	0.111	
	Southern aspect	0.28	2.4	3	19	0.097	.
	Logging on opposite side	0.38	3.8	3	19	0.027	*
	East coordinate	0.28	2.4	3	19	0.098	.
	Buffer width	0.54	7.5	3	19	0.002	**
	Selective logging	0.23	1.9	3	19	0.167	
	Southwestern aspect	0.09	0.7	3	19	0.589	
	Logging on opposite side	0.32	3.0	3	19	0.059	.
	East coordinate	0.23	1.9	3	19	0.161	

Significance: *** p<0.001, ** 0.001<p<0.1, * 0.1<p<0.05, . 0.05<p<0.1

339

340 3.3 Microclimatic refugia on northern side of trees

341 Air humidity was affected by the treatments on both the southern and northern sides of the trees
 342 (Table 5). Air temperature was affected more strongly on the southern than on the northern side,
 343 but the effect was significant on the northern side as well (Table 5).

344 Table 5. Results from the four MANOVAs on the impact of treatments on air humidity (mean, daily
 345 minimum and standard deviation) and temperature (mean, daily maximum and standard
 346 deviation) on the southern and northern sides of trees. The four separate MANOVAs are
 347 separated by horizontal lines. Pillai test statistic, approximate F-statistic, hypothesis and error
 348 degrees of freedom, and p-value.

Response	Explanatory	Pillai	F	Hypoth. df	Error df	p	Sign.
Humidity in south-facing loggers	Treatment logging	0.89	3.2	12	90	< 0.001	***
Humidity in north-facing loggers	Treatment logging	0.97	3.6	12	90	< 0.001	***
Temperature in south-facing loggers	Treatment logging	0.81	2.8	12	90	0.003	**
Temperature in north-facing loggers	Treatment logging	0.69	2.2	12	90	0.016	*

Significance: *** p<0.001, ** 0.001<p<0.1, * 0.1<p<0.05, . 0.05<p<0.1

349

350 3.4 Impact of physical conditions on mosses

351 Mean humidity, mean temperature and mean canopy openness each explained significantly the
 352 changes in the cover of the three moss species, and mean humidity had the strongest effect among
 353 the three variables (Table 6).

354 Table 6. Results from the three MANOVAs on the impacts of mean humidity, mean temperature and
 355 mean canopy openness on the change in the cover of three moss species (*H. splendens*, *P.*
 356 *cincliooides* and *P. commune*). The three separate MANOVAs are separated by horizontal
 357 lines. Pillai test statistic, approximate F-statistic, hypothesis and error degrees of freedom, and
 358 p-value.

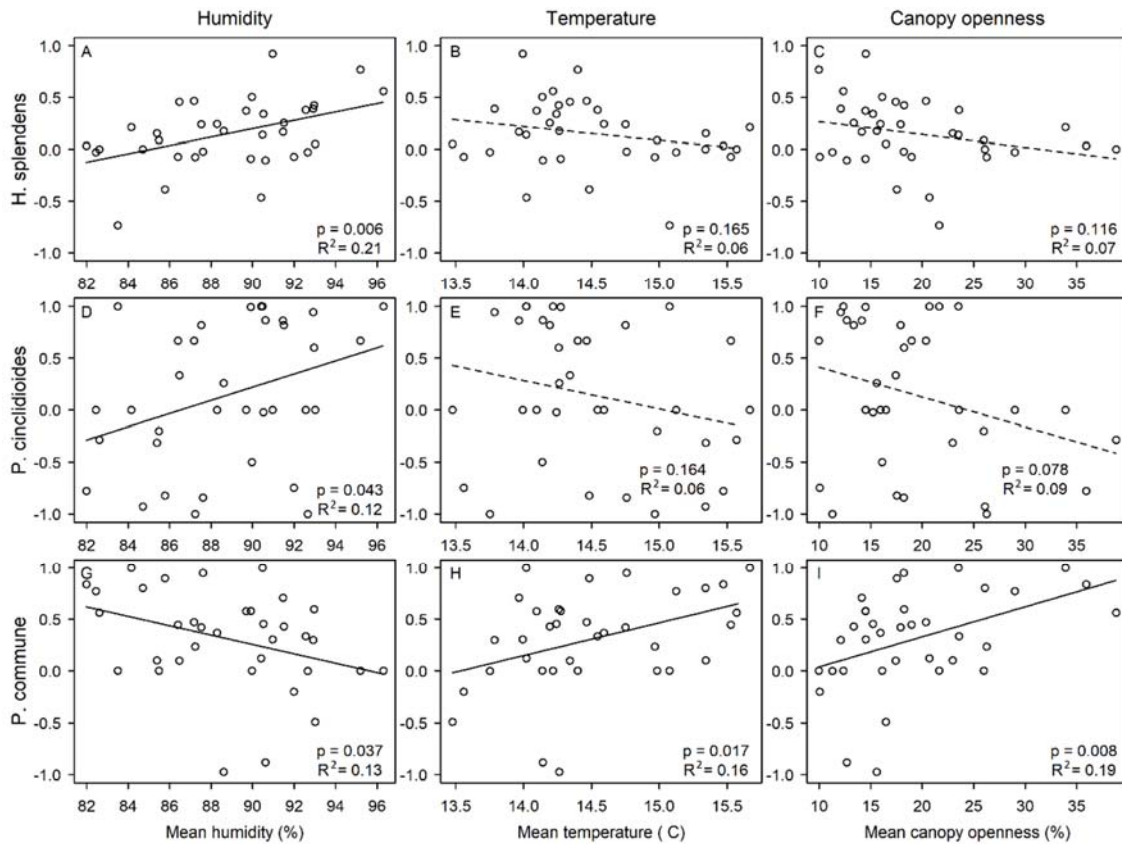
Response	Explanatory	Pillai	F	Hypoth. df	Error df	p	Sign.
Mosses	Mean humidity	0.39	6.7	3	31	0.001	**
	Mean temperature	0.24	3.3	3	31	0.033	*

Mean canopy openness 0.31 4.7 3 31 0.008 **

Significance: *** $p < 0.001$, ** $0.001 < p < 0.1$, * $0.1 < p < 0.05$, . $0.05 < p < 0.1$

359

360 The relative change in the cover of *H. splendens* was affected by humidity, which had a significant
 361 positive impact, while temperature and canopy openness did not have significant impacts on this
 362 species (Figure 3 A-C). Similarly, the relative change of *P. cinclidioides* was significantly and positively
 363 affected by humidity, while temperature and canopy openness did not have significant effects
 364 (Figure 3 D-F). In contrast, the relative change in *P. commune* was significantly affected by all three
 365 variables: negatively by humidity, and positively by temperature and canopy openness (Figure 3 G-I).
 366 Canopy openness had the largest impact on *P. commune* (Figure 3 I).



367

368 Figure 3. The impacts of mean relative humidity, mean temperature and mean canopy openness on
 369 the relative changes that have occurred in the cover of the three moss species (from pre-
 370 logging to 12 years post-logging): A-C) *Hylocomium splendens*, D-F) *Pseudobryum cinclidioides*,
 371 and G-I) *Polytrichum commune*. Solid regression lines indicate significant relationships
 372 ($p < 0.05$) and dashed lines indicate non-significant relationships ($p < 0.05$).

373

374 4 Discussion

375 4.1 Impact of logging on physical conditions

376 We found strong impacts of logging on the measured microclimatic variables of air temperature and
 377 relative humidity. As expected, the divergence from control site microclimates was in the order 15-
 378 meter selectively logged > 15-meter without selective logging > 30-meter selectively logged > 30-

379 meter without selective logging. The effects were similar for canopy openness at 10 meters from the
380 stream, while right at the stream shoreline only the most intensive logging (15 m selective logging)
381 resulted in significant difference from controls.

382 The 15-meter wide buffers, both those with and without selective logging, differed from control sites
383 in their microclimate. They had lower humidity and higher temperature, and both humidity and
384 temperature varied more. These logging-induced changes in microclimate are well known near clear-
385 cut edges in upland forests (Chen et al., 1995; Moore et al., 2005). Obviously, 15-meter buffers do
386 not fulfil the criteria of no changes in microclimate and are therefore illegal in Finnish Forest Act
387 habitats (Forest Act, 2013), although they have been common in practice (Ahonen, 2017). Our
388 measurements were made 12 years after logging, when the newly regenerated trees already
389 provided some protection, but there had also been abundant windfalls in many sites with 15-meter
390 buffers, which had resulted in more microclimatic changes by the time of our measurements.

391 Maximum daily temperature and minimum daily humidity differed more from the values found in
392 control sites than did the means of temperature and humidity. For example, in the sites with 15-
393 meter selectively logged buffers, mean temperature was on average 1.2 °C higher while mean daily
394 maximum temperature was 5.6 °C higher than in controls, and mean humidity was 8.1 % lower while
395 mean daily minimum humidity was 19.0 % lower. This is because at night unlogged forests are
396 somewhat warmer than logged areas, and the stream humidifies the surrounding air (Moore et al.,
397 2005; Rykken et al., 2007). The changes in the heat and dryness of the hottest time of the day may
398 be detrimental to sensitive organisms.

399 The differences in mean and maximum temperatures are comparable to the expected effects of
400 climate change in the area (mean temperature increases by 2-3 °C and the mean temperature of the
401 annual hottest day increases by 1.5-2 °C if global warming is limited to 1.5 °C; Hoegh-Guldberg et al.,
402 2018). However, climate change happens over several decades, while logging changes the
403 microclimate immediately (or in a time span of a few years if there are subsequent windfalls),
404 leaving very little time for sensitive organisms to adapt or migrate. It is likely that within a few
405 decades, the joined effect of climate change and logging causes peak temperatures of the logged
406 streamsidings to increase by several degrees compared to present values. In addition, logging with
407 narrow buffers destroys the possibilities of cool and humid streamsidings to function as microclimatic
408 refugia or dispersal corridors during climate change (see Ashcroft, 2010; Fremier et al., 2015; Isaak et
409 al., 2015). All this adds pressure to secure wide buffer strips.

410 Microclimatic changes were smaller in 30-meter buffers. On average, both the selectively logged and
411 the non-selectively logged 30-meter buffers were warmer and dryer and had more variation than did
412 the unlogged controls, but the difference from controls was mostly significant for only the selectively
413 logged ones. However, in the case of mean relative humidity also the 30-meter buffers without
414 selective logging were drier than control sites. Thus, based on our data, 30-meter wide buffers are
415 nearly wide enough to retain microclimatic conditions in streamside forests, but the buffers should
416 not be selectively logged. Our results are supported by Brososke et al. (1997) who found that 45-
417 meter buffers are mostly sufficient to protect riparian microclimatic gradients, and by the study of
418 Rykken et al. (2007) where 30-meter buffers were sufficient to retain similar microclimate as
419 unlogged forests. Thus, buffer width should exceed 30 meters when the aim is to conserve
420 microclimatic conditions in valuable habitats. Probably the buffer width should be about 40-50
421 meters, but more studies are needed to confirm this suggestion. On the other hand, if the primary
422 aim of leaving a buffer strip is not to conserve the microclimate, narrower or selectively logged
423 buffer strips can be sufficient. Selective logging within buffers may provide better emulation of
424 natural disturbances and increase habitat diversity and tree regeneration (Kreutzweiser et al., 2012;
425 Mallik et al., 2014). Therefore, selective logging could be applied in sites where microclimatic
426 protection is not considered necessary, thus increasing habitat heterogeneity at the landscape-scale.

427 Logging on the opposite side of the stream had significant impacts on all of the measured
428 temperature, humidity and canopy openness variables. This implies that a wider buffer should be
429 left if the other side has been logged recently, or there is a risk that it will be logged before the
430 currently logged area has reached high enough growing stock for resisting edge effects (in Finnish
431 conditions we expect this to happen in about three decades). Finally, additional variables such as
432 topography, hydrology or the sensitivity of the species communities, should be considered wherever
433 possible to modify buffer width case-by-case. For example, streamsides with groundwater discharge
434 or frequent flooding may be especially sensitive and may require wider buffers (Kuglerová et al.,
435 2014). If the retained buffer is too narrow to retain the microclimate and specific biodiversity values
436 in the particular streamside, it is not cost-efficient at all, because it concurs economic costs but the
437 most sensitive species are lost anyway.

438 *4.2 Impact of buffer width, selective logging and aspect on microclimate*

439 Buffer width exerted a much stronger impact on relative air humidity and temperature than did
440 selective logging within the buffer. This is not surprising as the two buffer strip treatments (15 or 30
441 meters) differed by 50 % tree removal, while selective logging removed 30 % of tree basal area. The
442 buffer width causes so much microclimatic changes that additional changes caused by selective
443 logging are smaller. However, the selectively logged sites differed more from controls than those
444 that were not selectively logged (see Figure 2). Thus, although buffer width seems to be the most
445 important factor determining microclimatic conditions, selective logging does exert some additional
446 changes. This is most likely due to canopy gaps resulting in increased solar radiation and increased
447 air temperature (Gray et al., 2002). In upland forests, forest density is the main driver of summer
448 temperature minima and maxima (Greiser et al., 2018), and selective logging results in clear
449 microclimatic changes (Zheng et al., 2000). In addition, microclimatic edge effects reach deeper into
450 the forest when the forest is more open (Heithecker and Halpern, 2007; Schmidt et al., 2017). On the
451 other hand, selective logging within the riparian buffer results in increased regeneration of tree
452 saplings and shrubs (Mallik et al., 2014; Zenner et al., 2012), which may provide microclimatic
453 protection (Kovács et al., 2017). As our sites had been logged 12 years before the measurements,
454 the shrubs and saplings can be already quite large, which may explain why the impact of selective
455 logging seems to be relatively small. In our study, the trees were removed evenly from the whole
456 width of the buffer strip, but the microclimate might be better protected by uneven logging where
457 more trees are removed closer to the clear-cut edge.

458 Southern or southwestern aspect of the clear-cut increased the impacts of the logging actions on
459 relative air humidity, and southern aspect also caused a small impact on air temperature. These
460 results are mostly in accordance with earlier results on the effects of aspect in upland forest edges
461 (Chen et al., 1995; Heithecker and Halpern, 2007; Moore et al., 2005). However, buffer width and
462 logging on the opposite side did cause larger impacts than aspect, especially on temperature.
463 Therefore, we recommend leaving buffer strips of more than 30 meters on all aspects, but
464 protecting air humidity requires even wider buffers if the clear-cut will be towards south or
465 southwest.

466 *4.3 Microclimatic refugia on northern side of trees*

467 We did not find evidence that the northern side of spruce trunks could provide small-scale
468 microclimatic refugia. Both humidity and temperature variables were affected by the logging
469 treatments on both the northern and southern sides of the trees. For the humidity variables, the
470 northern side of the trees did not provide any protection compared to the southern sides. Thus, for
471 species that are sensitive to changes in air humidity, there are no refugia on northern sides of trees
472 in riparian forests. For the temperature variables, the treatments caused larger differences on the
473 southern sides of trees than on northern sides of trees. This is most likely due to more sunlight on
474 the southern side, which heats up the tree bark as well as the data logger, and respectively the

475 organisms on it. Therefore, for those species that suffer from logging-induced increases in radiation
476 or temperature, there is a higher chance of survival on the northern sides of trees. However, on the
477 northern sides of the trees there were still differences in temperature between control sites and
478 treatment sites, which weakens the refugia.

479 Schmalholz and Hylander (2011) found that the northern sides of boulders and stumps provided
480 refugia for forest floor bryophytes on clear-cuts, where the microclimate changes more drastically
481 than in riparian buffers. It may be that the base of large boulders or large stumps provide more
482 constant microclimatic conditions also in riparian buffers. In addition, organisms that grow on the
483 forest floor, especially in concave depressions, are better protected than those on convex substrates
484 such as tree bases (Hylander et al., 2005).

485 4.4 Impact of physical conditions on mosses

486 The relative change in the cover of the three model moss species was affected by each of the
487 physical factors: mean relative humidity, mean temperature and canopy openness. Thus, the
488 logging-induced changes in the microclimatic conditions do result in changes in sensitive species
489 communities, which is in accordance with earlier studies from riparian buffer strips of various widths
490 (Elliott and Vose, 2016; Hylander et al., 2005; Oldén et al., 2019). The most significant of the three
491 variables was air humidity, which had a significant impact on the relative change of each of the three
492 moss species. This shows that changes in humidity must be avoided to prevent changes in moss
493 communities.

494 The relative change in the cover of the forest floor moss *Hylocomium splendens* was affected by
495 humidity: the cover of the species had increased in sites with high humidity and decreased or stayed
496 at the same level in sites with low humidity. Earlier studies have shown that the growth of *H.*
497 *splendens* decreases due to microclimatic edge effects, in both riparian buffers (Stewart and Mallik,
498 2006) and in retained upland forest patches (Caners et al., 2013; Hylander, 2005). Water is the major
499 limiting factor for the growth of *H. splendens*, because it does not have an internal water conducting
500 system and under dry conditions it dries out quickly (Callaghan et al., 1978). Busby et al. (1978)
501 showed that the growth of *H. splendens* was affected positively by precipitation frequency and
502 negatively by evaporation stress. Light and temperature were not significant factors in controlling
503 growth rates (Busby et al., 1978), which is in accordance with our results of no significant impacts of
504 temperature or canopy openness on the change in the species cover. Callaghan et al. (1978) showed
505 that the photosynthesis of *H. splendens* is positively affected by higher temperatures, but in high
506 temperature respiration exceeds gross photosynthesis, and therefore the growth of the species is
507 favored by low temperature.

508 Similarly to *H. splendens*, the relative change in the cover of *Pseudobryum cinclidioides* was also
509 positively affected by mean air humidity. This exemplifies that even the riparian species that grow on
510 the inundated soil right next to the stream may suffer from changed air humidity due to logging 15-
511 30 meters away from the stream. The decline in the abundance of *P. cinclidioides* in retention
512 patches has been recorded also by Perhans et al. (2009). The large leaves of the species may be
513 efficient in photosynthesizing in moist and humid conditions, but they are likely to dry out if air
514 humidity decreases, and even high soil moisture may not be able to buffer against this. Therefore, *P.*
515 *cinclidioides* could be used as an indicator species when studying microclimatic changes in riparian
516 communities. However, in our study sites the species often had low cover, and therefore even small
517 changes in cover results in large changes in relative cover, causing much variation in the data. *P.*
518 *cinclidioides* typically grows beside the stream in the zone that is inundated for a short period during
519 spring and then is waterlogged during the rest of the growing season (Darell and Cronberg, 2011).
520 For this reason, a better study setup for this species would have more study plots right next to the
521 stream.

522 *Polytrichum commune* showed an opposite response to increasing changes in microclimate: the
523 relative cover increased in sites with low humidity, high temperature and high canopy openness. *P.*
524 *commune* has an underground stem system, internal water conducting tissues and complex leaves
525 that are able to resist water loss, which enables the species to photosynthesize in dry conditions
526 (Bayfield, 1973). Instead of water availability, the growth of *P. commune* is limited by light
527 availability, and for this reason it grows fast in habitats where there is little shadow from other
528 vegetation (Callaghan et al., 1978). In addition, *P. commune* spreads efficiently to bare soil patches
529 via both sexual reproduction and vegetative reproduction from underground stems (Callaghan et al.,
530 1978). Thus, the death of other mosses due to damage from logging machinery or microclimatic
531 stress creates suitable habitats for this opportunistic moss.

532 We do not have pre-logging microclimatic data from the sites and therefore it is not possible to
533 analyze the effects of the treatments on changes that have happened in microclimate from pre-
534 logging to post-logging. The fact that the moss changes from pre-logging to post-logging correlate
535 well with the post-logging microclimatic data implies that there have indeed been logging-induced
536 changes in the buffer strip sites. Also, the results show that the microclimatic conditions, which were
537 measured in only one point at the height of 0.5 meters, caused changes in mosses that respond to
538 the conditions in their immediate surroundings at the ground-level. This indicates that moist soil
539 conditions or field layer vegetation were not enough to protect the ground-dwelling mosses against
540 the larger microclimatic changes within the site. On the other hand, only 15-meter buffers trips
541 resulted in significant changes in the relative covers of the mosses, while the impacts were more
542 varied for sites with 30-meter buffers trips (see Appendix A). More comprehensive studies with
543 more sites, more plots and more species are needed to confirm the minimum buffer width that is
544 adequate to conserve mosses.

545

546 **5 Conclusions**

547 We compared the microclimatic conditions in four different buffer strip treatments and unlogged
548 controls, and found that all the treatments affected some or all of the microclimate variables. The
549 conditions in 15-meter buffer strips (with or without selective logging) or in 30-meter buffer strips
550 with selective logging were so different from controls that they clearly do not meet the
551 requirements for no change in microclimate set by the Finnish Forest Act (Forest Act, 2013).

552 The 30-meter buffer strips without selective logging differed only little from controls, but they did
553 have significantly lower mean air humidity. The differences in mean air humidity between all of the
554 sites correlated with the responses of the three indicator moss species, suggesting that the changes
555 in this microclimatic component has biological impacts. In addition, we found no evidence of the
556 possibility of the northern side of large trees (or other similar objects) to provide microclimatic
557 refugia for species that are sensitive to changes in air humidity, although species sensitive to high
558 radiation and temperature might survive better on the northern side of the trees.

559 We conclude that to preserve riparian microclimatic conditions and species dependent on those,
560 buffer strips between the stream and the clear-cut should exceed 30 meters. We do not recommend
561 evenly distributed selective logging (of about 30 % basal area) even within wide buffer strips. Extra
562 wide buffer strips should be considered if the aspect of the clear-cut is towards south or southwest,
563 or if the two sides of a stream are logged at the same time or during subsequent years. It is
564 preferable to avoid logging both sides during subsequent decades.

565

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572

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