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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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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

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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<sup>-1</sup> (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 <sup>2</sup> /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.

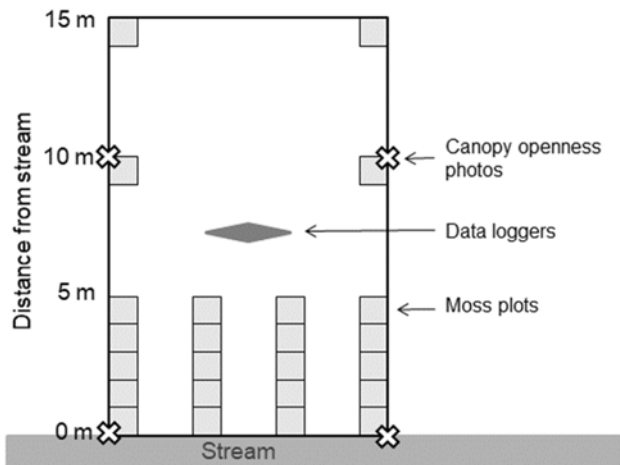
146 Originally, the logging treatment was performed on only one side of the stream, and mature forest  
147 was left standing on the opposite side. If by the year 2017 logging had also happened on the  
148 opposite side of the stream, we measured the distance from the stream to the edge of the clear 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 18<sup>th</sup> of July and 18<sup>th</sup> 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 m<sup>2</sup> 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  $\log_{10}$ -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

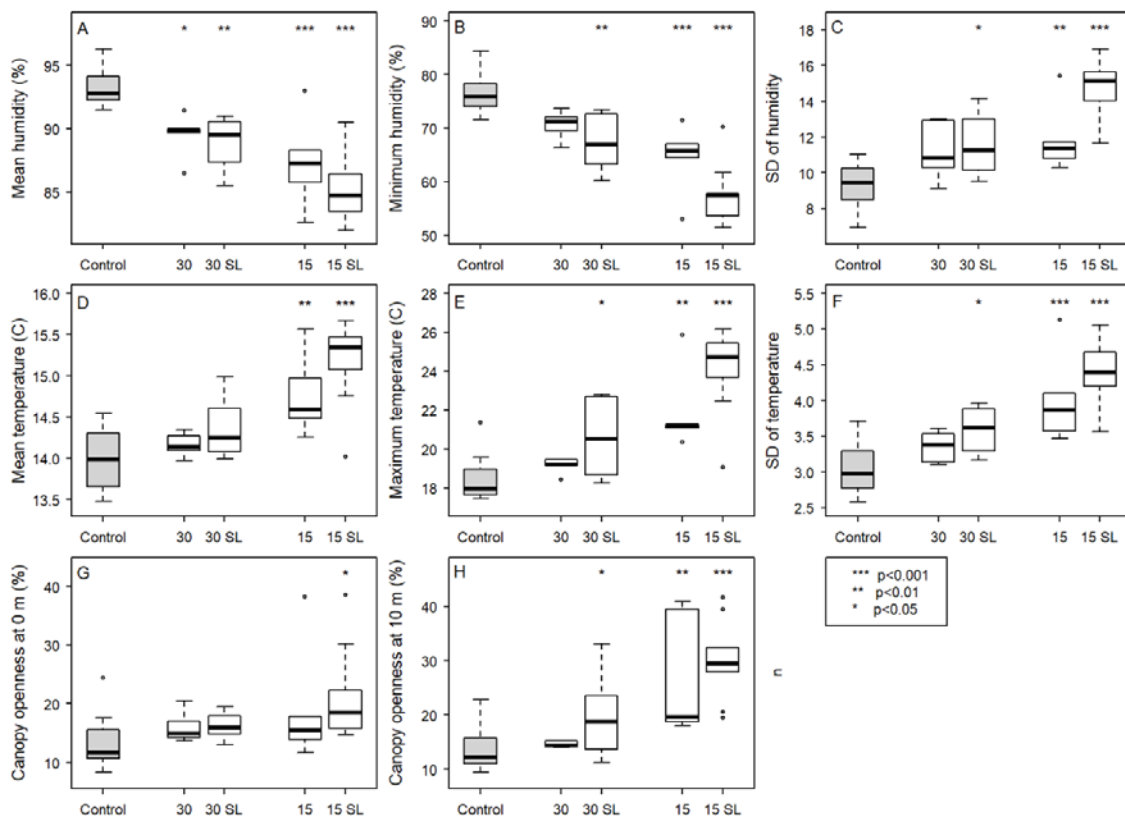
304 meters, all buffer strips, except for the 30-meter buffers without selective logging, had significantly  
 305 higher canopy openness than control sites (Figure 2 H). Logging on the opposite side increased  
 306 canopy openness as well (Table 3).

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			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.

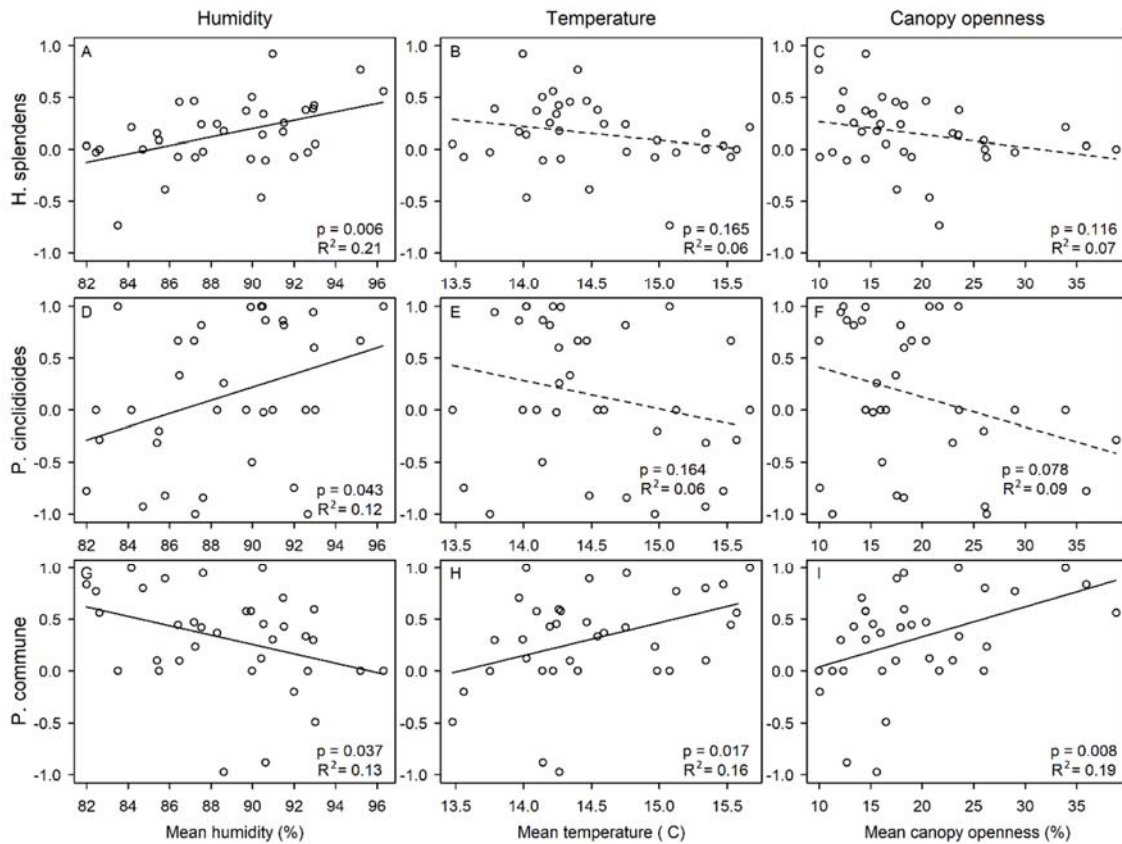
Response	Explanatory	Pillai	F	Hypoth. df	Error df	p	Sign.
Mosses	Mean humidity	0.39	6.7	3	31	0.001	**
	Mean temperature	0.24	3.3	3	31	0.033	*

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 streamsides to increase by several degrees compared to present values. In addition, logging with  
407 narrow buffers destroys the possibilities of cool and humid streamsides 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 Brosfoske 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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