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6 *Running head: Management-induced microclimate changes*

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8 **Unfolding the effects of different forestry treatments on microclimate in oak forests: results**
9 **of a 4-year experiment**

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26 **Abstract**

27 Stable below-canopy microclimate of forests is essential for their biodiversity and ecosystem
28 functionality. Forest management necessarily modifies the buffering capacity of woodlands.
29 However, the specific effects of different forestry treatments on site conditions, the temporal
30 recovery after the harvests and the reason of the contrasts between treatments are still poorly
31 understood.

32 The effects of four different forestry treatments (clear-cutting, retention tree group, preparation
33 cutting and gap-cutting) on microclimatic variables were studied within a field experiment in a
34 managed oak dominated stand in Hungary, before (2014) and after (2015–2017) the
35 interventions by complete block design with six replicates.

36 From the first post-treatment year, clear-cuts differed the most from the uncut control due to the
37 increased irradiance and heat load. Means and variability of air and soil temperature increased,
38 air became dryer along with higher soil moisture levels. Retention tree groups could effectively
39 ameliorate the extreme temperatures but not the mean values. Preparation cutting induced slight
40 changes from the original buffered and humid forest microclimate. Despite the substantially
41 more incoming light, gap-cutting could keep the cool and humid air conditions and showed the
42 highest increase in soil moisture after the interventions. For most microclimate variables, we
43 could not observe any obvious trend within three years. Though soil temperature variability
44 decreased with time in clear-cuts, while soil moisture difference continuously increased in gap-
45 and clear-cuts. Based on multivariate analyses, the treatments separated significantly based
46 mainly on the temperature maxima and variability.

47 We found that (i) the effect sizes among treatment levels were consistent throughout the years;
48 (ii) the climatic recovery time for variables appears to be far more than three years and (iii) the
49 applied silvicultural methods diverged mainly among the temperature maxima.

50 Based on our study, the spatially heterogeneous and fine-scaled treatments of continuous cover
51 forestry (gap-cutting, selection systems) are recommended. By applying these practices, the
52 essential structural elements creating buffered microclimate could be more successfully
53 maintained. Thus, forestry interventions could induce less pronounced alterations in
54 environmental conditions for forest-dwelling organism groups.

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58 **Keywords:** air temperature; forest ecological experiment; forest management; photosynthetically
59 active radiation (PAR); relative humidity; soil moisture; soil temperature; temperate deciduous
60 forests; vapor pressure deficit (VPD)

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63

64 **Introduction**

65 Microclimate studies as well as the integration of their outcomes into climate-dependent
66 models have become an important research area for both climatologists, ecologists and
67 practitioners in the last two decades. This topic is especially relevant facing the current
68 anthropogenic climate change and its effects on ecosystems and their functionality (Hannah et al.
69 2014, Frey et al. 2016, Bramer et al. 2018). The better understanding of microclimate can
70 contribute to the adjustment of climate and species distribution models. It has been revealed
71 since decades that organisms are exposed to the variability of climate on finer spatial scales than
72 it is typically measured by standard meteorological stations worldwide (Geiger et al. 1995, Potter
73 et al. 2013). This mismatch results in coarser scale abiotic data that are not entirely appropriate
74 for surveying and modelling biological processes (Suggitt et al. 2011, De Frenne and Verheyen
75 2016). Furthermore, local conditions can often result in microclimates that are substantially
76 different from the macroclimate; therefore, the ranges of the driving forces of species distribution
77 – e.g., climatic extremes – are narrowed (Suggitt et al. 2011, Scherrer et al. 2011, Scheffers et al.
78 2014). As a result, the lack of information about the upper or lower limits could cause either
79 over- or underprediction of the climatically suitable microenvironments for species (Ashcroft
80 and Gollan 2013, Hannah et al. 2014, Frey et al. 2016). Though woodlands have been identified
81 as a main factor shaping climatic microrefugia besides topography and moisture conditions
82 (Ashcroft and Gollan 2013, von Arx et al. 2013, Latimer and Zuckerberg 2017), there are still
83 limited data collected beneath forest canopies which would be essential for climatic predictions
84 as well as species distribution modelling (De Frenne and Verheyen 2016, Bramer et al. 2018).
85 Hence, it is necessary to explore the below-canopy microclimates in stand types, which are

86 different based on physiography, forest site conditions, tree species composition, vertical and
87 horizontal structure or natural and anthropogenic disturbance regimes.

88 It is widely known that forests create unique, stable and ameliorated below-canopy
89 microclimates which substantially differ from the adjoining open habitats (Geiger et al. 1995,
90 Chen et al. 1999, von Arx et al. 2012, Barry and Blanken 2016). In the trunk space, the mean and
91 variance of air and soil temperature are typically lower. Similarly, the vapor pressure deficit or
92 wind velocity is reduced, while the air humidity is higher than these characteristics in open-field.
93 This special buffered environment was proved to be an essential driver of biodiversity as well as
94 numerous biogeochemical processes and ecosystem functionality (Lewandowski et al. 2015,
95 Good et al. 2015, Ehbrecht et al. 2017, Davis et al. 2018). Among others, microclimate was
96 revealed as an important factor of vitality and survival of woodland herbs (Lendzion and
97 Leuschner 2009), species composition and community structure of understory vegetation (Aude
98 and Lawesson 1998, Godefroid et al. 2006, De Frenne et al. 2015), the frost sensibility of
99 saplings (von Arx et al. 2013, Charrier et al. 2015), the richness, abundance or vertical
100 occurrence of cryptogams (Coxson and Coyle 2003, Gaio-Oliveira et al. 2004, Fenton and Frego
101 2005, Dynesius et al. 2008), the species composition of spiders and saproxylic beetles (Košulič
102 et al. 2016, Seibold et al. 2016) and also the survival and population density of forest-inhabiting
103 birds (Betts et al. 2018).

104 The canopy cover and its structure are typically highlighted as one of the most important
105 drivers of the buffer capacity of a given forest stand (Bonan 2016, Latimer and Zuckerberg 2017,
106 De Frenne et al. 2019), which is necessarily altered by forest management practices (Chen et al.
107 1999, Hardwick et al. 2015, Lin et al. 2017, Ehbrecht et al. 2019). Forestry interventions creating
108 for example clear-felled areas or stands with large openings generate microclimatic conditions

109 which are considerably different from those in forests (Chen et al. 1999, Bonan 2016). It is an
110 important conservational aspect to study how these management types induced alterations affect
111 the climatically suitable habitats for forest-dwelling organism groups (De Frenne and Verheyen
112 2016). Furthermore, regeneration time of microclimatic conditions after anthropogenic
113 disturbances generated by silviculture is also a highly relevant question for the colonization (or
114 recovery) of forest-dwelling populations.

115 Forest management (especially clear-cutting) could have long-term effects on light regime,
116 moisture conditions of the forest soil, air temperature and humidity as well as vapor pressure
117 deficit. Changes in the environmental conditions after clear-cutting can persist over years or
118 decades whereupon microclimate can recover to pre-treatment levels (Matlack 1993, Dodonov et
119 al. 2013, Dovčiak and Brown 2014, Baker et al. 2014). In contrary, the observed alterations
120 following partial harvesting methods or gap-cutting are described usually as ephemeral processes
121 (Aussenac and Granier 1988, Anderson et al. 2007, Grayson et al. 2012). However, there is still
122 limited knowledge about the temporal climatic recovery after forestry interventions in Europe.

123 Beside the general and temporal effects of silvicultural management on forest microclimate, it
124 is also important to identify the most influential microclimatic variables that generate differences
125 between the certain forestry treatments. Many studies underline that forest-dwelling organisms are
126 more sensitive to extremes or the short-term variability of microclimatic conditions than to changes
127 of mean values that should be also considered during management planning (Brooks and Kyker-
128 Snowman 2008, Huey et al. 2009, Moning and Müller 2009, Suggitt et al. 2011, Lindo and
129 Winchester 2013, Scheffers et al. 2014).

130 The “Pilis Forestry Systems Experiment” (<https://piliskiserlet.okologia.mta.hu/en>) was
131 implemented to compare the long-term effects of forestry interventions belonging to the most

132 common silvicultural systems applicable to temperate forests in Europe on forest site conditions,
133 natural regeneration and forest biodiversity in a managed sessile oak (*Quercus petraea* Matt.
134 [Liebl.]) – hornbeam (*Carpinus betulus* L.) forest, which is a widespread woodland habitat type
135 across Europe (Janssen et al. 2016). In the framework of this forest ecological experiment, we
136 combined the prevalent treatment types of the regionally dominant rotation forestry system as
137 well as the recently introduced selection (continuous cover) forestry system (Pommerening and
138 Murphy 2004).

139 The aim of this study is to explore the effects of silvicultural treatments on below-canopy
140 microclimate, as well as its short-term recovery processes. Our specific questions were the
141 following: (i) to what extent do the treatments modify the studied microclimatic variables; (ii) do
142 these variables change in time during the first three growing seasons in the different treatments;
143 (iii) which are the most determinant microclimatic variables in the separation of the treatments?

144 We hypothesized that (i) clear-cutting has the most drastic effects on all variables resulting
145 in the highest differences from control; retention tree group can moderately compensate the
146 effects of clear-cutting; gap-cutting might be characterized by high light values and increased
147 soil moisture, but otherwise microclimate conditions remain buffered; while preparation cutting
148 only slightly differs from the closed forest control. It was also expected that (ii) the strongest
149 treatment effect is detected in the first year after the interventions, which is moderated by the
150 regeneration processes in the consecutive years. We assumed that (iii) temperature variables and
151 soil moisture are the most important in the separation of treatments, and it was also expected that
152 the daily maximum and minimum values have higher importance shaping microclimatic
153 differences among treatments than means.

154

155 **Materials and methods**

156 *The study area*

157 The study was conducted in the Pilis Mountains, Hungary (47°40' N, 18°54' E; Fig. 1.a)
158 using experimental plots situated on moderate (7.0–10.6°), northeast-facing slopes on a
159 broadened horst-plateau (Hosszú-hegy, 370–470 m above sea level). The climate is humid
160 continental (moderately cool–moderately wet class), the mean annual temperature is 9.0–9.5°C
161 (16.0–17.0°C during the growing season) and the mean annual precipitation is 650 mm (the total
162 summer precipitation is 350 mm) (Dövényi 2010). The bedrock consists of limestone and
163 sandstone with loess (Dövényi 2010). The soil depth varies along the slight topographic gradient
164 from 70 cm (near the ridge) to 250 cm (in the lower part of the site), although the physical and
165 chemical variables of the topsoil (the upper 50 cm) are similar in the area. Soils are slightly
166 acidic (pH of the 0–20 cm layer is 4.6 ± 0.2). The soil types are Luvisols (mainly brown forest
167 soil with clay illuviation) and Rendzic Leptosol (for further information, see Kovács et al. 2018).

168 The experimental site was established in a 40 ha sized homogeneous unit of managed, 80
169 years old two-layered sessile oak–hornbeam forest stand (Natura 2000 code: 91G0; Council
170 Directive 92/43/EEC 1992) with a relatively uniform structure, homogeneous canopy closure
171 (Appendix S1: Table S1) and tree species composition as a consequence of the applied
172 shelterwood silvicultural system. The upper canopy layer (mean height: 21 m) is dominated by
173 sessile oak, the subcanopy layer is primarily formed by hornbeam (mean height: 11 m). Other
174 woody species are rare, individuals of *Fraxinus ornus* L., *Fagus sylvatica* L., *Quercus cerris* L.,
175 and *Prunus avium* L. can be found as admixing tree species. Before the experimental treatments,
176 the shrub layer was scarce and mainly consisted of the regeneration of hornbeam and *Fraxinus*
177 *ornus* L. with a lower cover of shrub species (e.g., *Crataegus monogyna* Jacq., *Cornus mas* L.,

178 *Ligustrum vulgare* L., and *Euonymus verrucosus* Scop.). The understory layer was initially
179 formed by general and mesic forest species (*Carex pilosa* Scop., *Melica uniflora* Retz.,
180 *Cardamine bulbifera* L., *Galium odoratum* (L.) Scop., and *Galium schultesii* Vest.) and had a
181 cover of approximately 45%.

182

183 ***Experimental design***

184 Five treatment types were implemented following a randomized complete block design in
185 six replicates (hereafter blocks) that resulted in 30 plots (Figure 1b): (1) *control* (C) with
186 unaltered stand characteristics; (2) *clear-cutting* (CC) creating 0.5 ha sized circular clear-cuts by
187 eliminating every tree individual (DBH \geq 5 cm and/or height \geq 2 m) within areas of 80 m in
188 diameter; (3) *gap-cutting* (G) represented by circular artificial gaps with approximately 1:1 gap
189 diameter/intact canopy height ratio (diameter: 20 m, area: 0.03 ha); (4) *preparation cutting* (P) as
190 uniform partial cutting within a circle with a diameter of 80 m (the complete subcanopy-layer,
191 and 30% of the initial total basal area of the upper canopy layer was removed in a spatially even
192 arrangement); and (5) circular *retention tree group* (R) within the clear-cuts where all of the tree
193 and shrub individuals were retained as a 0.03 ha sized (diameter: 20 m) circular patch of retained
194 trees. Treatments were implemented in the winter of 2014–2015. A more detailed description of
195 the experimental design and the treatments can be found in the work of Kovács et al. (2018) and
196 in the Appendix S1 (Fig. S1.).

197

198 ***Data collection***

199 Systematic microclimate measurements were taken in the center of each plot. Temporally
200 synchronized data collection was carried out using 4-channeled Onset ‘HOBO H021-002’ data

201 loggers (Onset Computer Corporation, Bourne, MA, USA). In the studied years (2014–2017),
202 every month of the growing season (March–October), 72 hr logging periods were applied with
203 10 min logging intervals. Photosynthetically active radiation (PAR, $\lambda = 400\text{--}700\text{ nm}$;
204 $\mu\text{mol m}^{-2}\text{ s}^{-1}$) was measured at 150 cm above ground level, using Onset ‘S-LIA-M003’ quantum
205 sensors. Air temperature (T_{air} ; °C) and relative humidity (RH, %) data were collected 130 cm
206 above ground level with Onset ‘S-THB-M002’ sensors (Onset Computer Corporation, Bourne,
207 MA, USA) housed in standard radiation shields against direct sunlight. Soil temperature (T_{soil} ;
208 °C) was measured with ‘S-TMB-M002’ sensors (Onset Computer Corporation, Bourne, MA,
209 USA) placed 2 cm below ground. Soil water content (SWC; m^3/m^3) data were collected using
210 Onset ‘S-SMD-M005’ soil moisture sensors (Onset Computer Corporation, Bourne, MA, USA)
211 buried 20 cm below ground level to measure the average soil moisture at 10–20 cm soil depth.
212 Air temperature and relative humidity data were used to calculate vapor pressure deficit (VPD;
213 kPa), which characterize the actual drying capacity of air (using the equations recommended by
214 Allen et al. 1998).

215 The collected and manually screened microclimate data were imported into a SpatialLite
216 4.3.0a database (Furieri 2015) and were split into 24 h subsets. The experiment followed a
217 Before-After Control-Impact design (Stewart-Oaten et al. 1986): the measurement of all
218 variables started in 2014 (pre-treatment year) applying the same methodology and permanent
219 device-sets that were used in the post-harvest period (2015-2017).

220 *Data analysis*

221 For the univariate analyses, one randomly chosen 24 h microclimate dataset per month was
222 used (eight months in one growing season). For exploring the effects of treatment types, relative
223 values were calculated as differences from the control (separately in each block). Thereby, we
224 excluded the effects of the temporal differences of actual weather conditions and seasons, as well
225 as the spatial heterogeneity between the blocks. Daily mean, minimum, maximum and interquartile
226 range (IQR) of PAR, T_{air} , RH, VPD, T_{soil} , SWC variables were computed and analyzed. As SWC is
227 a rather stationary variable within a day, only its mean was involved in the analysis. For PAR,
228 measurements between 6.00 and 18.00 (local time) were analyzed, and the daily minimum and
229 maximum values were excluded from the modelling. To investigate the effect of the treatments and
230 years on the microclimate variables, linear mixed effects models (random intercept models) with a
231 Gaussian error structure were used (Faraway, 2006). Where necessary, the response variables were
232 transformed to achieve the normality of the model residuals. The treatment (four levels: CC, G, P,
233 R), year (three levels: 2015, 2016, 2017) and their interaction were used as fixed factors, while the
234 block was specified as a random factor. The models' goodness-of-fit values were measured by a
235 likelihood-ratio test-based coefficient of determination (R^2_{LR} ; Bartoń 2016), the explanatory power
236 of the fix factors were evaluated by analysis of deviance (F-statistics; Faraway 2006). The
237 differences between the treatment levels were evaluated using Tukey's multiple comparisons
238 procedure ($\alpha = 0.05$) for all of the pairwise comparisons based on the estimated marginal
239 means. The significance of the differences between the control and the other treatment levels was
240 tested by linear mixed effects models without intercept (Zuur 2009). The pre-treatment data
241 (collected in the growing season of 2014) were analyzed separately following the same
242 methodological framework (Appendix S1: Table S2.).

243 We applied multivariate ordination methods for exploring the relative importance of the
244 microclimate variables in the separation of the treatments. Absolute diurnal datasets (mean,
245 minima, maxima and IQR of the raw microclimate data) were used during these analyses
246 because control data were also involved in these comparisons. These analyses were carried out in
247 each studied year (2014–2017) separately. Only T_{air} , RH, VPD, T_{soil} and SWC variables were
248 used during the evaluations. PAR variables were excluded since their effect is hardly separated
249 from treatments (the applied treatments directly modified the canopy closure of the plots). The
250 separation of the plots by microclimate variables (using treatment as *a priori* grouping variable)
251 were explored by multivariate linear discriminant analysis (LDA; Podani 2000). We used
252 generalized microclimate data of the vegetation periods for the LDAs to exclude the effects of
253 seasonality, therefore standardized principal component analyses (PCA; Podani 2000) were
254 performed on the eight monthly measurements of each variable for all observed years separately;
255 and the first canonical axes were used to create input matrices (Appendix S1: Fig. S2.). The
256 explained variance of the first axes of these PCAs ranged between 38–88%. This approach
257 enabled to explain the highest proportion of the total variance of a given microclimate variable
258 throughout a growing season. During the four years of data collection the database contained
259 4.89% of missing values ranging 0%–20% between the months. For incomplete microclimate
260 datasets, the iterative PCA method (Ipca) suggested by Dray and Josse (2015) was performed.
261 Separation between the treatments was measured by permutational multivariate analysis of
262 variance (PERMANOVA based on Canberra metrics; Podani 2000, Anderson 2017) with 9999
263 permutations. The separability power of the microclimate variables among treatment levels were
264 tested by Wilks' lambda with F-test approximation performed in multivariate analysis of
265 variance (MANOVA) for each separate year (Borcard et al. 2018).

266 The data analyses were performed using R version 3.4.1 (R Core Team 2017). Add-on
267 package ‘nlme’ was applied for the linear mixed effects models (Pinheiro et al. 2017), ‘lsmeans’
268 for multiple comparisons (Lenth 2016), and ‘MuMIn’ package for pseudo- R^2 values (Bartón
269 2016). PCAs were obtained by ‘vegan’ (Oksanen et al. 2018), Ipca procedures by ‘missMDA’
270 (Josse and Husson 2016), and LDAs by ‘MASS’ (Venables et al. 2002) packages.

271

272 **Results**

273 **General treatment effects**

274 The pre-treatment conditions of the plots selected for the different treatment levels were
275 similar in 2014 – although there were some differences between the plots in the case of air
276 temperature (dT_{air}) and soil moisture ($dSWC$) due to the heterogeneity of the site conditions (Fig.
277 2–4., Appendix S1: Table S2).

278 In general, we detected strong treatment effects on each examined variables (Table 1). The
279 maxima and interquartile ranges (IQRs) of the microclimate variables departed from the control
280 values in every observed year, but in some cases means and minima could remain similar to the
281 conditions measurable in the closed stands (Fig. 2–4.). For each variable, the treatment effect
282 was much more pronounced than the time effect. The strongest treatment effect was observed for
283 light variables ($dPAR$), $dSWC$ and the interquartile range of dT_{air} , air humidity (dRH) and soil
284 temperature (dT_{soil}) (Table 1).

285 The most illuminated environment was created by clear-cutting (Fig. 2. a) with the highest
286 daily range and (Fig.2. b). Similarly, substantial increment but lower incoming radiation was
287 present in the gap-cuts (Fig.2. a). The light conditions were significantly lower and less

288 heterogeneous in the preparation cuts and the retention tree groups than in the prior two types,
289 but in both types, they were significantly higher than in the control.

290 The mean and the IQR of the dT_{air} was the highest in the clear-cuts (mean $\approx 0.3^{\circ}\text{C}$ and IQR
291 $> 1^{\circ}\text{C}$; Fig. 3. a and b), moreover, this was the only treatment where both minima and maxima
292 were significantly different from the other treatments (Fig. 3. c and d). The mean dT_{air} was
293 buffered the most in the preparation cuts and gap-cuts (Fig. 3. a). The variability of dT_{air} was
294 reduced most effectively in the gap-cuts and preparation cuts, however, the latter could buffer the
295 maxima more effectively (Fig. 3. b–d). The changes in mean dT_{air} in the retention tree groups
296 were similar to the clear-cut levels but IQRs and extrema were significantly reduced.

297 dRH means were the lowest in the retention tree groups and clear-cuts (Fig. 3. e). but in
298 clear-cuts it had higher variability and higher maximum values (Fig. 3. f–h). In the preparation
299 cuts and gap-cuts, the humidity remained similar to the control levels with the lowest variability
300 (Fig. 3. e, f). The mean of the vapor pressure deficit ($dVPD$) showed a similar pattern as dT_{air} but
301 its values did not depart significantly from the control levels in the gap- and partial cuts
302 (Appendix S1: Fig. S3.).

303 In general, dT_{soil} differed significantly in almost every treatment from the control, the only
304 exception was the mean in gap-cutting that could preserve the levels of uncut control (Fig. 4. a–
305 d). The highest dT_{soil} was measured in the clear-cuts and retention tree groups (approx. 1°C ; Fig.
306 4. a), however, the latter treatment type induced less variable temperature (Fig. 4. b). The coolest
307 soil environment with the lowest IQR was detected in the gap-cuts. dT_{soil} minima were
308 significantly lower in gap- and clear-cuts than in preparation cuts and retention tree groups (Fig.
309 4. c).

310 The highest soil moisture was detected in gap-cuts (Fig. 4. e). $dSWC$ was significantly
311 higher in the clear-cuts and even more in the gap-cuts than in the controls, while it remained
312 similar to the levels of the closed stands in preparation cuts and retention tree groups.

313

314 **Temporal changes**

315 In contrary to our expectations, in most cases there was no detectable unambiguous decrease
316 in the departures from the control levels between 2015 and 2017. The pattern of the microclimate
317 variables among the different treatment levels were relatively similar throughout the sampled
318 growing seasons, however, significant year effects were also discovered in many cases (Table 1,
319 Fig. 2–4.). The directions of these temporal changes were different and we often had unimodal
320 response: the differences from the uncut control increased from the first to the second post-
321 treatment year (from 2015 to 2016) and started to decrease between 2016 and 2017 returning to
322 the level of 2015 by 2017 (e.g., mean, IQRs and maxima of dT_{air} , or dRH variables in most of the
323 treatments Fig. 3.). However, the differences became more pronounced in the case of dT_{air}
324 minima (Fig. 3. a). We found that light variables decreased in preparation cuts and retention tree
325 groups during the three years, while they had a unimodal-like response in clear-cuts and gap-cuts
326 (Fig. 2.). Detectable moderating effect was present in the case of dT_{soil} mean, IQR and maxima,
327 mainly in case of clear-cuts and retention tree groups (Fig. 4. a, b, d), while minima had a
328 unimodal response (Fig. 4. c). Departures in $dSWC$ enhanced over time in gap-cuts and clear-
329 cuts (Fig. 4. e).

330 Furthermore, we also detected significant seasonal effect on the responses of microclimate
331 variables: in most cases the effect sizes were the highest in the peak of the growing season (in
332 summer), which is consistent in every observed year (Appendix S1: Fig. S4.).

333 **Separation among treatments**

334 As it was hypothesized, plots did not show clear pattern before the treatments ($F = 0.464$, P
335 $= 0.2145$ according to the performed PERMANOVAs), the first canonical axis explained 52.5%
336 of the total between group variance, the second axis 22.1% (Fig. 5. a). The strongest separation
337 could be detected in 2016 ($F = 4.342$, $P < 0.0001$), with 79.4% and 10.9% of explained variance
338 by LD1 and LD2, respectively (Fig. 5. c). Separability power of the LDAs were high in 2015
339 (Fig. 5. b) and 2017 (Fig. 5.d) as well ($F = 2.311$, $P < 0.0001$ and $F = 3.479$, $P < 0.0001$,
340 respectively). However, while separation of control and clear-cutting was more pronounced and
341 the other three groups overlapped in 2016 (Fig. 5. c), all treatment types showed higher
342 separation in 2015 and 2017 (Fig. 5. b and d, respectively), although the relative partition
343 between control and clear-cutting was weaker.

344

345 **The main drivers of the separation**

346 We demonstrated that if light variables are excluded, in the first three growing seasons,
347 treatment effect was mostly based on the microclimate variables that are closely related to the
348 incoming energy (T_{air} , VPD, T_{soil}) and principally their maxima and IQRs (Table 2). During the
349 observed three years, only a slight realignment was observed. In the first year after the cuttings
350 (2015), the IQR and maximum of T_{soil} was the most important variable, while in the next two
351 growing seasons, the highest F-values were related to the maximum and IQR of T_{air} . SWC can be
352 described as an important variable for separation only in the third growing season (2017).

353

354

355 **Discussion**

356 **General treatment effects**

357 As it was presumed, we could demonstrate strong and consistent treatment effects in the
358 case of the measured microclimate variables in the first three years after the silvicultural
359 interventions. Because all tree individuals were removed during clear-cutting, the most drastic
360 increase of incoming light, and consequently, the mean air and soil temperature, vapor pressure
361 deficit, and especially their variability were the highest in clear-cuts. Similarly, the extrema of
362 the variables were the most pronounced following clear-cutting. Soil water content increased
363 significantly compared to the control levels. A limited, but considerable moderating effect was
364 detected in the retention tree groups: although the means of dT_{air} , dRH , $dVPD$ and dT_{soil} were
365 similar to that in the clear-cuts, IQRs were ameliorated by these small patches of standing trees.
366 Gap-cutting could provide on the one hand an increased level of $dPAR$ and $dSWC$, but on the
367 other hand artificial gaps of the size of the average tree height could maintain a buffered, cool
368 and humid environment. As with gap-cutting, preparation cutting could notably preserve the
369 closed forest conditions, without the increase of $dSWC$ levels.

370 Light variables differed the most from the control levels because the applied treatments
371 modified the canopy closure and the spatial arrangement of the remained tree individuals first
372 and foremost (Chen et al. 1999, Heithecker and Halpern 2006, Grayson et al. 2012, Tinya et al.
373 2019). Incoming radiation was the highest and the most variable in the clear-cuts where all tree
374 individuals were harvested. Gap-cutting also created a brighter environment but PAR was
375 significantly lower than it was detected in the clear-cuts because of the smaller sky view factor
376 (Carlson and Groot 1997, Ritter et al. 2005, Kelemen et al. 2012). Insolation was lower and
377 similar to each other in the preparation cuttings and retention tree groups, although both were

378 significantly more illuminated than the uncut control plots in the surveyed years. Our results
379 from the preparation cuts are similar to moderate thinning and partial harvesting due to the
380 comparable harvesting processes (Weng et al. 2007, Grayson et al. 2012).

381 Air variables are primarily coupled to the incoming solar radiation. As clear-cutting created
382 the most open environment within this experimental framework, air temperature and vapor
383 pressure deficit were the highest, while air humidity was the lowest in this treatment. Many
384 studies reported substantial departures in these variables (e.g., Liechty et al. 1992, Keenan and
385 Kimmins 1993, Chen et al. 1999, Davies-Colley et al. 2000), our observations are the most
386 similar to the findings of Carlson and Groot (1997) and von Arx et al. (2012) who reported $<1^{\circ}\text{C}$
387 increase of T_{air} and $<5\%$ decrease of RH averaged to the whole growing season. However, the
388 measured departures can be significantly higher in the fully-leaved period (Kovács et al. 2018).
389 Effect sizes induced by the applied silvicultural treatments presumably depend on the
390 macroclimate (especially, temperature and precipitation), topography, site conditions (e.g. soil
391 moisture) and stand type (tree species composition and structural heterogeneity mainly)
392 (Aussenac 2000; von Arx et al. 2013; Ashcroft and Gollan, 2013; De Frenne et al. 2019).
393 Nevertheless, in the case of air temperature, we found similar order of magnitude of temperature
394 offset in various European forest stands reported by Zellweger et al. (2019).

395 We demonstrated that retention tree groups in the size of one tree height can mediate the
396 thermal extremes and drying capacity of the ambient air but not their mean values which are a
397 definite aim in creating aggregated retention trees (Vanha-Majamaa and Jalonen 2001).
398 However, we found that minimum T_{air} remains similar in retention tree groups, gap-cuts and
399 preparation cuts.

400 In contrary to the clear-cutting, gap-cutting induced only moderated increase in T_{air} despite
401 the high amount of incoming light. Abd Latid and Blackburn (2010) demonstrated that since the
402 diffuse fraction is more pronounced in gaps, the heating is less intensive. Furthermore, RH and
403 VPD levels are similar to the humidity of ambient air in closed stands which can be addressed to
404 the evaporative cooling, the shading of the surrounding tree individuals as well as the lowered
405 lateral air mixing (Ritter et al. 2005, Muscolo et al. 2014)

406 Regarding soil temperature variables, the increased solar irradiance had an even more
407 explicit effect than it was present for air temperature values which concurs previous studies
408 (Carlson and Groot 1997, Rambo and North 2009, von Arx et al. 2013). Thus, for example
409 retention tree group could moderate the extrema of T_{soil} better than T_{air} due to the shading
410 provided by remained overstory (Heithecker and Halpern 2006). The lowest and most stable T_{soil}
411 was present in the gap-cuts due to the shading effect of the neighboring trees and the evaporative
412 cooling of the moisture content of the topsoil (Gray et al. 2002, von Arx et al. 2013). Moreover,
413 opposing previous studies (e.g., Ritter et al. 2005, Abd Latif and Blackburn 2010), soil
414 temperature remained similar to the values of the uncut control.

415 In contrary to our expectations, the most significant increase in soil moisture was observable
416 in gap-cuttings, while clear-cuttings caused significant but smaller increment in SWC. Changes
417 in soil moisture following the different treatments are typically based on the changes in elements
418 of the hydrological routine: the lower is the rate of interception and canopy evaporation, the
419 more increased the throughfall is and the more decreased the transpiration is (Wood et al. 2007,
420 Muscolo et al. 2014, Good et al. 2015). Because of the great relative importance of transpiration,
421 a higher increase in soil moisture was presumed after clear-cutting than gap-cutting (Good et al.
422 2015). The experienced smaller increase of SWC in the clear-cuts can be explained by the high

423 evaporation rates, the drying effects of the air-mixing due to the higher wind exposure (Keenan
424 and Kimmins 1993, Geiger et al. 1995, Bonan 2016). The effects of these processes were
425 presumably enhanced by the increasing transpiration rates of the rapidly developing herb layer
426 dominated by annual weeds (e.g., *Conyza canadensis* (L.) Cronquist and *Erigeron annuus* (L.)
427 Pers) and later, tall perennials (e.g., *Calamagrostis epigeios* (L.) Roth and *Solidago gigantea*
428 Aiton) (Tinya et al. 2019). We also found that in the retention tree groups, despite the
429 significantly higher VPD, the enhanced heat load and the transpiration of remnant tree
430 individuals, soil water content was only slightly lower than in the uncut plots.

431

432 **Temporal changes following forestry treatments**

433 According to our expectations, microclimate variables changed immediately after the
434 interventions and differed from the homogeneous conditions created by the closed canopy. In our
435 previous work describing the microclimate of the treatments one year after the interventions, we
436 revealed the seasonal pattern of microclimatic variables (Kovács et al. 2018). The highest
437 treatment effect was detected in the peak of the growing season due to the buffering effect of the
438 closed canopy, which was in agreement with other studies (e.g., Clinton 2003, Ma et al. 2010,
439 von Arx et al. 2012). In this study, we focused on the effects of the years only, however, the
440 seasonality effect is unambiguous not just in the first growing season but also in the second and
441 third years (Appendix S1: Fig. S4.).

442 The effects of forest management on microclimate variables could have various temporal
443 dynamics. The long-term treatment effects on forest microclimate were demonstrated for clear-
444 cuts in different forest types typically based on chronosequence studies. For example, in northern
445 hardwood forests, Dovčiak and Brown (2014) stressed that all microclimate variables differed

446 from forest interior in five years old regeneration stands, while daily temperature minimum
447 remained disparate for 15 years. Baker et al. (2014) demonstrated differences in the means and
448 variability of air temperature, relative humidity and VPD between various aged regenerating
449 clear-felled areas (7, 27 and 47 years since clear-cutting) and mature stands in Tasmania. In
450 general, they found that differences from mature stands in daily means can last up to 27 years
451 while diurnal variances recover in 7 years. On the contrary, the microclimatic changes in both
452 natural and artificial gaps are rather short-term comparing the effects of rotation forestry. The
453 recovery of light climate has typically exponential relationship with time since gap-creation
454 (Domke et al. 2007). Previous studies reported that approximately in the first three years, there is
455 no significant changes in the center of the gaps but there is an observable lateral growth that
456 decreases insolation near the edges (Ritter et al. 2005, Kelemen et al. 2012). It was found that in
457 gaps created by group selection, light regime became similar to the uncut mature stand in 13
458 years (Beaudet et al. 2004). Lewandowski and colleagues (2015) found differences in soil
459 temperature between gaps and uncut control that lasted seven years. However, single-tree and
460 group selections in mixed oak-pine forests did not show a temporal trend in the recovery of air
461 and soil temperature and relative humidity based on the analyzed 1–13 yrs chronosequence
462 (Brooks and Kyker-Snowman 2008).

463 Based on our models, we can conclude that the effects of treatment on microclimate variables
464 were stronger than the effect of time, differences from control among the treatment levels were
465 consistent throughout the first three years. Our results did not show a continuously fading trend of
466 the vast majority of the microclimate variables, not even in gap-cuts or preparation cuts suggested
467 by previous studies (e.g., Gray et al. 2002 or Ritter et al. 2005). The time-span of the
468 microclimatic regeneration strongly depends on species composition, forest structure and site

469 conditions (Aschroft and Gollan, 2013; Renaud et al. 2011; Petritan et al. 2013; Lu et al. 2015).
470 A substantial aspect of the temporal changes is the species-specific response of trees since
471 differences in leaf morphology and leaf area, canopy structure and crown plasticity can lead to
472 diverging light transmittance and lateral branch infilling of canopy gaps (Runkle 1998;
473 McCarthy 2001; Pretzsch 2014). This is relevant if we compare the more frequently studied
474 European beech and the usually understudied sessile oak, the dominant tree species of this
475 experiment. Sessile oak individuals often have smaller canopies, lower crown plasticity and
476 usually respond slower to the available space due to gap-openings compared to European beech
477 (Petritan et al. 2013). These attributes might lead to a slower falloff in altered site conditions than
478 it can be observed in for example beech-dominated stands. Certainly, the observed three growing
479 seasons are just a fraction of the required time-span typically reported (e.g., Liechty et al. 1992,
480 Dovčiak and Brown 2014, Baker et al. 2014). Similarly to the results of Liechty and colleagues
481 (1992), we did not have an unambiguous trend in the values of most variables but have between-
482 years distinctions instead during the first few years of the study. We found enhanced differences
483 from control in several cases comparing the first post-treatment year and the subsequent growing
484 seasons, but there are some variables for which the recovery process was detectable. Zheng et al.
485 (2000) also stated that the alterations following the harvests are variable-dependent but in this
486 experiment, we could demonstrate the treatment-specificity as well.

487 Gradual changes were detected in some state variables of the air near the ground – the
488 minimum air temperature decreased even more in the clear-cuts, retention tree groups and
489 preparation cuts, while minimum VPD departed more pronouncedly with time in the gap-
490 cuttings. However, the other variables did not show clear temporal pattern within this three
491 growing seasons.

492 However, continuous decrease was found in the case of light variability of retention tree
493 groups and partial cuts where three years may be sufficient for significant regeneration of the
494 branch structure of the remained overstory trees. Additionally, in the first post-harvest year,
495 retention tree groups were more exposed to the lateral sunlight penetration which was somewhat
496 moderated throughout the following years by the emergence of the epicormic shoots. However,
497 similarly to the mean of the incoming radiation, $dPAR_{IQR}$ values are still significantly higher
498 than in the uncut control. The most noticeable hypothesized decrease in the differences over time
499 were present in the case of soil temperature. In the clear-cuts, both the mean, IQR and maximum
500 of the soil temperature seem to start converging continuously to the levels of control. Moreover,
501 this trend was also detected for $dT_{soil_{IQR}}$ in the retention tree groups and for maxima in the gap-
502 and preparation cuts. The recovery is presumably based on the natural regeneration of the herb
503 and shrub layer that were considerably different among the treatments (Tinya et al. 2019). Before
504 the treatments, understory vegetation was scarce and quasi-homogeneous. In the first year, the
505 cover and mean height were similar in the treatments and evolved distinctly after the cuttings.
506 The highest vegetation with the greatest total cover was present in the most illuminated
507 treatments, i.e. the clear-cuts and gaps. Understory vegetation absorbs a considerable amount of
508 incoming radiation, thus, lowers the surface temperature during daytime and it blocks the long-
509 wave radiative loss in the night ameliorating the cooling (Ritter et al. 2005, Brooks and Kyker-
510 Snowman 2008). This insulating effect was stressed primarily for bryophytes in boreal forests
511 (Bonan 1991, Nilsson and Wardle 2005), but it was also proved for understory herbs like
512 *Calamagrostis canadensis* (Michx.) Beauv. (Matsushima and Chang 2007). Interestingly, we
513 could capture the insulating effects of tree canopies in the case of minimum soil temperature. We
514 presume that the cooling of the topsoil due to the radiative loss might be less pronounced under

515 the remained individuals in the overstory layer of the retention tree groups and preparation cuts
516 than in the gap-cuts or in the clear-cuts where the sky view factor is higher (Carlson and Groot
517 1997, Blennow 1998).

518 Based on previous studies, the recovery of soil moisture was typically reported as a more
519 rapid process: it was less than five years in clear-cuts (Adams et al. 1991), in thinned stands
520 (Aussenac and Granier 1988) as well as in gaps (Gray et al. 2002, Ritter et al. 2005,
521 Lewandowski et al. 2015). Immediately after the felling, a transitory increase of soil water
522 content is present but as the vegetation is emerging and regenerating, water balance returns to the
523 pre-treatment level due to the enhanced transpiration by natural regeneration. This process is
524 necessarily faster in stands where partial cutting or gap-cutting was applied because of the
525 improved lateral growth of bordering branches, enhanced crown expansion and increased root
526 extraction from the adjacent closed stands towards the small openings. Additionally, recovery of
527 soil microclimate in gaps can be faster in broadleaved stands than in forests dominated by
528 coniferous species (Lindo and Visser 2003). However, we found an opposing response: the clear-
529 and gap-cutting were followed by a steady increase in the departures from the uncut control level
530 despite the regenerating herb layer. Liechty et al. (1992) reported similar processes when they
531 examined the recovery of soil moisture content in five-year-old clear-cuts created in temperate
532 hardwood forests.

533 As Davis et al. (2018) and Liechty et al. (1992) underlined, most studies focusing on the
534 temporal changes of the microclimate variables in woodlands or the buffering capacity of forest
535 canopies are often based on datasets from short term (typically 1–3 yrs) investigations.
536 Considering that the processes may be under the way, we continue the systematic measurements

537 (applying the same protocol) in the framework of this long-term experiment to follow up the
538 microclimatic recovery.

539

540 **Separation of silvicultural treatments based on microclimatic variables**

541 Beside analyzing the treatment effects on microclimate variables, we aimed to identify those
542 variables which are accountable for the possible changes in the local environment after the
543 interventions. We presumed that by unfolding the effects of treatments, we could get a more
544 complete picture about the microclimatic processes in treated forest sites, thus, better
545 conservational implications could be emerged (De Frenne et al. 2013).

546 As in the case of the temporal analyses, after a more or less homogeneous pre-treatment
547 state, the greatest separation was expected in the first post-treatment year (2015), because the
548 highest treatment effect could be presumed right after the interventions when modified canopy
549 closure is the most explicit and the effects of the regeneration of the understory as well as lateral
550 growth of the canopy are negligible, which could influence both thermal (shading and insulating)
551 and humidity conditions (via transpiration). This initial phase should be followed by a
552 homogenization as the sites recover, the natural regeneration develop and the canopy closure
553 evolve. However, the greatest separation was observed in the second year after the harvests. We
554 detected two different phenomena according to the observational years: (i) the greatest overall
555 separation in 2016 was congruent with the greatest divergence between the uncut control and
556 clear-cutting, while the other treatments pooled and overlapped; (ii) in the adjoining two years,
557 the between-group separation was more pronounced and even. These could be addressed to the
558 masking effect of the extremely modified environment followed by the clear-cutting.

559 We found that the applied treatments separated among the temperature (T_{air} and T_{soil}) and
560 VPD maxima and their interquartile ranges and the roles of the individual variables in the

561 treatment effect were more or less consistent throughout the years. As it was presumed, soil
562 temperature was the most important determinant in the first year after the interventions, but in
563 the following years, the relative importance of air temperature increased. Surprisingly, soil
564 moisture became a significant determinant only in the third year in spite of the rather strong
565 treatment effect – especially in the gap-cuts and clear-cuts.

566 With the performed multivariate analyses, we can also demonstrate the reduced buffering
567 ability of the forest canopy and stand structure as a frequently stressed consequence of forest
568 management (Chen et al. 1999, Heithecker and Halpern 2006, Ewers and Banks-Leite 2013, De
569 Frenne et al. 2013, Hardwick et al. 2015). The microclimatic buffering capacity of the canopy
570 and even pronouncedly, variables related to forest structure are typically more noticeable
571 regarding the thermal maxima and the minima than the means (Liechty et al. 1992,
572 Vanwalleghem and Meentemeyer 2009, Ewers and Banks-Leite 2013, Frey et al. 2016, De
573 Frenne et al. 2019). In closed stands with different structural complexity, Frey et al. (2016) found
574 that maximum temperatures in old-growth stands could be more ameliorated than minimum
575 values (-2,5 °C and +0,7 °C, respectively). Greiser et al. (2018) observed comparable differences
576 in the effect size of the summer temperature extremes in central Sweden: the detected maximum
577 temperatures decreased by 12 °C, while minima increased by 4 °C. In congruence with these,
578 paired (forest–non-forest) studies reported similar trends: larger differences in temperature
579 maxima than in minima as well as in VPD_{max} than in VPD_{min} extremes (e.g., Chen and Franklin
580 1997, Vanwalleghem and Meentemeyer 2009, Renaud et al. 2011, von Arx et al. 2013, Davis et
581 al. 2018). Based on our results and in line with the literature compiled, it can be stated that forest
582 canopy performs its buffering capacity more on the maxima than on the minima of microclimatic
583 variables. We can suppose that through the reflectance and absorption of shortwave radiation

584 within the active layer of the canopy and through the shading of the understory is more effective
585 than the capturing and reflectance of longwave radiation from the soil.

586 The results of the multivariate analyses underpin that, as it has been argued in the recent
587 years, not the means of the microclimatic conditions, but rather the extrema are the most
588 influential factors shaping biological processes and ecological interactions (Suggitt et al. 2011,
589 Thompson et al. 2013, Bramer et al. 2018). Moreover, according to our results, it seems that the
590 applied forestry treatments can differently enhance the changes in the set of variables modifying
591 local climates.

592

593 **Conclusions and perspectives**

594 Based on the measurements performed in the first three years after the forestry treatments,
595 we can conclude that (i) the effect sizes among treatment levels were consistent throughout the
596 first three years; (ii) the climatic recovery time for variables appears to be far more than three
597 years – except for soil temperature – in all treatments and (iii) the applied silvicultural methods
598 diverged mainly among the temperature maxima. The most drastic changes were observed in
599 clear-cuts where retention tree groups could impinge only a limited buffering effect (on the
600 variability and extrema, though not on the mean). However, a relatively large gap size (one tree
601 height/gap diameter ratio) could provide a reasonably stable and humid but more illuminated
602 environment. Preparation cutting changed the forest environment only to a lesser degree.

603 Our results suggest that in mesic broadleaved forests, forestry treatments induce long-lasting
604 changes in microclimate near the ground that substantially alters the environmental conditions.
605 These changes may cause the promptly occurring alterations in communities of the forest-
606 dwelling species – which were shown for different taxa in the framework of this experiment –
607 especially in the case of organisms groups with limited movement ability (Elek et al. 2018, Tinya

608 et al. 2019, Boros et al. 2019). Due to the high probability of extreme thermal events, clear-
609 cutting enhances the frost damage, the heat stress as well as higher exposure of draught causing
610 local extinctions and significant compositional shifts. Moreover, from a broader prospect,
611 management types causing considerable canopy-openness on large areas, independently of the
612 characteristics (i.e. aggregated or dispersed), may precipitate the effects of climate change in
613 forested landscapes.

614 We can conclude that in managed temperate broadleaved forests (like in this study, in oak–
615 hornbeam stands), for biodiversity conservation purposes, small-scale or spatially dispersed
616 forestry treatments are desired. By applying actions belonging to continuous cover forestry (e.g.,
617 gap-cutting, irregular shelterwood system), the original characteristics of the forest environment
618 can be preserved.

619

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636

637 **Author’s contributions**

638 The experiment was planned by P. Ó.; P.Ó. and B. K. conceived the ideas and designed the
639 methodology for the study; fieldwork was organized and performed by B. K., Cs. N. and F.T.;
640 statistical analyses were performed by B. K.; and the manuscript was written by B. K. and P. Ó.
641 with the approval of F.T. and Cs. N.

642

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927

928 **Table 1.** The results of the linear mixed effects models. Dependent variables are coded as PAR –
 929 photosynthetically active radiation; T_{air} – air temperature; RH – relative humidity; VPD – vapor pressure
 930 deficit; T_{soil} – soil temperature and SWC – soil moisture. d refers to the difference from the values
 931 measured in the control plots (relative data).

932

Dependent variable	Model			Treatment		Year		Treatment:Year	
	Chi ²	<i>P</i>	R ² _{LR}	F	<i>P</i>	F	<i>P</i>	F	<i>P</i>
$dPAR$ mean	363.0907	< 0.0001	0.489	164.241	< 0.0001	2.442	0.0880	1.683	0.1230
$dPAR$ IQR	437.1786	< 0.0001	0.554	208.105	< 0.0001	6.574	0.0015	3.803	0.0010
dT_{air} mean	67.2150	< 0.0001	0.136	19.724	< 0.0001	3.526	0.0301	0.633	0.7040
dT_{air} IQR	207.3817	< 0.0001	0.317	68.953	< 0.0001	17.311	< 0.0001	0.900	0.4943
dT_{air} min	126.2807	< 0.0001	0.258	33.864	< 0.0001	17.595	< 0.0001	0.388	0.8868
dT_{air} max	158.4704	< 0.0001	0.253	52.240	< 0.0001	6.736	0.0013	1.621	0.1390
dRH mean	85.8444	< 0.0001	0.385	23.037	< 0.0001	6.058	0.0025	1.681	0.1237
dRH IQR	173.6899	< 0.0001	0.289	46.628	< 0.0001	26.824	< 0.0001	1.441	0.1969
dRH min	137.6227	< 0.0001	0.348	41.181	< 0.0001	11.305	< 0.0001	1.362	0.2281
dRH max	35.9720	0.0002	0.261	8.452	< 0.0001	1.518	0.2203	1.334	0.2402
$dVPD$ mean	85.1361	< 0.0001	0.267	27.849	< 0.0001	0.930	0.3951	0.854	0.5287
$dVPD$ IQR	86.9652	< 0.0001	0.158	24.073	< 0.0001	8.205	0.0030	0.664	0.6788
$dVPD$ min	23.2642	0.0162	0.192	4.333	0.0050	2.380	0.0936	0.914	0.4845
$dVPD$ max	73.1878	< 0.0001	0.154	23.002	< 0.0001	1.547	0.2140	0.795	0.5743
dT_{soil} mean	43.7028	< 0.0001	0.088	10.982	< 0.0001	4.403	0.0127	0.464	0.8352
dT_{soil} IQR	129.7824	< 0.0001	0.213	42.387	< 0.0001	5.728	0.0035	0.792	0.5767
dT_{soil} min	104.6072	< 0.0001	0.205	29.188	< 0.0001	11.386	< 0.0001	0.431	0.8580
dT_{soil} max	91.4572	< 0.0001	0.155	24.400	< 0.0001	11.102	< 0.0001	0.377	0.8975
$dSWC$ mean	265.2427	< 0.0001	0.485	103.042	< 0.0001	6.537	0.0016	2.337	0.0309

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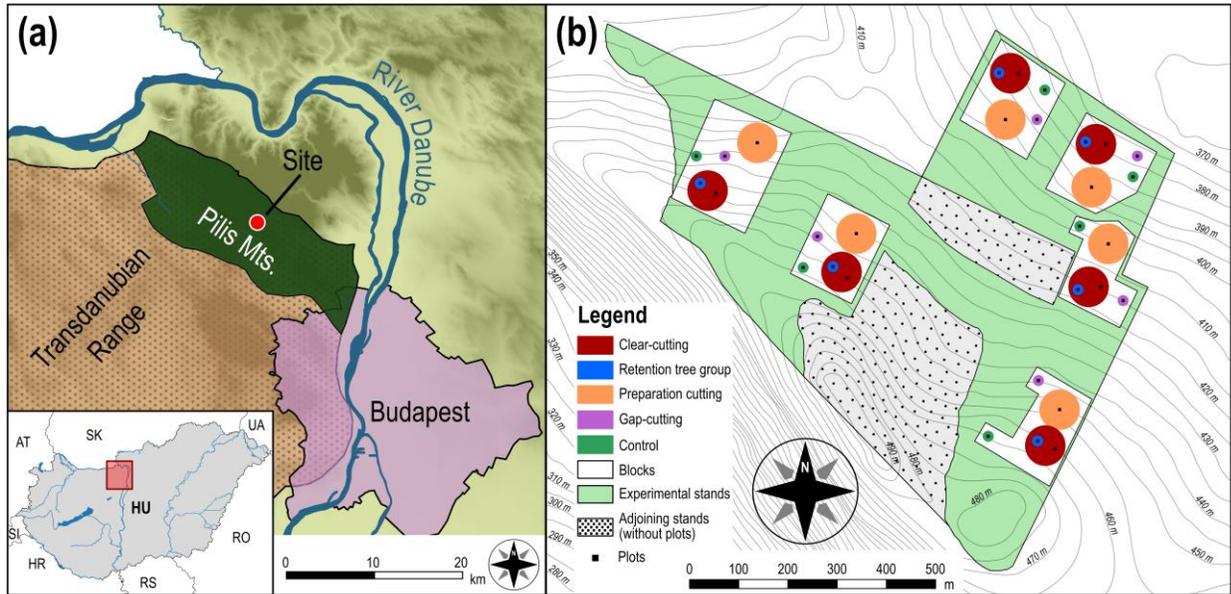
934

935 **Table 2.** The results of linear discriminant analysis of variance performed for the individual growing
936 seasons separately. Variables are coded as T_{air} – air temperature; RH – relative humidity; VPD – vapor
937 pressure deficit; T_{soil} – soil temperature and SWC – soil moisture. The most important six variables based
938 on the F-values of the Wilks test in a given year are typed in bold.
939

Variable	2014		2015		2016		2017	
	F	P	F	P	F	P	F	P
T_{air} mean	0.090	0.9846	0.214	0.9281	9.015	0.0001	1.381	0.2690
T_{air} min	0.090	0.9846	0.086	0.9858	1.972	0.1298	5.909	0.0017
T_{air} max	0.142	0.9650	21.013	< 0.0001	36.154	< 0.0001	44.372	< 0.0001
T_{air} IQR	0.036	0.9974	19.984	< 0.0001	47.787	< 0.0001	18.714	< 0.0001
RH mean	0.069	0.9907	0.572	0.6852	2.26	0.0911	2.914	0.0416
RH min	0.205	0.9332	3.647	0.0179	6.348	0.0011	6.059	0.0015
RH max	0.069	0.9907	0.185	0.9439	0.558	0.6951	0.886	0.4868
RH IQR	0.073	0.9896	0.208	0.9314	10.650	< 0.0001	3.092	0.0338
VPD mean	0.089	0.9851	1.321	0.2896	4.648	0.0061	6.066	0.0015
VPD min	0.021	0.9991	0.098	0.9821	0.839	0.5138	1.009	0.4214
VPD max	0.081	0.9876	8.826	0.0001	13.071	< 0.0001	14.404	< 0.0001
VPD IQR	0.069	0.9907	3.722	0.0165	15.092	< 0.0001	6.123	0.0014
T_{soil} mean	1.209	0.3317	14.200	< 0.0001	10.314	< 0.0001	4.468	0.0073
T_{soil} min	0.876	0.4923	4.721	0.0056	6.999	0.0006	8.241	0.0002
T_{soil} max	1.746	0.1716	26.847	< 0.0001	19.651	< 0.0001	10.204	< 0.0001
T_{soil} IQR	2.159	0.1031	34.026	< 0.0001	33.024	< 0.0001	17.28	< 0.0001
SWC mean	1.079	0.3877	6.591	0.0009	6.748	0.0008	9.974	< 0.0001

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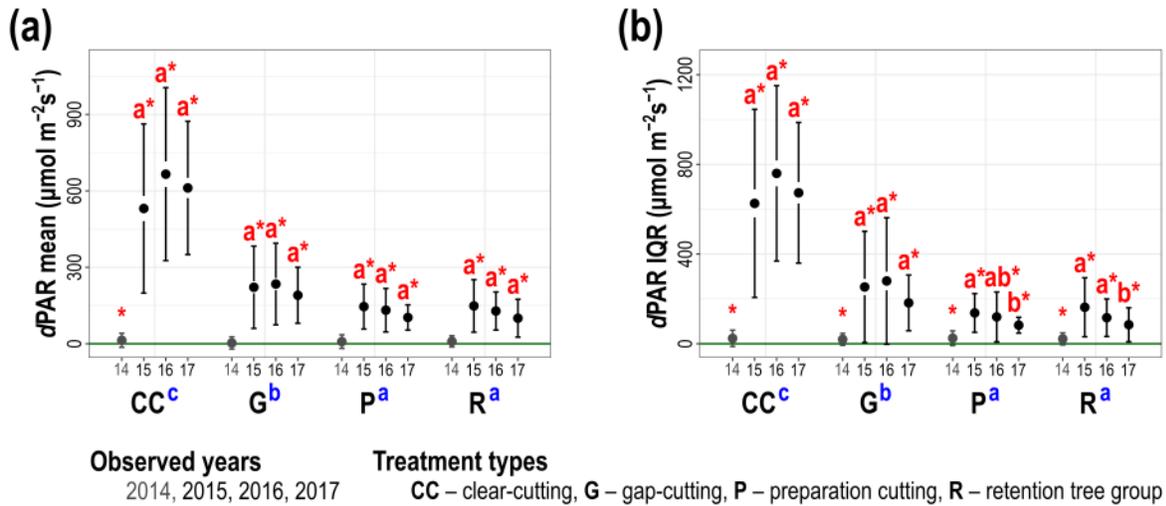
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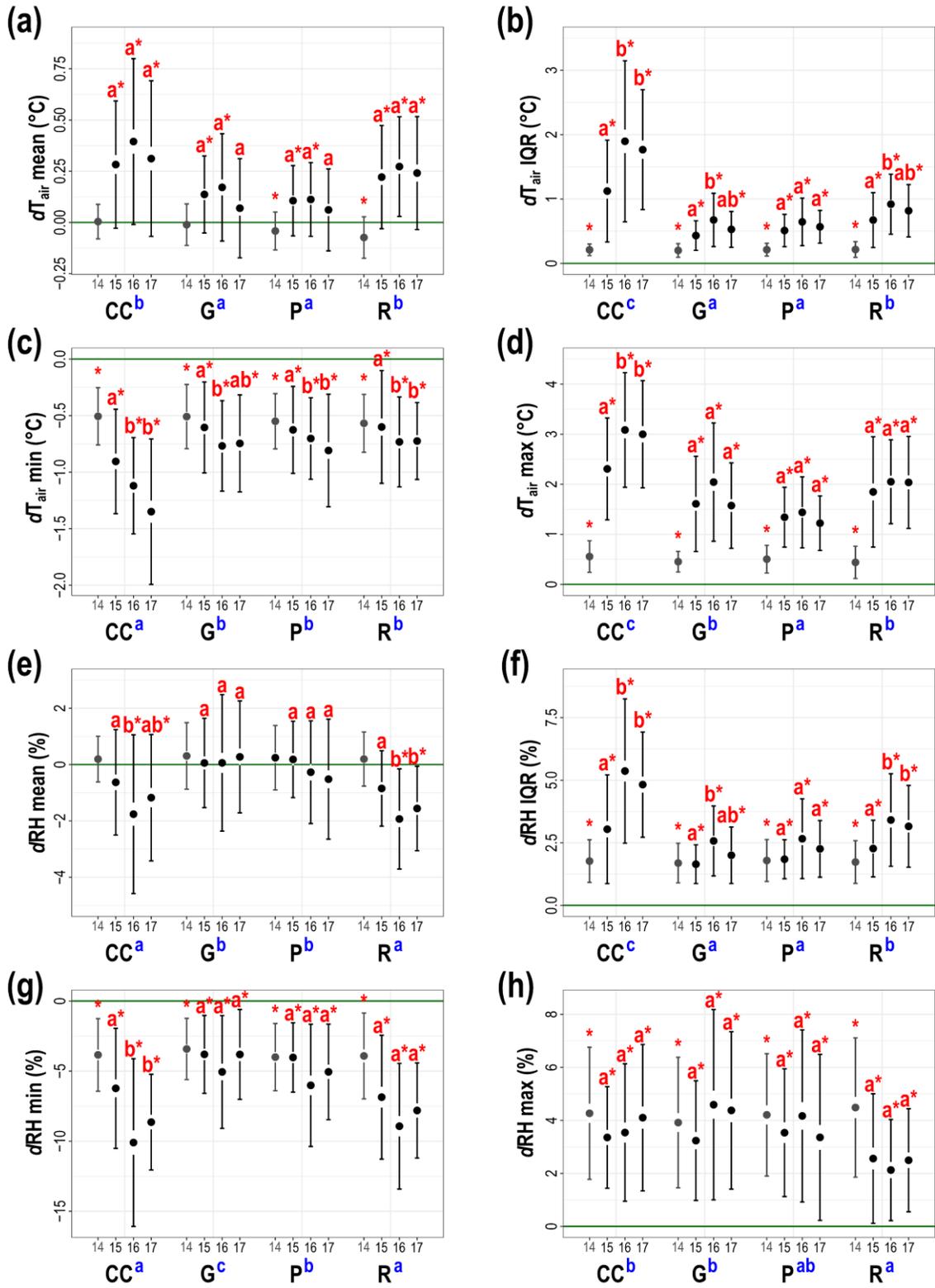
944 **Figure 1.** The study site of the “Pilis Forestry Systems Experiment” in Northern Hungary. (a) Site location (47°40’
945 N, 18°54’ E) in the Pilis Mountains (Transdanubian Range). (b) Experimental design showing the five treatments
946 replicated within six blocks. Microclimate measurements were performed in the center of the plots.

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950 **Figure 2.** Means (a) and interquartile ranges (IQR, b) of the relative light (differences from the control; $dPAR$)
 951 among the applied silvicultural treatments throughout the observation years (2014–2017). The treatment types were
 952 CC – clear-cutting, G – gap-cutting, P – preparation cutting and R – retention tree group. Full circles show the mean,
 953 vertical lines denote the standard deviation and white bands in between indicate standard error of the samples.
 954 Letters demonstrate the results of the pairwise multiple comparison (Tukey test, $\alpha = 0.05$) based on the
 955 performed linear mixed effects models between treatments (related to the whole 2015–2017 period, blue letters) and
 956 between years (2015–2017) within treatment levels (red letters). Asterisks mark significant differences from the
 957 values measured at the control plots (linear mixed effects models without intercept, $P < 0.05$). The horizontal green
 958 lines demonstrate the 0-level of the control.
 959



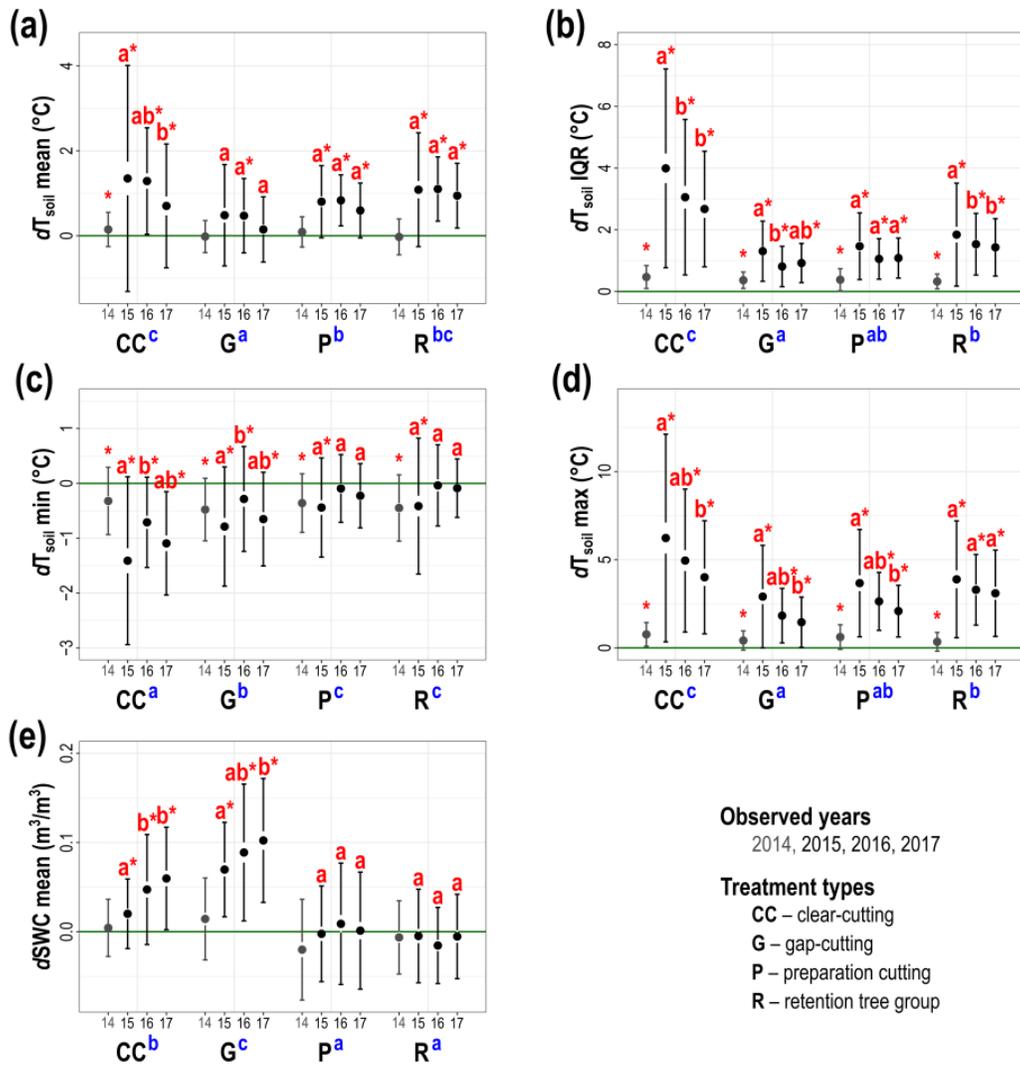
Observed years

2014, 2015, 2016, 2017

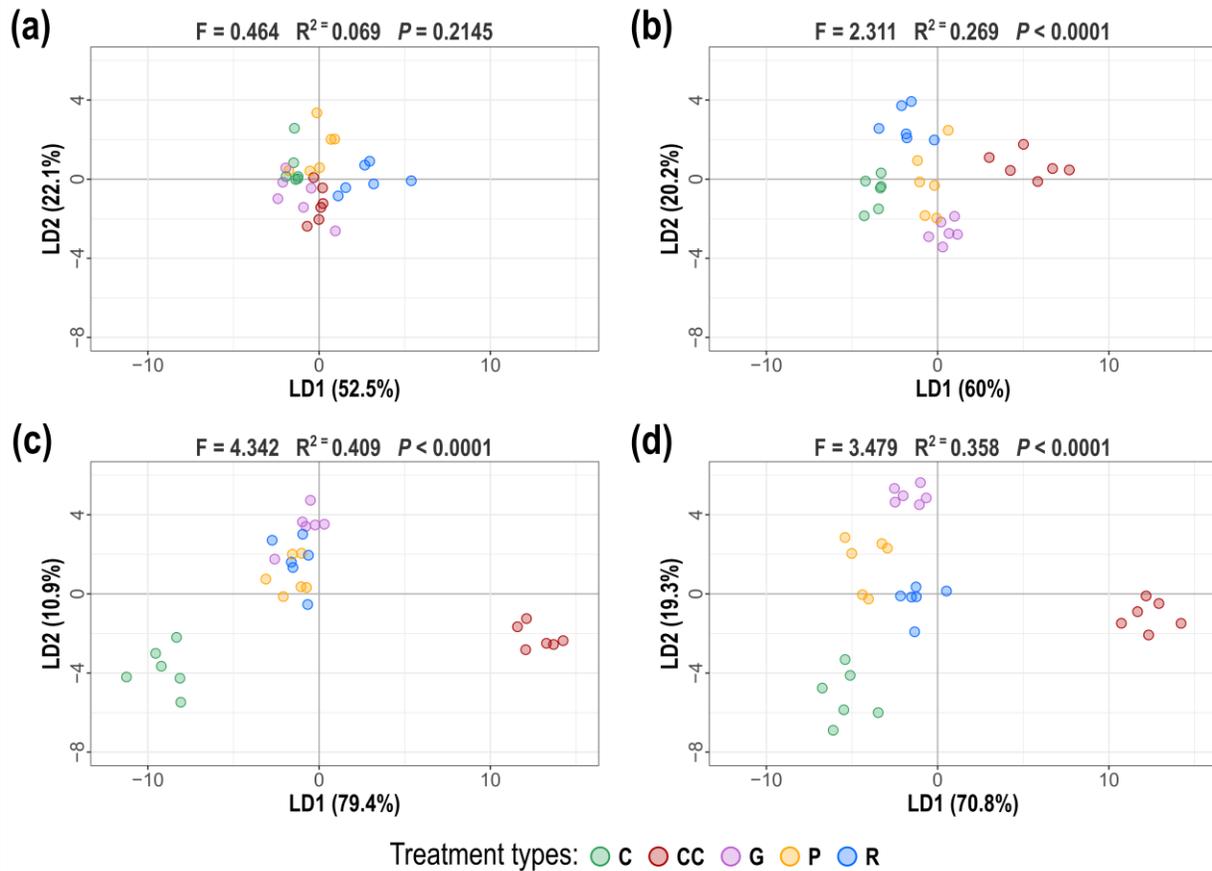
Treatment types

CC – clear-cutting, G – gap-cutting, P – preparation cutting, R – retention tree group

961 **Figure 3.** Means, interquartile ranges (IQR), minima and maxima of the relative values (differences from the control)
962 of (a–d) air temperature (dT_{air}) and (e–h) relative humidity (dRH) among the applied silvicultural treatments throughout
963 the observation years (2014–2017). The treatment types were CC – clear-cutting, G – gap-cutting, P – preparation
964 cutting and R – retention tree group. Full circles show the mean, vertical lines denote the standard deviation and white
965 bands in between indicate standard error of the samples. Letters demonstrate the results of the pairwise multiple
966 comparison (Tukey test, $\alpha = 0.05$) based on the performed linear mixed effects models between treatments (related
967 to the whole 2015–2017 period, blue letters) and between years (2015–2017) within treatment levels (red letters).
968 Asterisks mark significant differences from the values measured at the control plots (linear mixed effects models
969 without intercept, $P < 0.05$). The horizontal green lines demonstrate the 0-level of the control.



970
 971
 972 **Figure 4.** Means (a), interquartile ranges (IQR, b), minima (c) and maxima (d) of the relative values (differences
 973 from the control) of soil temperature (dT_{soil}) and (e) means of soil moisture ($dSWC$) among the applied silvicultural
 974 treatments throughout the observation years (2014–2017). The treatment types were CC – clear-cutting, G – gap-
 975 cutting, P – preparation cutting and R – retention tree group. Full circles show the mean, vertical lines denote the
 976 standard deviation and white bands in between indicate standard error of the samples. Letters demonstrate the results
 977 of the pairwise multiple comparison (Tukey test, $\alpha = 0.05$) based on the performed linear mixed effects models
 978 between treatments (related to the whole 2015–2017 period, blue letters) and between years (2015–2017) within
 979 treatment levels (red letters). Asterisks mark significant differences from the values measured at the control plots
 980 (linear mixed effects models without intercept, $P < 0.05$). The horizontal green lines demonstrate the 0-level of the
 981 control.



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985 **Figure 5.** Ordination plots of the four treatment types and the control according to the linear discriminant analyses

986 (LDA). LDAs were performed for the individual years separately: (a) 2014; (b) 2015; (c) 2016 and (d) 2017.

987 Explained variance of the canonical axes (LD1 and LD2) are shown. Beside the results of the LDAs, the F-, pseudo-

988 R²- and p-values of the PERMANOVAs are also indicated for the observed years separately. Treatment types are

989 coded as CC – clear-cutting; G – gap-cutting; P – preparation cutting; R – retention tree group.

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Supporting information to the manuscript

Unfolding the effects of different forestry treatments on microclimate in oak forests: results of a 4-year experiment

by Bence Kovács^{1,2,3,*}, Flóra Tinya¹, Csaba Németh², and Péter Ódor^{1,2}

submitted to Ecological Applications

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1015 **List of Appendices**

1016

1017 **Table S1** **3**

1018 Characteristics of forest structure around the plots before and after treatments. Structural
1019 attributes (mean ± standard deviation) presented here are diameter at breast height (DBH, cm),
1020 canopy height (m), basal area (m²ha⁻¹) and canopy closure (%).

1021 **Figure S1** **4**

1022 The stand structure and canopy closure (fish-eye photos) of the different treatment types created
1023 in the framework of the ‘Pilis Systems Experiment’: control, clear-cutting, retention tree group,
1024 preparation cutting and gap-cutting. The established treatments represent common forestry
1025 practices belonging to the rotation forestry system (clear-cutting, retention tree group,
1026 preparation cutting), while the recently introduced selection or continuous cover forestry system
1027 was also studied via gap-cutting. The photographs were taken in the first year after the
1028 interventions (in 2015).

1029 **Table S2** **5**

1030 Effect of treatments on microclimate, litter and soil variables in 2014 (pre-treatment year). The
1031 results of linear mixed effects models performed for relative values of the microclimate variables with
1032 the mean (± standard deviation) among the treatment levels in 2014.

1033 **Figure S2** **6**

1034 Correlation biplots based on the performed standardized principal component analysis for 20
1035 microclimate variables (plot titles) analyzed by measurement years (in brackets) separately.

1036 **Figure S3** **19**

1037 Means, interquartile ranges (IQR), minima and maxima of the relative values of vapor pressure
1038 deficit (VPD) among the applied silvicultural treatments throughout the studied four years (2014-
1039 2017).

1040 **Figure S4** **20**

1041 Means, interquartile ranges (IQR), minima and maxima of the relative values of the microclimate
1042 variables among the applied silvicultural treatments throughout the seasons of the observation
1043 years (2014-2017).

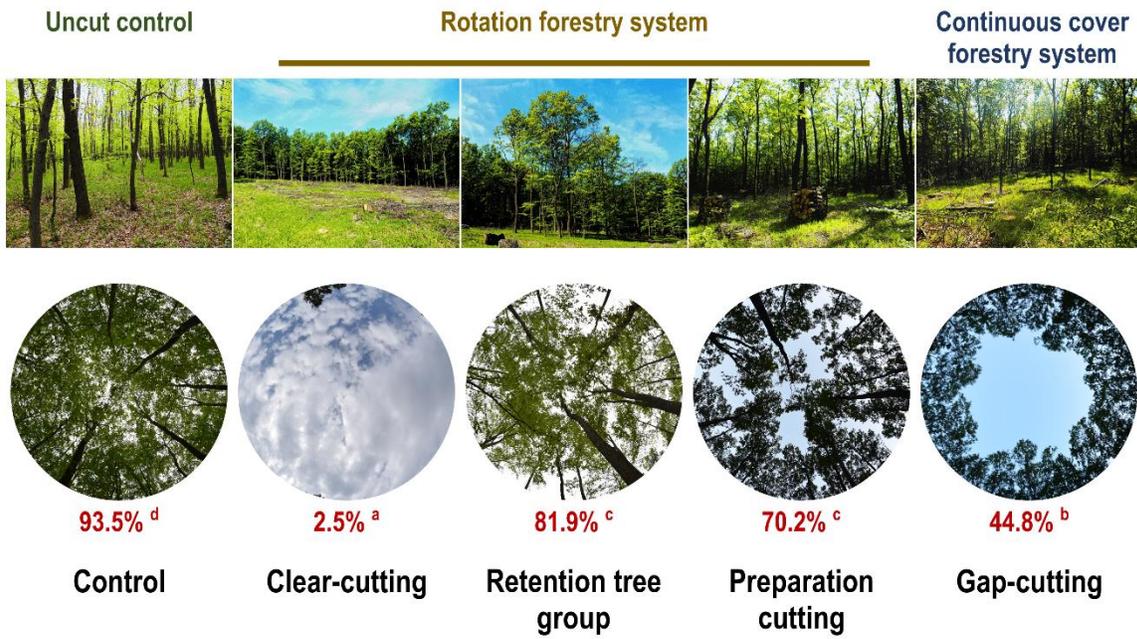
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1045 **Table S1** Characteristics of forest structure around the plots before and after treatments.
 1046 Structural attributes (mean \pm standard deviation) presented here are diameter at breast height
 1047 (DBH, cm), canopy height (m), basal area (m^2ha^{-1}) and canopy closure (%). Letter U refers to upper
 1048 layer and S to sub-canopy layer. C – control; CC – clear-cutting; G – gap-cutting; P – preparation
 1049 cutting and R – retention tree group. Mean and standard deviation were calculated based on the
 1050 six replicates for each treatment type.
 1051

Treatment	DBH				Height				Pre-treatment (2014)			Post-treatment (2015)		
	U		S		U		S		Basal area		Canopy closure	Basal area		Canopy closure
	U	S	U	S	U	S	U	S	U	S	U	S	U	S
C	28.0	11.9	20.9	10.8	29.32	8.83	89.8	29.32	8.83	93.5	29.32	8.83	93.5	
	± 5.8	± 3.8	± 1.5	± 3.5	± 0.12	± 0.10	± 2.6	± 0.12	± 0.10	± 3.9	± 0.12	± 0.10	± 3.9	
CC	28.0	11.8	21.6	10.4	29.58	9.98	87.9	0.00	0.00	2.5	0.00	0.00	2.5	
	± 5.7	± 4.2	± 1.6	± 3.8	± 6.47	± 4.66	± 3.6			± 2.1			± 2.1	
G	27.3	12.5	20.5	11.2	29.53	9.33	88.4	0.00	0.00	44.8	0.00	0.00	44.8	
	± 5.3	± 2.8	± 1.1	± 2.9	± 9.03	± 4.51	± 4.4			± 10.4			± 10.4	
P	27.2	10.9	21.2	10.0	28.07	8.03	89.4	19.67	0.00	70.2	19.67	0.00	70.2	
	± 5.3	± 4.1	± 1.4	± 3.5	± 2.10	± 1.33	± 4.4	± 1.48		± 6.9	± 1.48		± 6.9	
R	27.3	11.1	20.4	11.8	30.47	8.17	88.7	30.47	8.17	81.9	30.47	8.17	81.9	
	± 5.8	± 3.4	± 1.9	± 3.9	± 3.73	± 2.35	± 3.2	± 3.73	± 2.35	± 9.2	± 3.73	± 2.35	± 9.2	

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1054 **Figure S1** The stand structure and canopy closure (fish-eye photos) of the different treatment
 1055 types created in the framework of the 'Pilis Systems Experiment': control, clear-cutting, retention
 1056 tree group, preparation cutting and gap-cutting. The established treatments represent common
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 1058 preparation cutting), while the recently introduced selection or continuous cover forestry system
 1059 was also studied via gap-cutting. The photographs were taken in the first year after the
 1060 interventions (in 2015). Means of the estimated canopy closure are also shown here. Superscripts
 1061 refer to significant differences among treatments (pairwise Tukey comparisons, alpha = 0.05), based on
 1062 linear mixed effect model.
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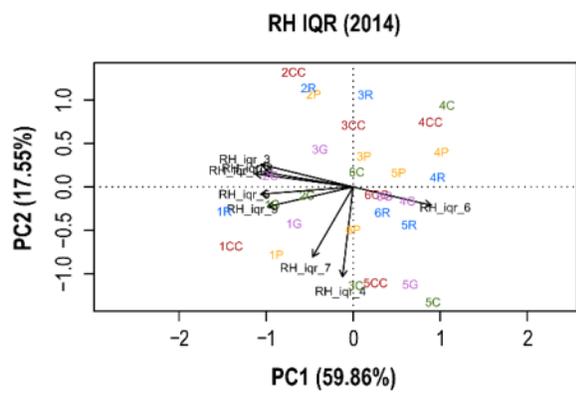
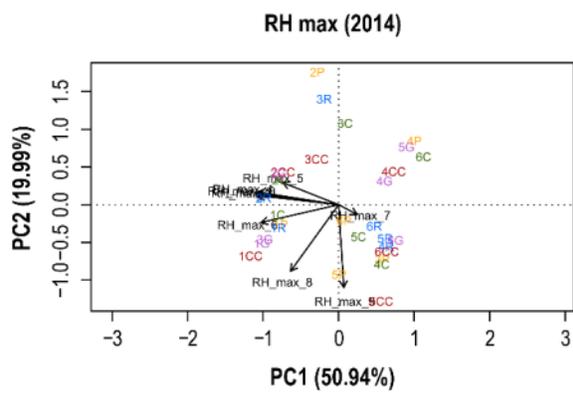
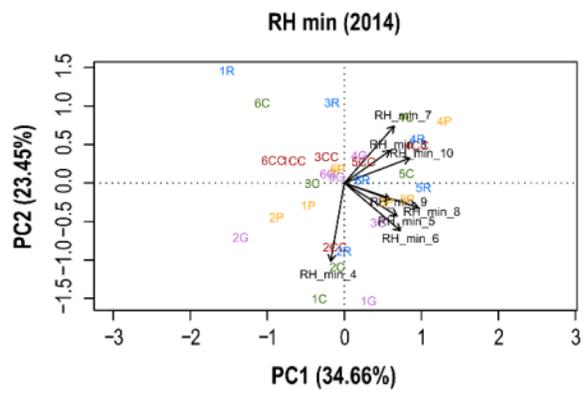
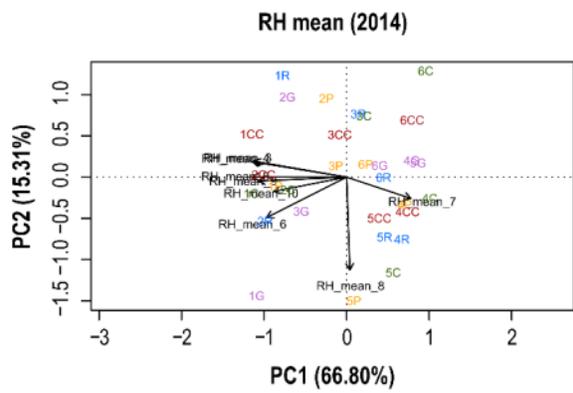
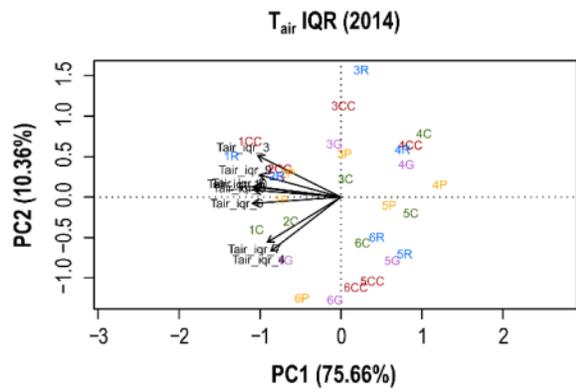
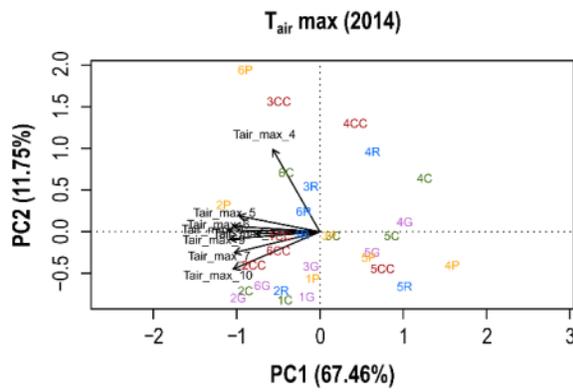
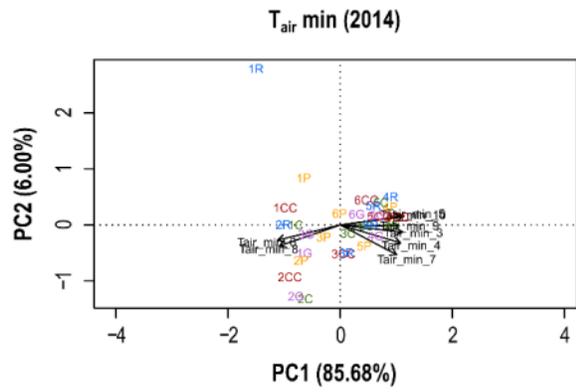
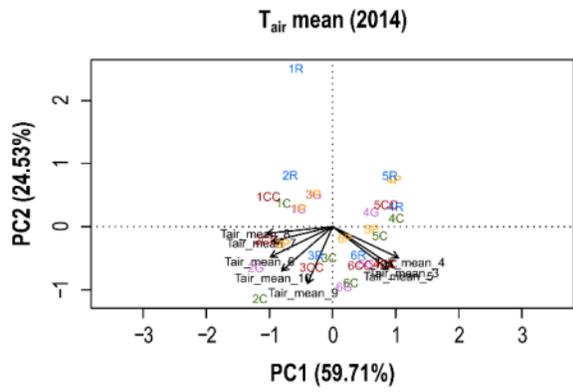
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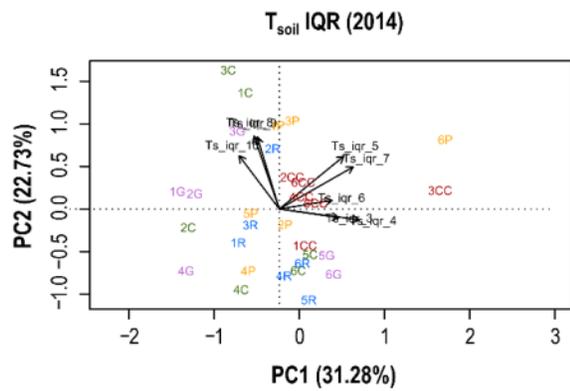
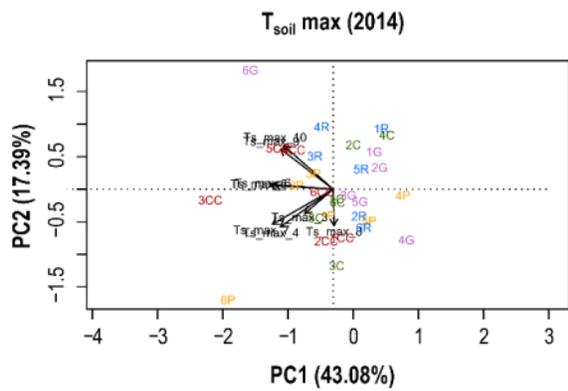
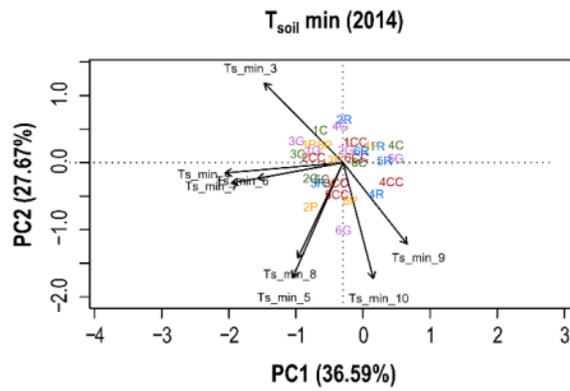
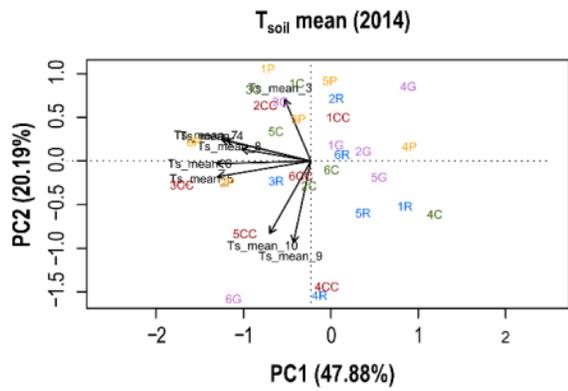
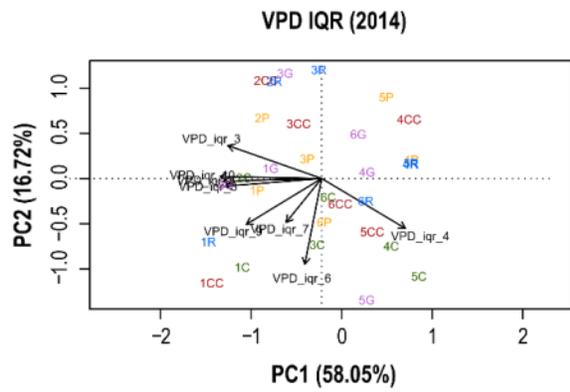
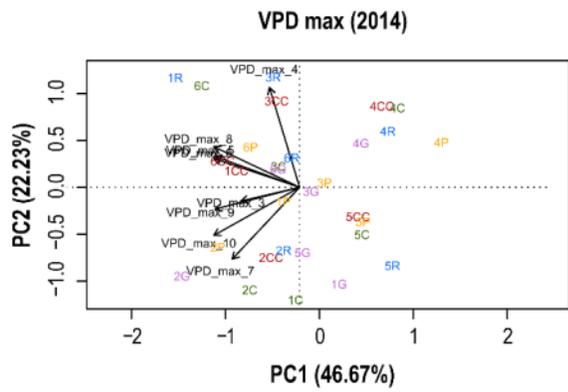
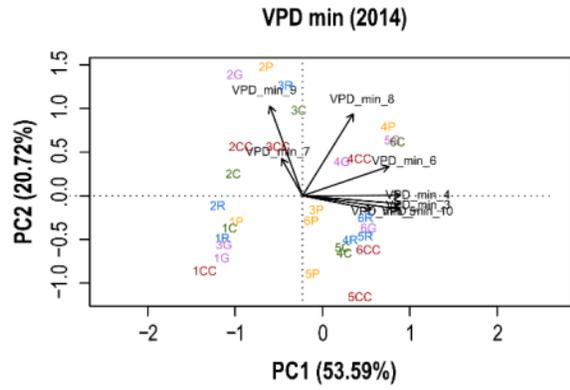
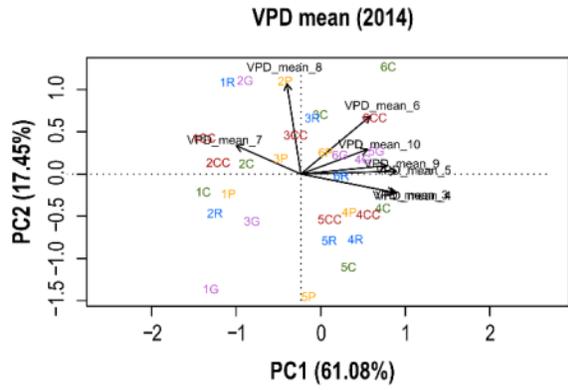
1066 **Table S2** Effect of treatments on microclimate, litter and soil variables in 2014 (pre-treatment
 1067 year). The results of linear mixed effects models performed for relative values of the microclimate
 1068 variables with the mean (\pm standard deviation) among the treatment levels in 2014. *d*PAR:
 1069 photosynthetically active radiation; *d*T_{air}: air temperature; *d*RH: relative humidity; *d*VPD: vapor pressure
 1070 deficit; *d*T_{soil}: soil temperature; *d*SWC: soil moisture. For modelling, 24-hour-means were used except in
 1071 the case of PAR, where daytime (6:00-18:00 local time) means were calculated. Treatment was used as
 1072 fixed while block as random factor. F and p values of the model statistics are presented. Superscripts
 1073 refer to significant differences among treatments (pairwise Tukey comparisons, alpha = 0.05), treatment
 1074 codes marked with bold indicates significant departures from control (alpha = 0.05).
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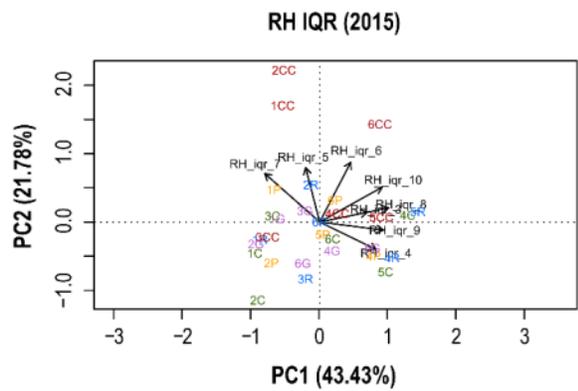
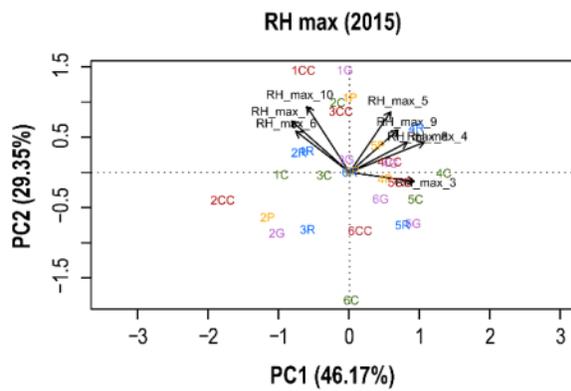
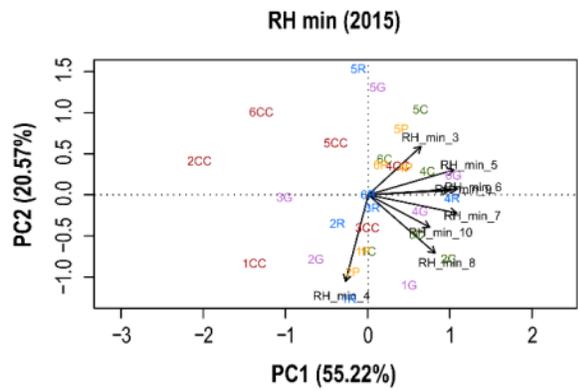
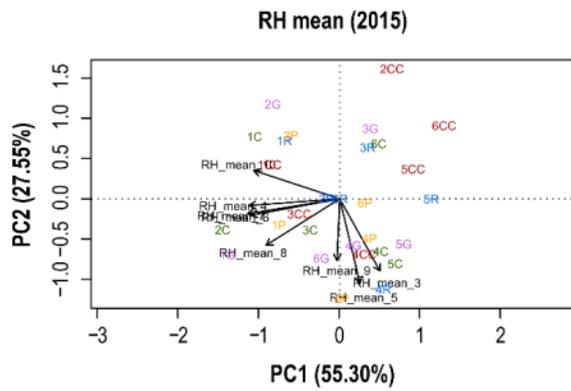
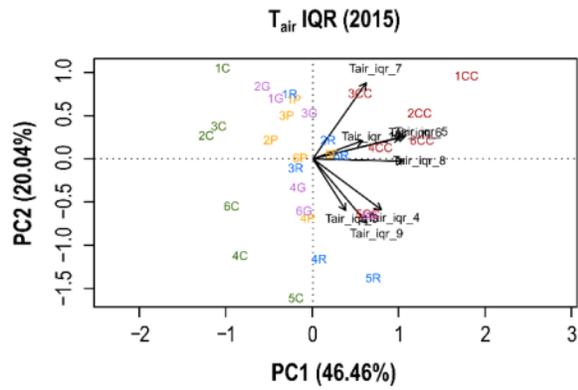
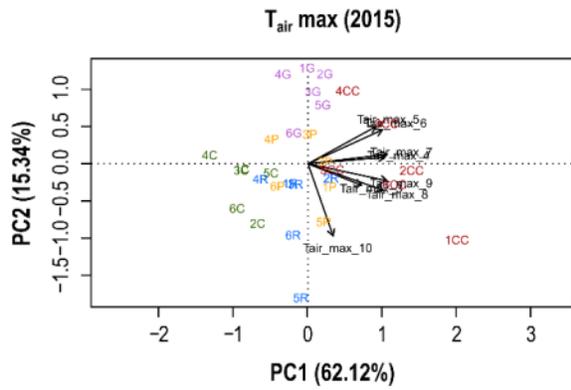
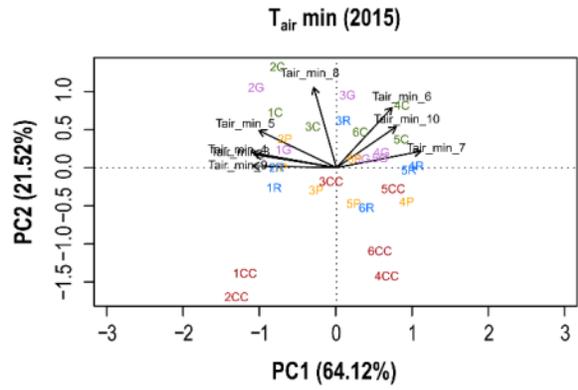
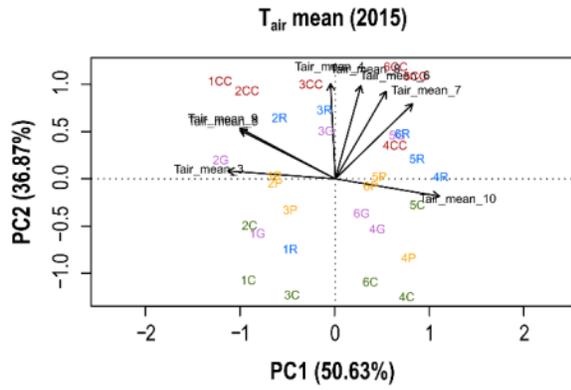
Dependent variable	F	p	Clear-cutting	Gap-cutting	Preparation cutting	Retention tree group
<i>d</i> PAR mean	2.217	0.0878	13.58 \pm 27.64	3.09 \pm 23.90	8.36 \pm 26.72	9.22 \pm 21.89
<i>d</i> PAR IQR	0.657	0.5794	23.94 \pm 36.49	19.58 \pm 26.72	24.63 \pm 32.75	21.51 \pm 26.93
<i>d</i> T _{air} mean	6.943	0.0002	0.004 \pm 0.084 ^a	-0.011 \pm 0.101 ^a	-0.042 \pm 0.093 ^{ab}	-0.074 \pm 0.101 ^b
<i>d</i> T _{air} IQR	0.234	0.8729	0.211 \pm 0.090	0.201 \pm 0.106	0.213 \pm 0.099	0.216 \pm 0.121
<i>d</i> RH mean	0.241	0.8677	0.194 \pm 0.812	0.307 \pm 1.181	0.243 \pm 1.142	0.196 \pm 0.961
<i>d</i> RH IQR	0.009	0.9608	1.770 \pm 0.851	1.691 \pm 0.791	1.793 \pm 0.837	1.731 \pm 0.853
<i>d</i> VPD mean	0.523	0.6671	-0.001 \pm 0.018	-0.004 \pm 0.024	-0.004 \pm 0.022	-0.004 \pm 0.021
<i>d</i> VPD IQR	0.078	0.9721	0.035 \pm 0.023	0.033 \pm 0.022	0.034 \pm 0.021	0.035 \pm 0.025
<i>d</i> T _{soil} mean	2.529	0.0588	0.148 \pm 0.402	-0.019 \pm 0.377	0.089 \pm 0.356	-0.027 \pm 0.422
<i>d</i> T _{soil} IQR	2.240	0.0852	0.467 \pm 0.373	0.363 \pm 0.266	0.379 \pm 0.358	0.322 \pm 0.240
<i>d</i> SWC mean	7.404	0.0001	0.004 \pm 0.032 ^{ab}	0.014 \pm 0.046 ^b	-0.02 \pm 0.056 ^c	-0.006 \pm 0.041 ^{ac}

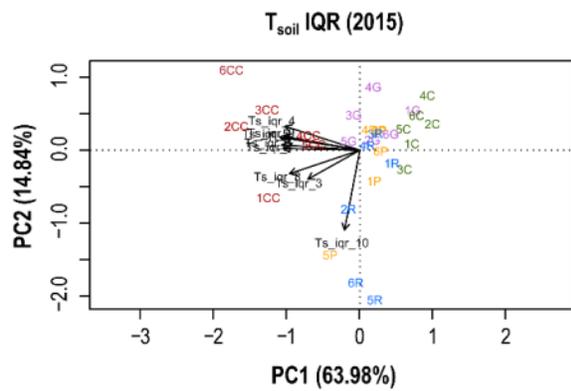
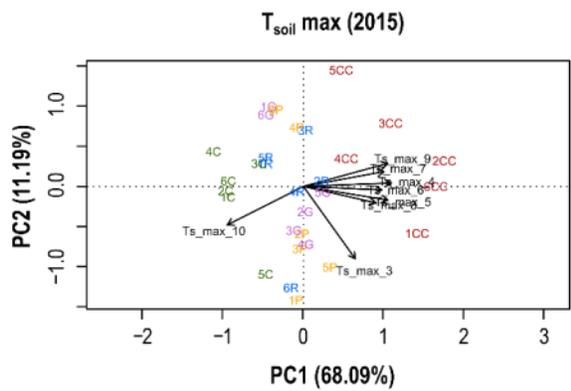
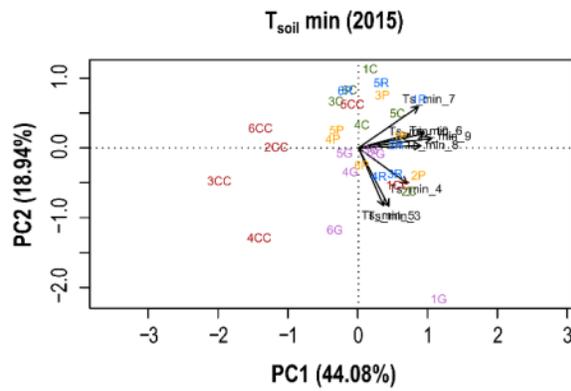
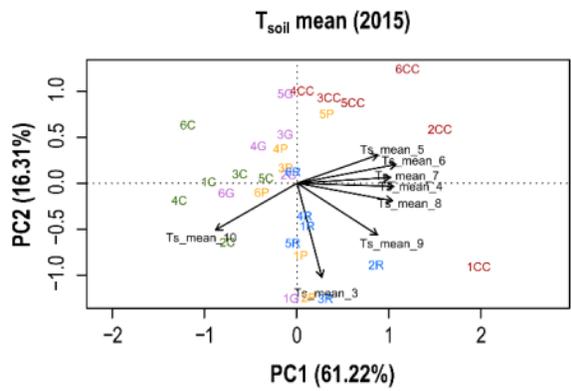
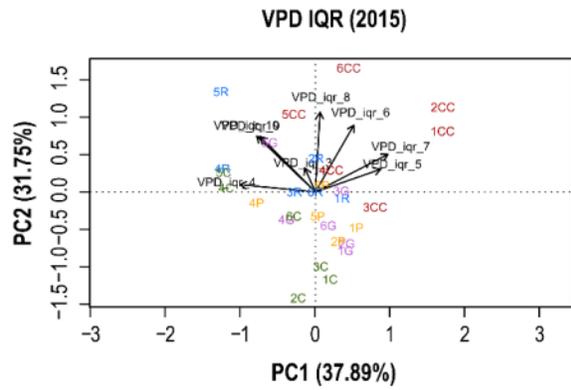
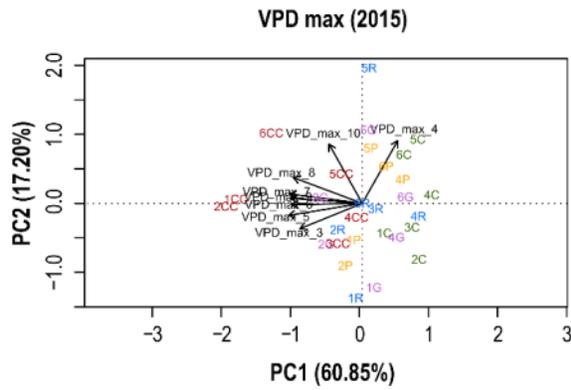
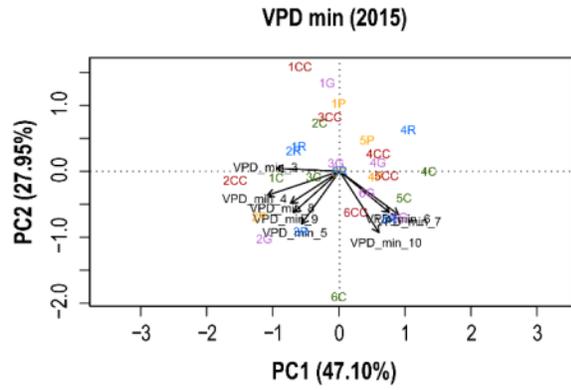
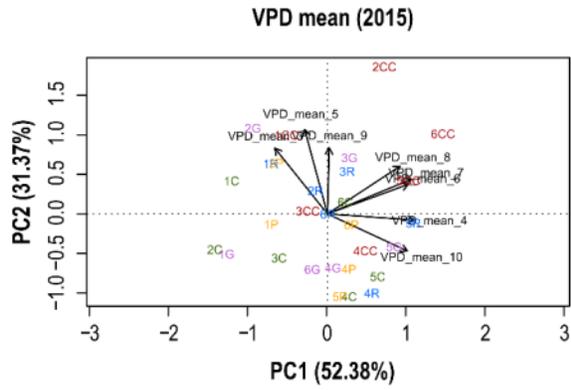
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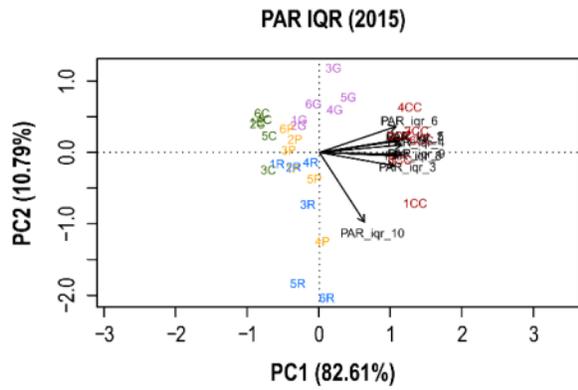
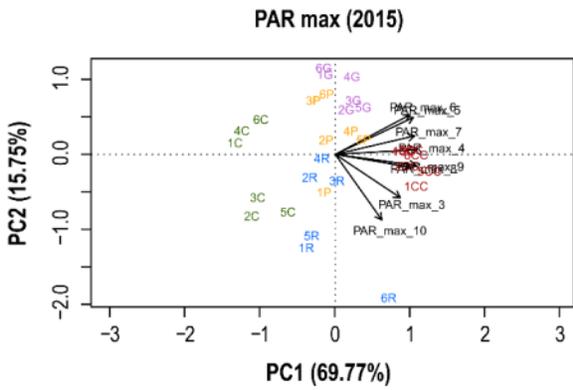
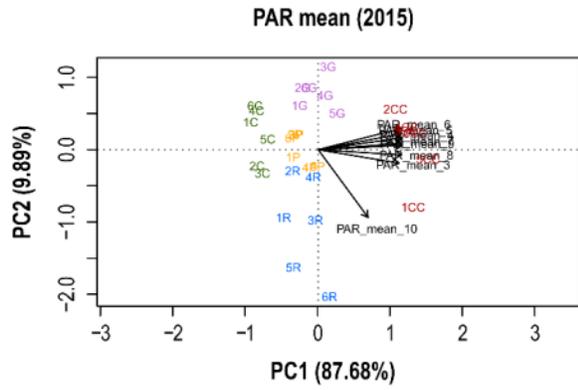
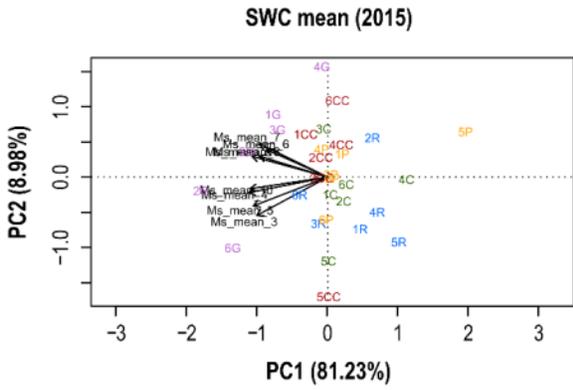
1078 **Figure S2** Correlation biplots based on the performed standardized principal component analysis
1079 for 20 microclimate variables (plot titles) analyzed by measurement years (in brackets) separately.
1080 Variables are abbreviated as PAR: photosynthetically active radiation ($\mu\text{mol m}^{-2}\text{s}^{-1}$) T_{air} : air temperature
1081 ($^{\circ}\text{C}$); RH: relative humidity (%); VPD: vapor pressure deficit (kPa); T_{soil} : soil temperature ($^{\circ}\text{C}$); SWC: soil
1082 moisture (m^3/m^3). Numbers of the variables (3–11) refer to the months within one growing season
1083 (3 codes March, 4 marks April, etc.). The objects were coded by block numbers and treatment
1084 abbreviations. These are coded and depicted with different colors as C – control (green); CC – clear-
1085 cutting (deep red); G – gap-cutting (purple); P – preparation cutting (orange) and R – retention tree group
1086 (blue). The explained variance of the first and second axes are displayed (as proportion of the total
1087 variance).
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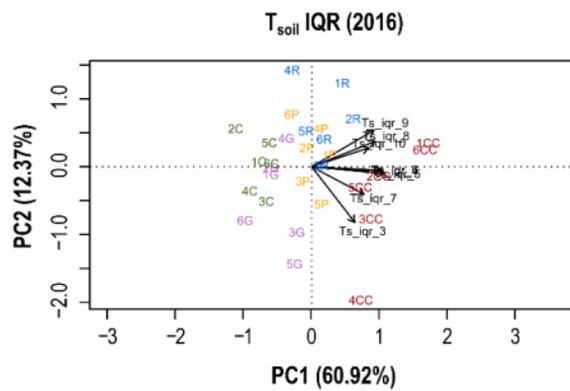
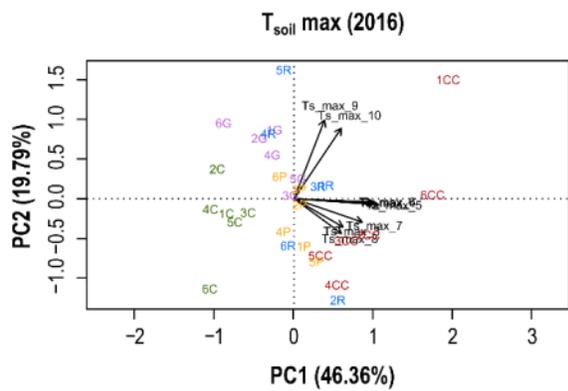
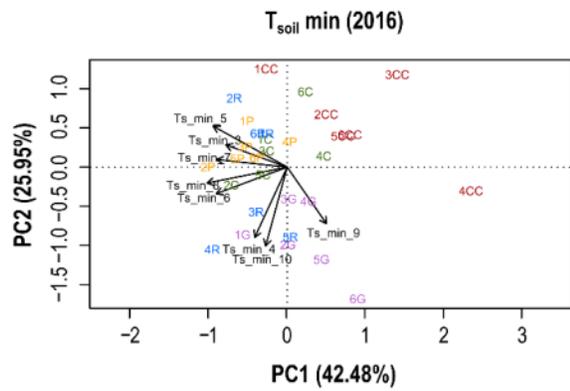
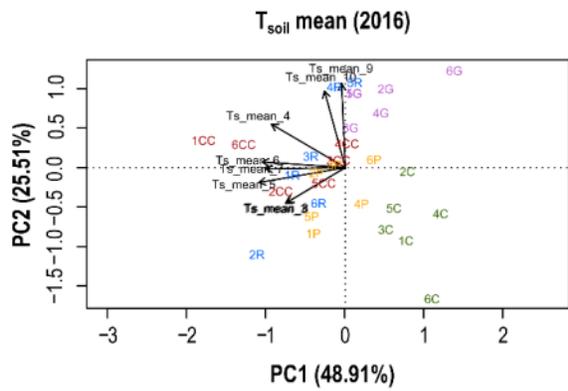
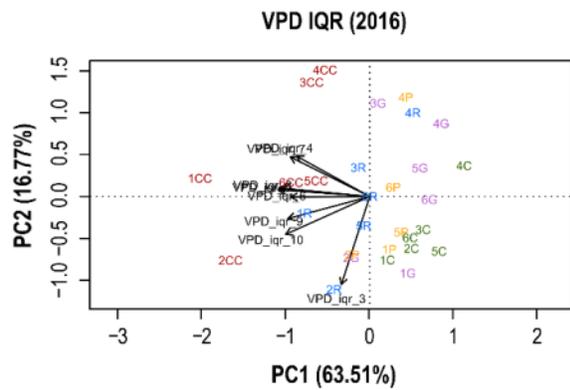
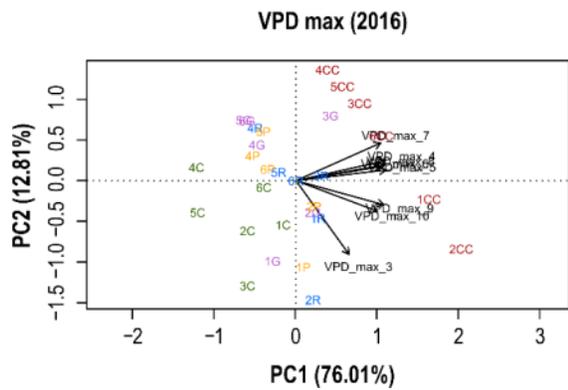
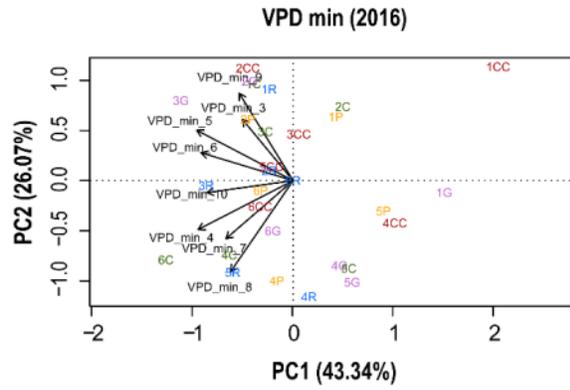
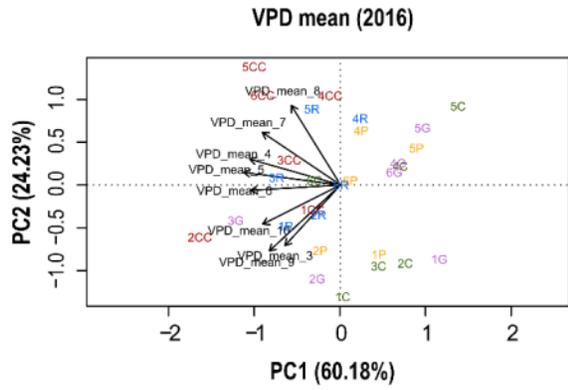


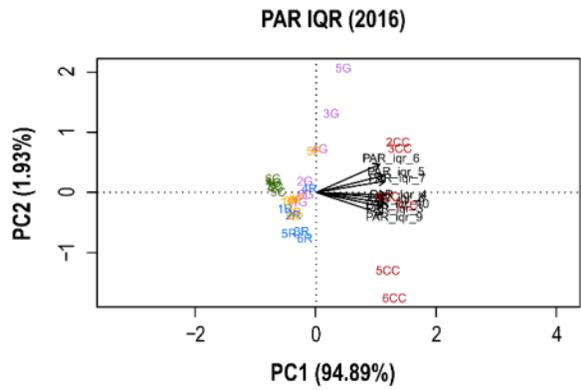
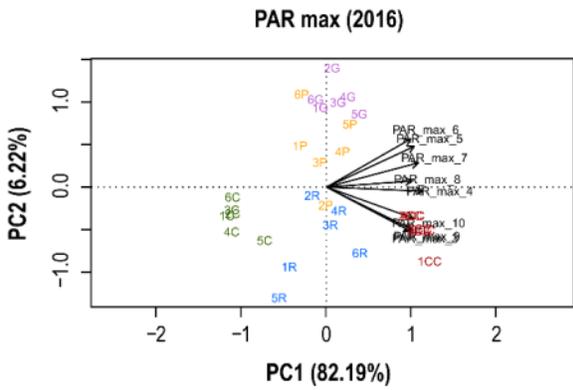
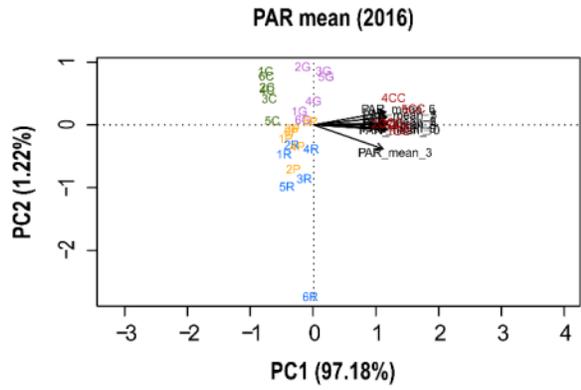
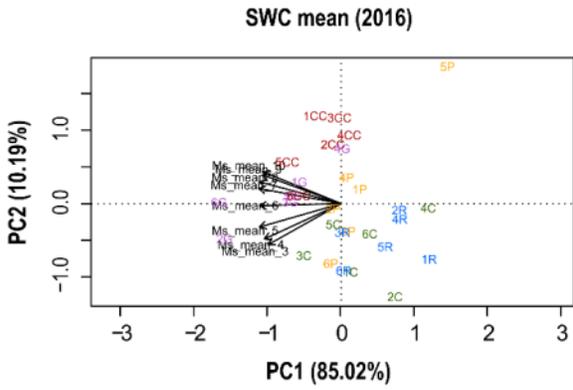


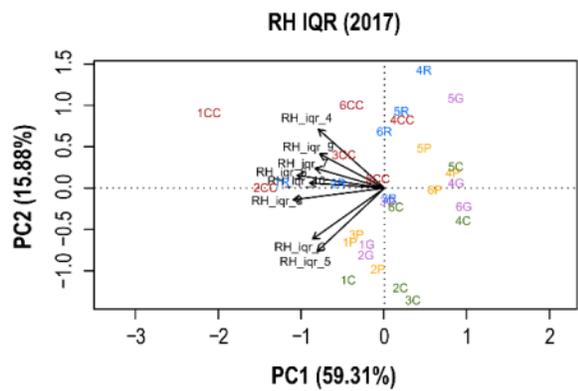
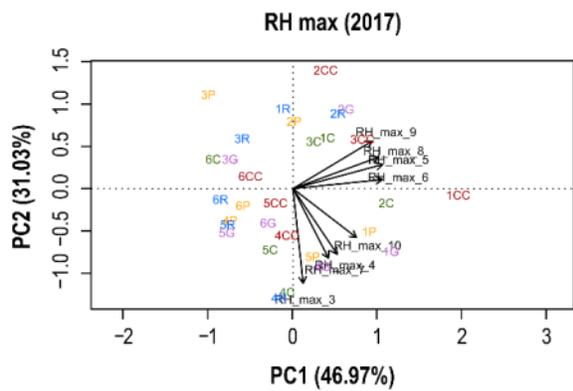
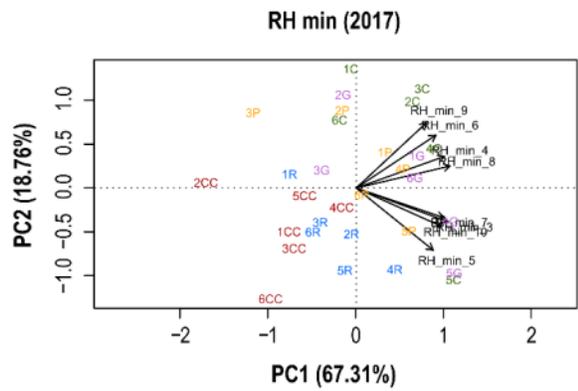
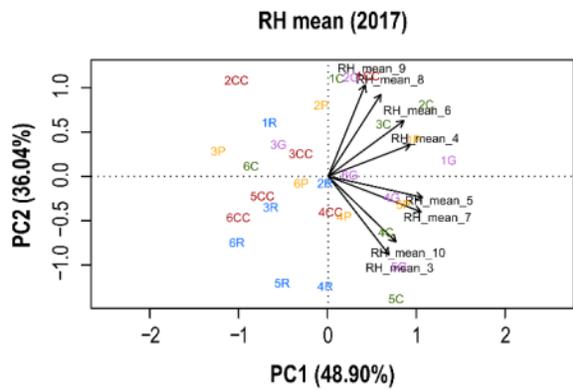
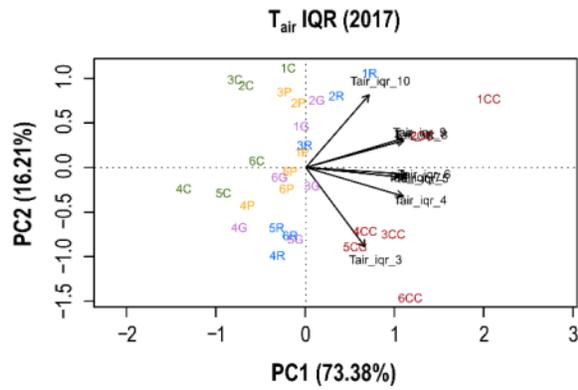
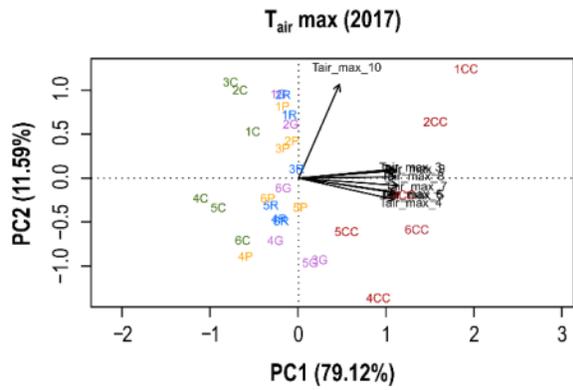
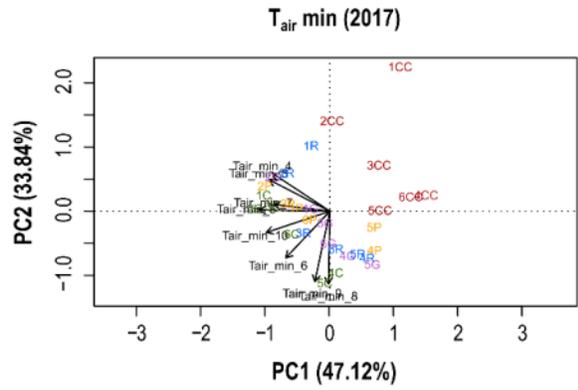
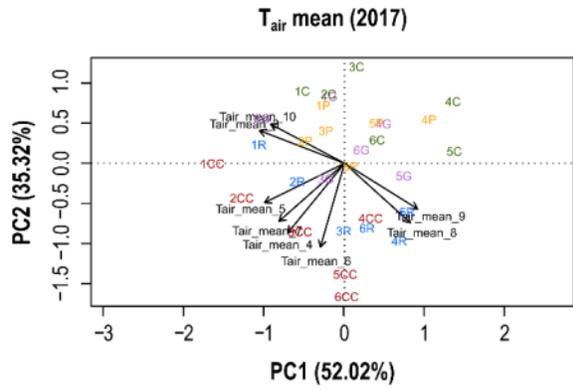


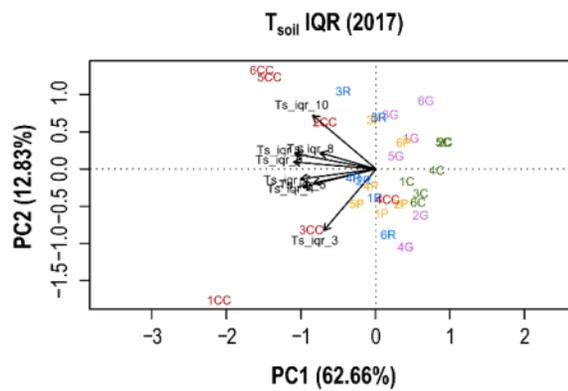
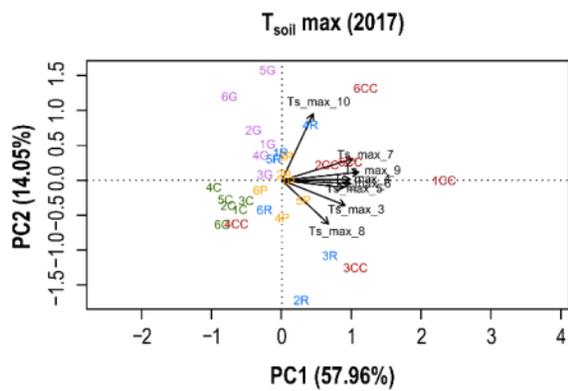
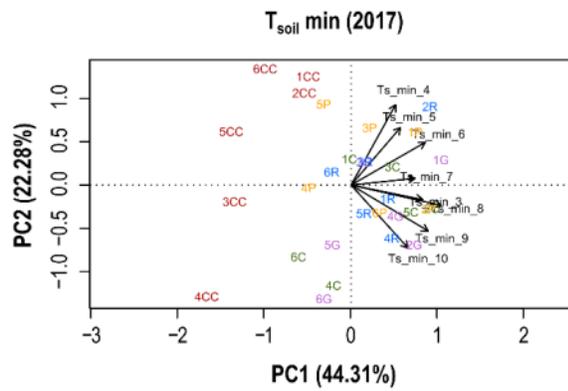
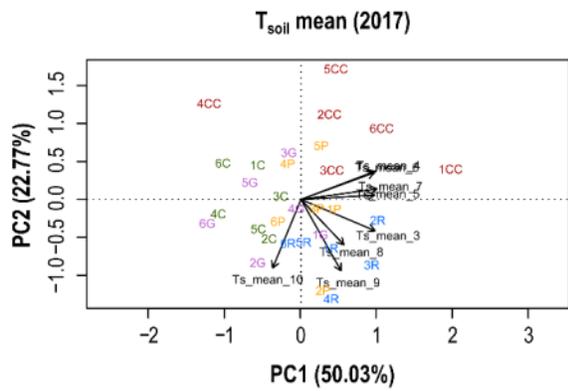
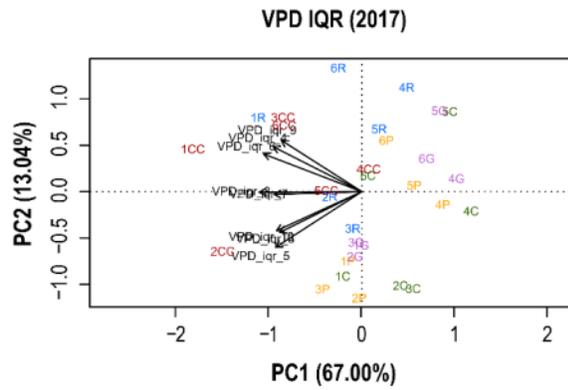
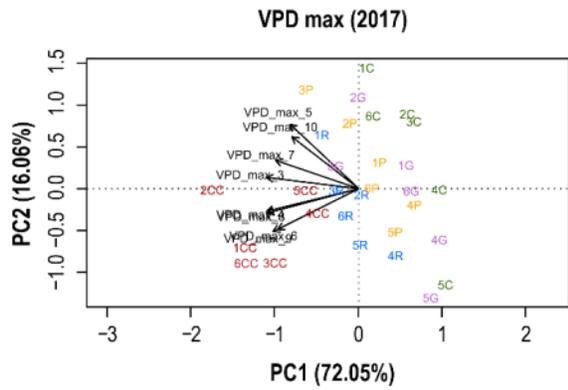
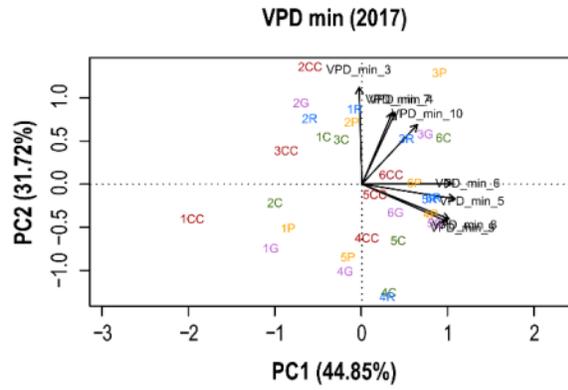
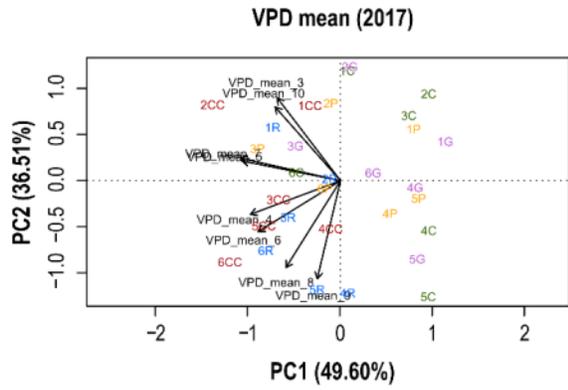


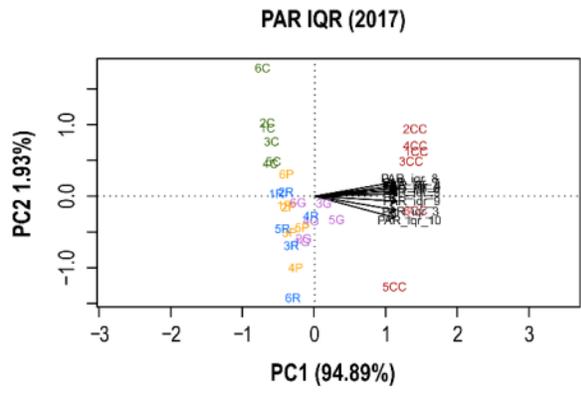
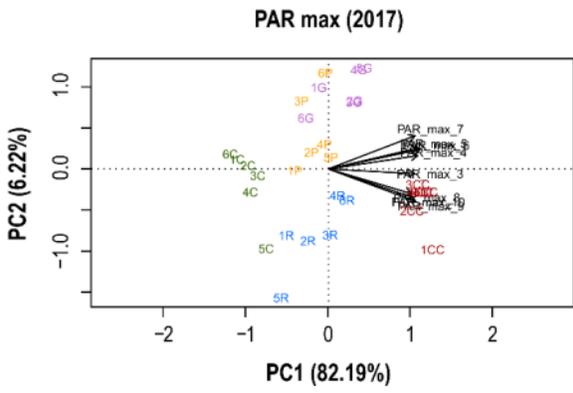
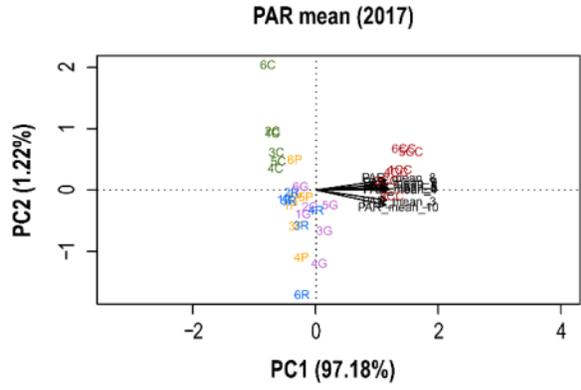
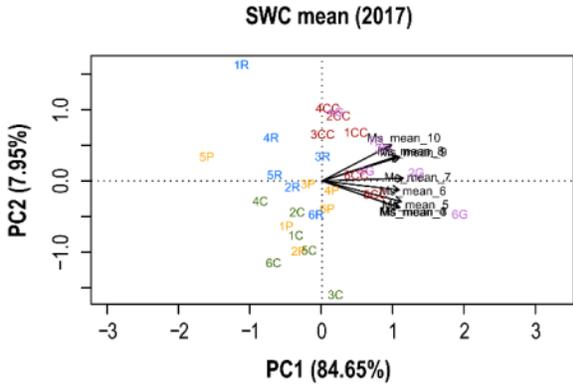






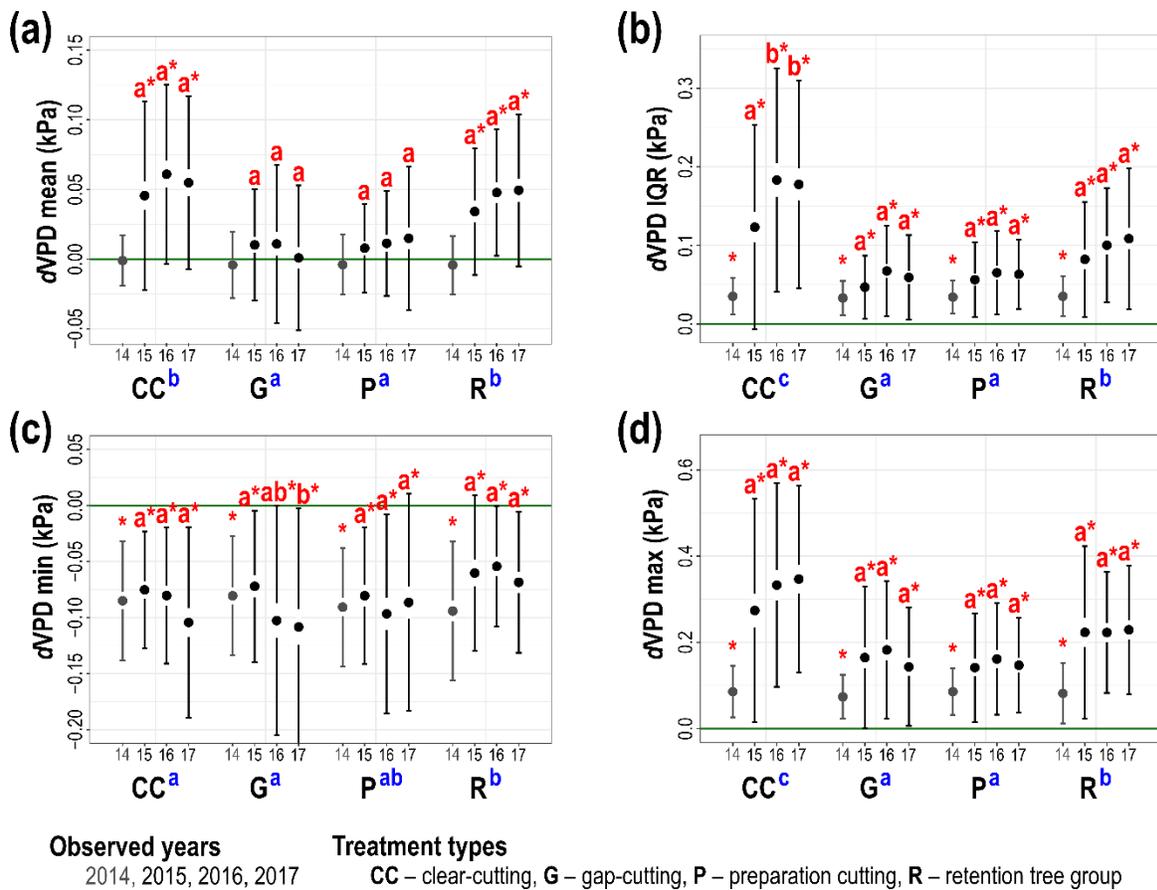






1101

1102 **Figure S3** (a) Means, (b) interquartile ranges (IQR), (c) minima and (d) maxima of the relative values
 1103 (differences from the control) of vapor pressure deficit ($dVPD$) among the applied silvicultural
 1104 treatments throughout the observation years (2014–2017). The treatment types were CC – clear-
 1105 cutting, G – gap-cutting, P – preparation cutting and R – retention tree group. Full circles show the
 1106 mean, vertical lines denote the standard deviation and white bands in between indicate standard
 1107 error of the samples. Letters demonstrate the results of the pairwise multiple comparison (Tukey
 1108 test, alpha = 0.05) based on the performed linear mixed effects models between treatments
 1109 (related to the whole 2015–2017 period, blue letters) and between years (2015–2017) within
 1110 treatment levels (red letters). Asterisks mark significant differences from the values measured at
 1111 the control plots (linear mixed effects models without intercept, $P < 0.05$). The horizontal green
 1112 lines demonstrate the 0-level of the control.
 1113



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1116 **Figure S4** Means, interquartile ranges (IQR), minima and maxima of the relative values (differences
1117 from the control) of the microclimate variables among the applied silvicultural treatments
1118 throughout the seasons of the observation years (2014-2017). The first letters of the months refer
1119 to the seasons (MAM – Spring, JJA – Summer, SOP – Autumn). Variables are coded as: $dPAR$ –
1120 photosynthetically active radiation ($\mu E m^{-2} s^{-1}$); dT_{ai} – air temperature ($^{\circ}C$); dRH – relative humidity
1121 (%); (g) mean and (h) IQR of vapor pressure deficit ($dVPD$; kPa); (i) mean and (j) IQR of soil
1122 temperature (dT_{soil} ; $^{\circ}C$); (k) mean of soil moisture ($dSWC$; m^3/m^3). Treatment types are depicted
1123 by different colors: deep red – clear-cutting; purple – gap-cutting; orange – preparation cutting;
1124 blue – retention tree group. Circles show the mean, vertical lines denote the standard error of the
1125 samples. The horizontal green lines demonstrate the 0-level of the control.
1126

