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

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Abstract. A stable below-canopy microclimate of forests is essential for their biodiversity and ecosystem functionality. Forest management necessarily modifies the buffering capacity of woodlands. However, the specific effects of different forestry treatments on site conditions, the temporal recovery after the harvests, and the reason for the contrasts between treatments are still poorly understood. The effects of four different forestry treatments (clear-cutting, retention tree group, preparation cutting, and gap-cutting) on microclimatic variables were studied within a field experiment in a managed oak-dominated stand in Hungary, before (2014) and after (2015–2017) the interventions by complete block design with six replicates. From the first post-treatment year, clear-cuts differed the most from the uncut control due to the increased irradiance and heat load. Means and variability of air and soil temperature increased, air became dryer along with higher soil moisture levels. Retention tree groups could effectively ameliorate the extreme temperatures but not the mean values. Preparation cutting induced slight changes from the original buffered and humid forest microclimate. Despite the substantially more incoming light, gap-cutting could retain the cool and humid air conditions and showed the highest increase in soil moisture after the interventions. For most microclimate variables, we could not observe any obvious trend within 3 yr. However, soil temperature variability decreased with time in clear-cuts, while soil moisture difference continuously increased in gap- and clear-cuts. Based on multivariate analyses, the treatments separated significantly based mainly on the temperature maxima and variability. We found that (1) the effect sizes among treatment levels were consistent throughout the years, (2) the climatic recovery time for variables appears to be far more than 3 yr, and (3) the applied silvicultural methods diverged mainly among the temperature maxima. Based on our study, the spatially heterogeneous and fine-scaled treatments of continuous cover forestry (gap-cutting, selection systems) are recommended. By applying these practices, the essential structural elements creating buffered microclimate could be more successfully maintained. Thus, forestry interventions could induce less pronounced alterations in environmental conditions for forest-dwelling organism groups.

Key words: air temperature; forest ecological experiment; forest management; photosynthetically active radiation (PAR); relative humidity; soil moisture; soil temperature; temperate deciduous forests; vapor pressure deficit (VPD).

INTRODUCTION

Microclimate studies, as well as the integration of their outcomes, into climate-dependent models have become an important research area for climatologists, ecologists, and practitioners in the last two decades. This topic is especially relevant facing the current anthropogenic climate change and its effects on ecosystems and their functionality (Hannah et al. 2014, Frey et al. 2016, Bramer et al. 2018). A better understanding of microclimate can contribute to the adjustment of climate and species distribution models. For decades, it has been known that organisms are exposed to the variability of climate on finer spatial scales than it is typically measured by standard meteorological stations worldwide (Geiger et al. 1995, Potter et al. 2013). This mismatch results in coarser scale abiotic data that are not entirely appropriate for surveying and modeling biological processes (Suggitt et al. 2011, De Frenne and Verheyen 2016). Furthermore, local conditions can often result in microclimates that are substantially different from the...
macroclimate; therefore, the ranges of the driving forces of species distribution, e.g., climatic extremes, are narrowed (Scherrer et al. 2011, Suggitt et al. 2011, Scheffers et al. 2014). As a result, the lack of information about the upper or lower limits could cause either over- or underprediction of the climatically suitable microenvironments for species (Ashcroft and Gollan 2013, Hannah et al. 2014, Frey et al. 2016). Though woodlands have been identified as a main factor shaping climatic microrefugia, along with topography and moisture conditions (Ashcroft and Gollan 2013, von Arx et al. 2013, Latimer and Zuckerberg 2017), there are still limited data collected beneath forest canopies, which would be essential for climatic predictions as well as species distribution modeling (De Frenne and Verheyen 2016, Bra- mer et al. 2018). Hence, it is necessary to explore the below-canopy microclimates in stand types, which are different based on physiography, forest site conditions, tree species composition, vertical and horizontal structure, or natural and anthropogenic disturbance regimes.

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

Canopy cover and its structure are typically highlighted as one of the most important drivers of the buffer capacity of a given forest stand (Bonan 2016, Latimer and Zuckerberg 2017, De Frenne et al. 2019), which is necessarily altered by forest management practices (Chen et al. 1999, Hardwick et al. 2015, Lin et al. 2017, Ehbrecht et al. 2019). Forestry interventions creating, for example, clear-felled areas or stands with large openings, generate microclimatic conditions that are considerably different from those in forests (Chen et al. 1999, Bonan 2016). It is an important conservation aspect to study how these management types induced alterations that affect the climatically suitable habitats for forest-dwelling organism groups (De Frenne and Verheyen 2016). Furthermore, regeneration time of microclimatic conditions after anthropogenic disturbances generated by silviculture is also a highly relevant question for the colonization (or recovery) of forest-dwelling populations.

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

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

The Pilis Forestry Systems Experiment (Ödor 2018) was implemented to compare the long-term effects of forestry interventions belonging to the most common silvicultural systems applicable to temperate forests in Europe on forest site conditions, natural regeneration, and forest biodiversity in a managed sessile oak (Quercus petraea Matt. [Liebl.]) – hornbeam (Carpinus betulus L.) forest, which is a widespread woodland habitat type across Europe (Janssen et al. 2016). In the framework of this forest ecological experiment, we combined the prevalent treatment types of the regionally dominant rotation forestry system as well as the recently introduced selection (continuous cover) forestry system (Pommerening and Murphy 2004).

The aim of this study is to explore the effects of silvicultural treatments on below-canopy microclimate, as well as its short-term recovery processes. Our specific questions were the following: (1) To what extent do the treatments modify the studied microclimatic variables? (2) Do these variables change in time during the first three growing seasons in the different treatments? (3) Which are the most determinant microclimatic variables in the separation of the treatments?

We hypothesized that (1) clear-cutting has the most drastic effects on all variables resulting in the highest differences from control; retention tree group can moderately
compensate for the effects of clear-cutting; gap-cutting might be characterized by high light values and increased soil moisture, but otherwise microclimate conditions remain buffered; while preparation cutting only slightly differs from the closed forest control. It was also expected that (2) the strongest treatment effect is detected in the first year after the interventions, which is moderated by the regeneration processes in the consecutive years. We assumed that (3) temperature variables and soil moisture are the most important in the separation of treatments, and it was also expected that the daily maximum and minimum values have higher importance shaping microclimatic differences among treatments than means.

**Materials and Methods**

**The study area**

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

The experimental site was established in a 40-ha homogeneous unit of managed, 80-yr-old, two-layered, sessile oak–hornbeam forest stand (Natura 2000 code: 91G0; Council Directive 92/43/EEC 1992) with a relatively uniform structure, homogeneous canopy closure (Appendix S1: Table S1), and tree species composition as a consequence of the applied shelterwood silvicultural system. The upper canopy layer (mean height 21 m) is dominated by sessile oak, the subcanopy layer is primarily formed by hornbeam (mean height 11 m). Other woody species are rare, individuals of Fraxinus ornus L., Fagus sylvatica L., Quercus cerris L., and Prunus avium L. can be found as admixing tree species. Before the experimental treatments, the shrub layer was scarce and mainly consisted of the regeneration of hornbeam and Fraxinus ornus L. with a lower cover of shrub species (e.g., Crataegus monogyna Jacq., Cornus mas L., Ligustrum vulgare L., and Euonymus verrucosus Scop.). The understory layer was initially formed by general and mesic forest species (Carex pilosa Scop., Melica uniflora Retz., Cardamine bulbifera L., Galium odoratum (L.) Scop., and Galium schultesii Vest.) and had a cover of approximately 45%.

**Experimental design**

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

Data collection

Systematic microclimate measurements were taken in the center of each plot. Temporally synchronized data collection was carried out using four-channel Onset HOBO H021-002 data loggers (Onset Computer Corporation, Bourne, Massachusetts, USA). In the years studied (2014–2017), every month of the growing season (March–October), 72-hr logging periods were used with 10-minute logging intervals. Photosynthetically active radiation (PAR, λ = 400–700 nm; μmol·m⁻²·s⁻¹) was measured at 150 cm above ground level, using Onset S-LIA-M003 quantum sensors. Air temperature (Tair; °C) and relative humidity (RH, %) data were collected 130 cm above ground level with Onset S-THB-M002 sensors housed in standard radiation shields against direct sunlight. Soil temperature (Tsoil; °C) was measured with Onset S-TMB-M002 sensors placed 2 cm below ground. Soil water content (SWC; m³/m³) data were collected using Onset S-SMD-M005 soil moisture sensors buried 20 cm below ground level to measure the average soil moisture at 10–20 cm soil depth. Air temperature and relative humidity data were used to calculate vapor pressure deficit (VPD; kPa), which characterize the actual drying capacity of air (using the equations recommended by Allen et al. [1998]).

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

Data analysis

For the univariate analyses, one randomly chosen 24-h microclimate data set per month was used (eight months in one growing season). For exploring the effects of treatment types, relative values were calculated as differences from the control (separately in each block). Thereby, we excluded the effects of the temporal differences of actual weather conditions and seasons, as well as the spatial heterogeneity between the blocks. Daily mean, minimum, maximum, and interquartile range (IQR) of PAR, Tair, RH, VPD, Tsoil, and SWC variables were computed and analyzed. As SWC is a rather stationary variable within a day, only its mean was involved in the analysis. For PAR, measurements between 06:00 and 18:00 (local time) were analyzed, and the daily minimum and maximum values were excluded from the modeling. To investigate the effect of the treatments and years on the microclimate variables, linear mixed effects models (random intercept models) with a Gaussian error structure were used (Faraway 2006). Where necessary, the response variables were transformed to achieve the normality of the model residuals. The treatment (four levels: CC, G, P, R), year (three levels: 2015, 2016, 2017), and their interaction were used as fixed factors, while the block was specified as a random factor. The models’ goodness-of-fit values were measured by a likelihood-ratio test-based coefficient of determination (R² LR; Barto 2016), the explanatory power of the fix factors were evaluated by analysis of deviance (F statistics; Faraway 2006). The differences between the treatment levels were evaluated using Tukey’s multiple comparisons procedure (alpha = 0.05) for all of the pairwise comparisons based on the estimated marginal means. The significance of the differences between the control and the other treatment levels was tested by linear mixed effects models without intercept (Zuur 2009). The pretreatment data (collected in the growing season of 2014) were analyzed separately following the same methodological framework (Appendix S1: Table S2).

We applied multivariate ordination methods for exploring the relative importance of the microclimate variables in the separation of the treatments. Absolute diurnal data sets (mean, minima, maxima, and IQR of the raw microclimate data) were used during these analyses because control data were also involved in these comparisons. These analyses were carried out in each studied year (2014–2017) separately. Only Tair, RH, VPD, Tsoil, and SWC variables were used during the evaluations. PAR variables were excluded since their effect is hardly separated from treatments (the applied treatments directly modified the canopy closure of the plots). The separation of the plots by microclimate variables (using treatment as an a priori grouping variable) were explored by multivariate linear discriminant analysis (LDA; Podani 2000). We used generalized microclimate data of the vegetation periods for the LDAs to exclude the effects of seasonality, therefore standardized principal component analyses (PCA; Podani 2000) were performed on the eight monthly measurements of each variable for all observed years separately; and the first canonical axes were used to create input matrices (Appendix S1: Fig. S2). The explained variance of the first axes of these PCAs ranged...
between 38% and 88%. This approach enabled to explain the highest proportion of the total variance of a given microclimate variable throughout a growing season. During the 4 yr of data collection, the database contained 4.89% of missing values ranging 0–20% between the months. For incomplete microclimate data sets, the iterative PCA method (Ipcas) suggested by Dray and Josse (2015) was performed. Separation between the treatments was measured by permutational multivariate analysis of variance (PERMANOVA based on Canberra metrics; Podani 2000, Anderson 2017) with 9,999 permutations. The separability power of the microclimate variables among treatment levels was tested by Wilks’ lambda with F test approximation performed in multivariate analysis of variance (MANOVA) for each separate year (Borcard et al. 2018).

The data analyses were performed using R version 3.4.1 (R Core Team 2017). The package nlme was used for the linear mixed effects models (Pinheiro et al. 2017), lsmeans was used for multiple comparisons (Lenth 2016), and the MuMln package was used for pseudo-R² values (Barton 2016). PCAs were obtained using vegan (Oksanen et al. 2018), Ipcas procedures by missMDA (Josse and Husson 2016), and LDAs by MASS (Venables et al. 2002) packages.

RESULTS

General treatment effects

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

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

The most illuminated environment was created by clear-cutting (Fig. 2a) with the highest daily range and (Fig. 2b). Similarly, substantial increment but lower incoming radiation was present in the gap-cuts (Fig. 2a). The light conditions were significantly lower and less heterogeneous in the preparation cuts and the retention tree groups than in the prior two types, but in both types, they were significantly higher than in the control.

The mean and the IQR of the $dT_\text{air}$ was the highest in the clear-cuts (mean ≈ 0.3°C and IQR > 1°C; Fig. 3a, b), moreover, this was the only treatment where both minima and maxima were significantly different from the other treatments (Fig. 3c, d). The mean $dT_\text{air}$ was buffered the most in the preparation cuts and gap-cuts (Fig. 3a). The variability of $dT_\text{air}$ was reduced most effectively in the gap-cuts and preparation cuts, however, the latter could buffer the maxima more effectively.
Observed years 2014, 2015, 2016, 2017
Treatment types CC – clear-cutting, G – gap-cutting, P – preparation cutting, R – retention tree group

FIG. 3. Means, interquartile ranges (IQR), minima, and maxima of the relative values (differences from the control) of (a–d) air temperature ($dT_{air}$) and (e–h) relative humidity ($dRH$) among the applied silvicultural treatments throughout the observation years (2014–2017). Figure components are as in Fig. 2.
The changes in mean $dT_{\text{air}}$ in the retention tree groups were similar to the clear-cut levels but IQRs and extrema were significantly reduced.

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

In general, $dT_{\text{soil}}$ differed significantly in almost every treatment from the control, the only exception was the mean in gap-cutting that could preserve the levels of

![Fig. 4](image-url)
uncut control (Fig. 4a–d). The highest $dT_{\text{soil}}$ was measured in the clear-cuts and retention tree groups (~1°C; Fig. 4a), however, the latter treatment type induced less variable temperature (Fig. 4b). The coolest soil environment with the lowest IQR was detected in the gap-cuts. The $dT_{\text{soil}}$ minima were significantly lower in gap- and clear-cuts than in preparation cuts and retention tree groups (Fig. 4c).

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

**Temporal changes**

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

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

**Separation among treatments**

As it was hypothesized, plots did not show clear patterns before the treatments ($F_{4,25} = 0.464, P = 0.2145$ according to the performed PERMANOVAs), the first canonical axis explained 52.5% of the total between group variance, the second axis 22.1% (Fig. 5a). The strongest separation could be detected in 2016 ($F_{4,25} = 4.342, P < 0.0001$), with 79.4% and 10.9% of explained variance by LD1 and LD2, respectively (Fig. 5c). Separability power of the LDAs were high in 2015 (Fig. 5b) and 2017 (Fig. 5d) as well ($F_{4,25} = 2.311,$

### Table 1. The results of the linear mixed effects models.

| Dependent variable | Model | Treatment (numDF=3) | Year (numDF=2) | Treatment:Year (numDF=6) |
|--------------------|-------|---------------------|---------------|--------------------------|
|                    | Chi²  | $R^2_{\text{LR}}$  | $dF$ | $P$ | $dF$ | $P$ | $dF$ | $P$ |
| $dPAR$ mean        | 363.0907 | <0.0001 | 0.489 | 525 | 164.241 | <0.0001 | 525 | 2.442 | 0.0880 | 525 | 1.683 | 0.1230 |
| $dPAR$ IQR         | 437.1786 | <0.0001 | 0.554 | 526 | 208.105 | <0.0001 | 526 | 6.574 | 0.0015 | 526 | 3.803 | 0.0010 |
| $dT_{\text{air}}$ mean | 67.2150 | <0.0001 | 0.136 | 527 | 19.724 | <0.0001 | 527 | 3.526 | 0.0301 | 527 | 0.633 | 0.7040 |
| $dT_{\text{air}}$ IQR | 207.3817 | <0.0001 | 0.317 | 527 | 68.953 | <0.0001 | 527 | 17.311 | <0.0001 | 527 | 0.900 | 0.4943 |
| $dT_{\text{air}}$ min | 126.2807 | <0.0001 | 0.258 | 527 | 33.864 | <0.0001 | 527 | 17.595 | <0.0001 | 527 | 0.388 | 0.8868 |
| $dT_{\text{air}}$ max | 158.4704 | <0.0001 | 0.253 | 527 | 52.240 | <0.0001 | 527 | 6.736 | 0.0013 | 527 | 1.621 | 0.1390 |
| $dRH$ mean         | 85.8444 | <0.0001 | 0.385 | 495 | 23.037 | <0.0001 | 495 | 6.058 | 0.0025 | 495 | 1.681 | 0.1237 |
| $dRH$ IQR          | 173.6899 | <0.0001 | 0.289 | 495 | 46.628 | <0.0001 | 495 | 26.824 | <0.0001 | 495 | 1.441 | 0.1969 |
| $dRH$ min          | 137.6227 | <0.0001 | 0.348 | 494 | 41.181 | <0.0001 | 494 | 11.305 | <0.0001 | 494 | 1.362 | 0.2281 |
| $dRH$ max          | 35.9720  | 0.0002  | 0.261 | 495 | 8.452  | <0.0001 | 495 | 1.518  | 0.2203 | 495 | 1.334 | 0.2402 |
| $dVPD$ mean        | 85.1361  | <0.0001 | 0.267 | 491 | 27.849 | <0.0001 | 491 | 9.350  | 0.0391 | 491 | 0.854 | 0.5287 |
| $dVPD$ IQR         | 86.9652  | <0.0001 | 0.158 | 491 | 24.073 | <0.0001 | 491 | 8.205  | <0.0001 | 491 | 0.664 | 0.6788 |
| $dVPD$ min         | 23.2642  | 0.0162  | 0.192 | 490 | 4.333  | 0.0500  | 490 | 2.380  | 0.0936 | 490 | 0.914 | 0.4845 |
| $dVPD$ max         | 73.1878  | <0.0001 | 0.154 | 491 | 23.002 | <0.0001 | 491 | 1.547  | 0.2140 | 491 | 0.795 | 0.5743 |
| $dSWC$ mean        | 43.7028  | <0.0001 | 0.088 | 526 | 10.982 | <0.0001 | 526 | 4.403  | 0.0127 | 526 | 0.464 | 0.8352 |
| $dSWC$ IQR         | 129.7824 | <0.0001 | 0.213 | 526 | 42.387 | <0.0001 | 526 | 5.728  | 0.0035 | 526 | 0.792 | 0.5767 |
| $dSWC$ min         | 104.6072 | <0.0001 | 0.205 | 526 | 29.188 | <0.0001 | 526 | 11.386 | <0.0001 | 526 | 0.431 | 0.8580 |
| $dSWC$ max         | 91.4572  | <0.0001 | 0.155 | 526 | 24.400 | <0.0001 | 526 | 11.102 | <0.0001 | 526 | 0.377 | 0.8975 |

Notes: Significant explanatory variables (at $P < 0.05$) are marked in bold. Dependent variables are PAR, photosynthetically active radiation; $T_{\text{air}}$, air temperature; RH, relative humidity; VPD, vapor pressure deficit; $T_{\text{soil}}$, soil temperature; and SWC, soil moisture. numDF is 3 for Treatment, 2 for Year and 6 for the Treatment:Year interaction term, respectively. The $d$ refers to the difference from the values measured in the control plots (relative data).
However, while separation of control and clear-cutting was more pronounced and the other three groups overlapped in 2016 (Fig. 5c), all treatment types showed higher separation in 2015 and 2017 (Fig. 5b, d, respectively), although the relative partition between control and clear-cutting was weaker.

The main drivers of the separation

We demonstrated that if light variables are excluded, in the first three growing seasons, treatment effect was mostly based on the microclimate variables that are closely related to the incoming energy (\(T_{\text{air}}, \text{VPD}, T_{\text{soil}}\)) and principally their maxima and IQRs (Table 2). During the observed 3 yr, only a slight realignment was observed. In the first year after the cuttings (2015), the IQR and maximum of \(T_{\text{soil}}\) was the most important variable, while in the next two growing seasons, the highest \(F\) values were related to the maximum and IQR of \(T_{\text{air}}\). SWC can be described as an important variable for separation only in the third growing season (2017).

**DISCUSSION**

**General treatment effects**

As it was presumed, we could demonstrate strong and consistent treatment effects in the case of the measured microclimate variables in the first 3 yr after the silvicultural interventions. Because all tree individuals were removed during clear-cutting, the most drastic increase of incoming light, and consequently, the mean air and soil temperature, vapor pressure deficit, and especially their variability were the highest in clear-cuts. Similarly, the extrema of the variables were the most pronounced following clear-cutting. Soil water content increased significantly compared to the control levels. A limited, but considerable moderating effect was detected in the retention tree groups: although the means of \(dT_{\text{air}}, d\text{RH}, d\text{VPD}, \text{and } dT_{\text{soil}}\) were similar to that in the clear-cuts, IQRs were ameliorated by these small patches of standing trees. Gap-cutting could provide on the one hand an increased level of \(d\text{PAR}\) and \(d\text{SWC}\), but on the other hand artificial gaps of the size of the average tree height.
could maintain a buffered, cool, and humid environment. As with gap-cutting, preparation cutting could notably preserve the closed forest conditions, without the increase of dSWC levels.

Light variables differed the most from the control levels because the applied treatments modified the canopy closure and the spatial arrangement of the remained tree individuals first and foremost (Chen et al. 1999, Heithecker and Halpern 2006, Grayson et al. 2012, Tinya et al. 2019). Incoming radiation was the highest and the most variable in the clear-cuts where all tree individuals were harvested. Gap-cutting also created a brighter environment but PAR was significantly lower than it was in the clear-cuts because of the smaller sky view factor (Carlson and Groot 1997, Ritter et al. 2005, Kelemen et al. 2012). Insolation was lower and similar to each other in the preparation cuttings and retention tree groups, although both were significantly more illuminated than the uncut control plots in the surveyed years. Our results from the preparation cuts are similar to moderate thinning and partial harvesting due to the comparable harvesting processes (Weng et al. 2007, Grayson et al. 2012).

Air variables are primarily coupled to the incoming solar radiation. As clear-cutting created the most open environment within this experimental framework, air temperature and vapor pressure deficit were the highest, while air humidity was the lowest in this treatment. Many studies reported substantial departures in these variables (e.g., Liechty et al. 1992, Keenan and Kimmings 1993, Chen et al. 1999, Davies-Colley et al. 2000), our observations are the most similar to the findings of Carlson and Groot (1997) and von Arx et al. (2012) who reported < 1°C increase of $T_{air}$ and < 5% decrease of RH averaged to the whole growing season. However, the measured departures can be significantly higher in the fully leaved period (Kovács et al. 2018). Effect sizes induced by the applied silvicultural treatments presumably depend on the macroclimate (especially temperature and precipitation), topography, site conditions (e.g., soil moisture) and stand type (mainly tree species composition and structural heterogeneity; Aussenac 2000; von Arx et al. 2013, Ashcroft and Gollan 2013, De Frenne et al. 2015). Nevertheless, in the case of air temperature, we found similar order of magnitude of temperature offset in various European forest stands reported by Zellweger et al. (2019).

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

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

Regarding soil temperature variables, the increased solar irradiance had an even more explicit effect than could maintain a buffered, cool, and humid environment. As with gap-cutting, preparation cutting could notably preserve the closed forest conditions, without the increase of dSWC levels.

| Variable          | 2014 F(4,25) | P         | 2015 F(4,25) | P         | 2016 F(4,25) | P         | 2017 F(4,25) | 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   |
| $T_{soil}$ 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    |
| VPD mean          | 0.073       | 0.8986    | 0.208       | 0.9314    | 10.650      | <0.0001   | 3.092       | 0.0338    |
| VPD min           | 0.089       | 0.9851    | 1.321       | 0.2896    | 4.648       | 0.0061    | 6.066       | 0.0015    |
| VPD max           | 0.021       | 0.9991    | 0.098       | 0.9821    | 0.839       | 0.5138    | 1.009       | 0.4214    |
| VPD IQR           | 0.081       | 0.8976    | 8.826       | <0.0001   | 13.071      | <0.0001   | 14.404      | <0.0001   |
| $T_{soil}$ mean   | 0.069       | 0.9907    | 3.722       | 0.0165    | 15.092      | <0.0001   | 6.123       | 0.0014    |
| $T_{soil}$ min    | 1.209       | 0.3317    | 14.200      | <0.0001   | 10.314      | <0.0001   | 4.468       | 0.0073    |
| $T_{soil}$ max    | 0.876       | 0.4923    | 4.721       | 0.0056    | 6.999       | 0.0006    | 8.241       | 0.0002    |
| $T_{soil}$ IQR    | 1.746       | 0.1716    | 26.847      | <0.0001   | 19.651      | <0.0001   | 10.204      | <0.0001   |
| SWC mean          | 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   |

Notes: Variables are $T_{air}$, air temperature; RH, relative humidity; VPD, vapor pressure deficit; $T_{soil}$, soil temperature; and SWC, soil moisture. The most important six variables based on the F values of the Wilks test in a given year are shown in boldface type.
was present for air temperature values, which concurs with previous studies (Carlson and Groot 1997, Rambo and North 2009, von Arx et al. 2013). Thus, for example retention tree group could moderate the extrema of $T_{soil}$ better than $T_{air}$ due to the shading provided by remained overstory (Heithecker and Halpern 2006). The lowest and most stable $T_{soil}$ was present in the gap-cuts due to the shading effect of the neighboring trees and the evaporative cooling of the moisture content of the topsoil (Gray et al. 2002, von Arx et al. 2013). Moreover, opposing previous studies (e.g., Arx, Ritter et al. 2005, Abd Latif and Blackburn 2010), soil temperature remained similar to the values of the uncut control.

In contrary to our expectations, the most significant increase in soil moisture was observable in gap-cuts, while clear-cuttings caused significant but smaller increment in SWC. Changes in soil moisture following the different treatments are typically based on the changes in elements of the hydrological routine: the lower is the rate of interception and canopy evaporation, the more increased the throughfall is and the more decreased the transpiration is (Wood et al. 2007, Muscolo et al. 2014, Good et al. 2015). Because of the great relative importance of transpiration, a higher increase in soil moisture was presumed after clear-cutting than gap-cutting (Good et al. 2015). The experienced smaller increase of SWC in the clear-cuts can be explained by the high evaporation rates, the drying effects of the air-mixing due to the higher wind exposure (Keenan and Kimmins 1993, Geiger et al. 1995, Bonan 2016). The effects of these processes were presumably enhanced by the increasing transpiration rates of the rapidly developing herb layer dominated by annual weeds (e.g., Conyza canadensis (L.) Cronquist and Erigeron annuus (L.) Pers) and later, tall perennials (e.g., Calamagrostis epigeios (L.) Roth and Solidago gigantea Aiton) (Tinya et al. 2019). We also found that in the retention tree groups, despite the significantly higher VPD, the enhanced heat load and the transpiration of remnant tree individuals, soil water content was only slightly lower than in the uncut plots.

*Temporal changes following forestry treatments*

According to our expectations, microclimate variables changed immediately after the interventions and differed from the homogeneous conditions created by the closed canopy. In our previous work describing the microclimate of the treatments 1 yr after the interventions, we revealed the seasonal pattern of microclimatic variables (Kovács et al. 2018). The highest treatment effect was detected in the peak of the growing season due to the buffering effect of the closed canopy, which was in agreement with other studies (e.g., Clinton 2003, Ma et al. 2010, von Arx et al. 2012). In this study, we focused on the effects of the years only, however, the seasonality effect is unambiguous not just in the first growing season but also in the second and third years (Appendix S1: Fig. S4).

The effects of forest management on microclimate variables could have various temporal dynamics. The long-term treatment effects on forest microclimate were demonstrated for clear-cutting in different forest types typically based on chronosequence studies. For example, in northern hardwood forests, Dočiak and Brown (2014) stressed that all microclimate variables differed from forest interior in 5-yr-old regeneration stands, while daily temperature minimum remained disparate for 15 yr. Baker et al. (2014) demonstrated differences in the means and variability of air temperature, relative humidity and VPD between various aged regenerating clear-felled areas (7, 27 and 47 yr since clear-cutting) and mature stands in Tasmania. In general, they found that differences from mature stands in daily means can last up to 27 yr while diurnal variances recover in 7 yr. On the contrary, the microclimatic changes in both natural and artificial gaps are rather short-term comparing the effects of rotation forestry. The recovery of light climate has typically exponential relationship with time since gap-creation (Domke et al. 2007). Previous studies reported that approximately in the first 3 yr, there are no significant changes in the center of the gaps but there is an observable lateral growth that decreases insolation near the edges (Ritter et al. 2005, Kelemen et al. 2012). It was found that in gaps created by group selection, light regime became similar to the uncut mature stand in 13 yr (Beaudet et al. 2004). Lewandowski et al. (2015) found differences in soil temperature between gaps and uncut control that lasted 7 yr. However, single-tree and group selections in mixed oak-pine forests did not show a temporal trend in the recovery of air and soil temperature and relative humidity based on the analyzed 1–13 yr chronosequence (Brooks and Kyker-Snowman 2008).

Based on our models, we can conclude that the effects of treatment on microclimate variables were stronger than the effect of time, differences from control among the treatment levels were consistent throughout the first 3 yr. Our results did not show a continuously fading trend of the vast majority of the microclimate variables, not even in gap-cuts or preparation cuts suggested by previous studies (e.g., Gray et al. 2002 or Ritter et al. 2005). The time-span of the microclimatic regeneration strongly depends on species composition, forest structure and site conditions (Renaud et al. 2011, Ashcroft and Gollan 2013, Petritan et al. 2013, Lu et al. 2015). A substantial aspect of the temporal changes is the species-specific response of trees since differences in leaf morphology and leaf area, canopy structure and crown plasticity can lead to diverging light transmittance and lateral branch infilling of canopy gaps (Runkle 1998, McCarthy 2001, Pretzsch 2014). This is relevant if we compare the more frequently studied European beech and the usually understudied sessile oak, the dominant tree species of this experiment. Sessile oak individuals often have smaller canopies, lower crown plasticity and usually respond slower to the available space due to gap
openings compared to European beech (Petritan et al. 2013). These attributes might lead to a slower fall off in altered site conditions than it can be observed in, for example, beech-dominated stands. Certainly, the observed three growing seasons are just a fraction of the required time span typically reported (e.g., Liechty et al. 1992, Baker et al. 2014, Dovcěa and Brown 2014). Similarly to the results of Liechty et al. (1992), we did not have an unambiguous trend in the values of most variables but have between-year distinctions instead during the first few years of the study. We found enhanced differences from control in several cases comparing the first post-treatment year and the subsequent growing seasons, but there are some variables for which the recovery process was detectable. Zheng et al. (2000) also stated that the alterations following the harvests are variable-dependent but in this experiment, we could demonstrate the treatment specificity as well.

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

However, continuous decrease was found in the case of light variability of retention tree groups and partial cuts where 3 yr may be sufficient for significant regeneration of the branch structure of the remained overstory trees. Additionally, in the first post-harvest year, retention tree groups were more exposed to the lateral sunlight penetration, which was somewhat moderated throughout the following years by the emergence of the epicormic shoots. However, similarly to the mean of the incoming radiation, \( dP \text{AR}_{IQR} \) values are still significantly higher than in the uncut control. The most noticeable hypothesized decrease in the differences over time were present in the case of soil temperature. In the clear-cuts, both the mean, IQR, and maximum of the soil temperature seem to start converging continuously to the levels of control. Moreover, this trend was also detected for \( dT_{\text{soil IQR}} \) in the retention tree groups and for maxima in the gap- and preparation cuts. The recovery is presumably based on the natural regeneration of the herb and shrub layer that were considerably different among the treatments (Tinya et al. 2019). Before the treatments, understory vegetation was scarce and quasi-homogeneous. In the first year, the cover and mean height were similar in the treatments and evolved distinctly after the cuttings. The highest vegetation with the greatest total cover was present in the most illuminated treatments, i.e. the clear-cuts and gaps. Understory vegetation absorbs a considerable amount of incoming radiation, thus, lowers the surface temperature during daytime and it blocks the long-wave radiative loss in the night ameliorating the cooling (Ritter et al. 2005, Brooks and Kyker-Snowman 2008). This insulating effect was stressed primarily for bryophytes in boreal forests (Bonan 1991, Nilsson and Wardle 2005), but it was also proved for understory herbs like Calamagrostis canadensis (Michx.) Beauv. (Matsushima and Chang 2007). Interestingly, we could capture the insulating effects of tree canopies in the case of minimum soil temperature. We presume that the cooling of the topsoil due to the radiative loss might be less pronounced under the remained individuals in the overstory layer of the retention tree groups and preparation cuts than in the gap-cuts or in the clear-cuts where the sky view factor is higher (Carlson and Groot 1997, Blennow 1998).

Based on previous studies, the recovery of soil moisture was typically reported as a more rapid process: it was less than 5 yr in clear-cuts (Adams et al. 1991), in thinned stands (Aussenac and Granier 1988) as well as in gaps (Gray et al. 2002, Ritter et al. 2005, Lewandowski et al. 2015). Immediately after the felling, a transitory increase of soil water content is present but as the vegetation is emerging and regenerating, water balance returns to the pretreatment level due to the enhanced transpiration by natural regeneration. This process is necessarily faster in stands where partial cutting or gap-cutting was applied because of the improved lateral growth of bordering branches, enhanced crown expansion and increased root extraction from the adjacent closed stands towards the small openings. Additionally, recovery of soil microclimate in gaps can be faster in broadleaved stands than in forests dominated by coniferous species (Lindo and Visser 2003). However, we found an opposing response: the clear- and gap-cutting were followed by a steady increase in the departures from the uncut control level despite the regenerating herb layer. Liechty et al. (1992) reported similar processes when they examined the recovery of soil moisture content in 5-yr-old clear-cuts created in temperate hardwood forests. As Davis et al. (2018) and Liechty et al. (1992) underlined, most studies focusing on the temporal changes of the microclimate variables in woodlands or the buffering capacity of forest canopies are often based on data sets from short-term (typically 1–3 yr) investigations. Considering that the processes may be under the way, we continue the systematic measurements (applying the same protocol) in the framework of this long-term experiment to follow up the microclimatic recovery.

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

Besides analyzing the treatment effects on microclimatic variables, we aimed to identify those variables that account for the possible changes in the local environment after the interventions. We presumed that, by unfolding the effects of treatments, we could get a more complete picture about the microclimatic processes in treated forest sites, thus, better conservational implications could emerge (De Frenne et al. 2013).

As in the case of the temporal analyses, after a more or less homogeneous pretreatment state, the greatest
separation was expected in the first post-treatment year (2015), because the highest treatment effect could be presumed right after the interventions when modified canopy closure is the most explicit and the effects of the regeneration of the understory as well as lateral growth of the canopy are negligible, which could influence both thermal (shading and insulating) and humidity conditions (via transpiration). This initial phase should be followed by a homogenization as the sites recover, the natural regeneration develops, and the canopy closure evolves. However, the greatest separation was observed in the second year after the harvests. We detected two different phenomena according to the observational years: (1) the greatest overall separation in 2016 was congruent with the greatest divergence between the uncut control and clear-cutting, while the other treatments pooled and overlapped; (2) in the adjoining two years, between-group separation was more pronounced and even. These could be attributed to the masking effect of the extremely modified environment followed by the clear-cutting.

We found that the applied treatments separated among the temperature \((T_{\text{air}}\) and \(T_{\text{soil}}\)) and VPD maxima and their interquartile ranges and the roles of the individual variables in the treatment effect were more or less consistent throughout the years. As it was presumed, soil temperature was the most important determinant in the first year after the interventions, but in the following years, the relative importance of air temperature increased. Surprisingly, soil moisture became a significant determinant only in the third year, in spite of the rather strong treatment effect, especially in the gap-cuts and clear-cuts.

With the performed multivariate analyses, we can also demonstrate the reduced buffering ability of the forest canopy and stand structure as a frequently stressed consequence of forest management (Chen et al. 1999, Heithecker and Halpern 2006, De Frenne et al. 2013, Ewers and Banks-Leite 2013, Hardwick et al. 2015). The microclimatic buffering capacity of the canopy and, even pronouncedly, variables related to forest structure are typically more noticeable regarding the thermal maxima and the minima than the means (Liechty et al. 1992, Vanwallegeh and Meentemeyer 2009, Ewers and Banks-Leite 2013, Frey et al. 2016, De Frenne et al. 2019). In closed stands with different structural complexity, Frey et al. (2016) found that maximum temperatures in old-growth stands could be more ameliorated than minimum values (-2.5°C and + 0.7°C, respectively). Greiser et al. (2018) observed comparable differences in the effect size of the summer temperature extremes in central Sweden; the detected maximum temperatures decreased by 12°C, while minima increased by 4°C. In congruence with these, paired (forest–non-forest) studies reported similar trends: larger differences in temperature maxima than in minima as well as in VPDmax than in VPDmin extremes (e.g., Chen and Franklin 1997, Vanwallegeh and Meentemeyer 2009, Renaud et al. 2011, von Arx et al. 2013, Davis et al. 2018). Based on our results and in line with the literature compiled, it can be stated that forest canopy performs its buffering capacity more on the maxima than on the minima of microclimatic variables. We can suppose that through the reflectance and absorption of shortwave radiation within the active layer of the canopy and through the shading of the understory is more effective than the capturing and reflectance of longwave radiation from the soil.

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

**Conclusions and Perspectives**

Based on the measurements performed in the first 3 yr after the forestry treatments, we can conclude that (1) the effect sizes among treatment levels were consistent throughout the first 3 yr, (2) the climatic recovery time for variables appears to be far more than 3 yr, except for soil temperature, in all treatments, and (3) the applied silvicultural methods diverged mainly among the temperature maxima. The most drastic changes were observed in clear-cuts where retention tree groups could have only a limited buffering effect (on the variability and extrema, though not on the mean). However, a relatively large gap size (one tree height/gap diameter ratio) could provide a reasonably stable and humid but more illuminated environment. Preparation cutting changed the forest environment only to a lesser degree.

Our results suggest that, in mesic broad-leaved forests, forestry treatments induce long-lasting changes in microclimate near the ground that substantially alters the environmental conditions. These changes may cause the promptly occurring alterations in communities of the forest-dwelling species, which were shown for different taxa in the framework of this experiment, especially in the case of organisms groups with limited movement ability (Elek et al. 2018, Boros et al. 2019, Tinya et al. 2019). Due to the high probability of extreme thermal events, clear-cutting enhances frost damage and heat stress as well as higher exposure to drought, causing local extinctions and significant compositional shifts. Moreover, from a broader prospect, management types causing considerable canopy openness on large areas, independently of the characteristics (i.e., aggregated or dispersed), may precipitate the effects of climate change in forested landscapes.

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

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