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

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Abstract

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 of 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 keep 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 three years. Though 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 (i) the effect sizes among treatment levels were consistent throughout the years; (ii) the climatic recovery time for variables appears to be far more than three years and (iii) 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.

Keywords: 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 both 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). The better understanding of microclimate can contribute to the adjustment of climate and species distribution models. It has been revealed since decades 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 modelling 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 (Suggitt et al. 2011, Scherrer 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 besides 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 modelling (De Frenne and Verheyen 2016, Bramer 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 these characteristics in open-field. This special buffered environment was proved to be an essential driver of biodiversity as well as numerous biogeochemical processes and ecosystem functionality (Lewandowski et al. 2015, Good 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 (Košulič et al. 2016, Seibold et al. 2016) and also the survival and population density of forest-inhabiting birds (Betts et al. 2018).

The 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 which are considerably different from those in forests (Chen et al. 1999, Bonan 2016). It is an important conservational aspect to study how these management types induced alterations 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 pre-treatment levels (Matlack 1993, Dodonov et al. 2013, Dovčiak and Brown 2014, Baker et al. 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.

Beside 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 the 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” (https://piliskiserlet.okologia.mta.hu/en) 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: (i) to what extent do the treatments modify the studied microclimatic variables; (ii) do these variables change in time during the first three growing seasons in the different treatments; (iii) which are the most determinant microclimatic variables in the separation of the treatments?

We hypothesized that (i) clear-cutting has the most drastic effects on all variables resulting in the highest differences from control; retention tree group can moderately compensate 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 (ii) 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 (iii) 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. 1.a) 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) (Dövényi 2010). The bedrock consists of limestone and sandstone with loess (Dövényi 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 sized homogeneous unit of managed, 80 years 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 (Figure 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 within 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 sized (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 4-channeled Onset ‘HOBO H021-002′ data loggers (Onset Computer Corporation, Bourne, MA, USA). In the studied years (2014–2017), every month of the growing season (March–October), 72 hr logging periods were applied with 10 min 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 (T_{air}; °C) and relative humidity (RH, %) data were collected 130 cm above ground level with Onset 'S-THB-M002′ sensors (Onset Computer Corporation, Bourne, MA, USA) housed in standard radiation shields against direct sunlight. Soil temperature (T_{soil}; °C) was measured with 'S-TMB-M002′ sensors (Onset Computer Corporation, Bourne, MA, USA) placed 2 cm below ground. Soil water content (SWC; m^3/m^3) data were collected using Onset 'S-SMD-M005′ soil moisture sensors (Onset Computer Corporation, Bourne, MA, USA) 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 (Stewart-Oaten et al. 1986): the measurement of all variables started in 2014 (pre-treatment 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 dataset 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, T_{air}, RH, VPD, T_{soil}, 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 6.00 and 18.00 (local time) were analyzed, and the daily minimum and maximum values were excluded from the modelling. 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 (R^2_{LR}; Bartoń 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 pre-treatment 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 datasets (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 T_{air}, RH, VPD, T_{soil} 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 *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 38−88%. This approach enabled to explain the highest proportion of the total variance of a given microclimate variable throughout a growing season. During the four years of data collection the database contained 4.89% of missing values ranging 0%−20% between the months. For incomplete microclimate datasets, the iterative PCA method (Ipca) 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 9999 permutations. The separability power of the microclimate variables among treatment levels were 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). Add-on package ‘nlme’ was applied for the linear mixed effects models (Pinheiro et al. 2017), ‘lsmeans’ for multiple comparisons (Lenth 2016), and ‘MuMIn’ package for pseudo-R^2 values (Bartoń 2016). PCAs were obtained by ‘vegan’ (Oksanen et al. 2018), Ipca procedures by ‘missMDA’ (Josse and Husson 2016), and LDAs by ‘MASS’ (Venables et al. 2002) packages.

Results

General treatment effects

The pre-treatment 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_{air}) and soil moisture (*d*SWC) due to the heterogeneity of the site conditions (Fig. 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 (Fig. 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 (*d*PAR), *d*SWC and the interquartile range of dT_{air}, air humidity (*d*RH) and soil temperature (dT_{soil}) (Table 1).

The most illuminated environment was created by clear-cutting (Fig. 2. a) with the highest daily range and (Fig.2. b). Similarly, substantial increment but lower incoming radiation was present in the gap-cuts (Fig.2. a). 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_{air} was the highest in the clear-cuts (mean ≈ 0.3°C and IQR > 1°C; Fig. 3. a and b), moreover, this was the only treatment where both minima and maxima were significantly different from the other treatments (Fig. 3. c and d). The mean dT_{air} was buffered the most in the preparation cuts and gap-cuts (Fig. 3. a). The variability of dT_{air} was reduced most effectively in the gap-cuts and preparation cuts, however, the latter could buffer the maxima more effectively (Fig. 3. b–d). The changes in mean dT_{air} in the retention tree groups were similar to the clear-cut levels but IQRs and extrema were significantly reduced.

*d*RH means were the lowest in the retention tree groups and clear-cuts (Fig. 3. e). but in clear-cuts it had higher variability and higher maximum values (Fig. 3. f–h). In the preparation cuts and gap-cuts, the humidity remained similar to the control levels with the lowest variability (Fig. 3. e, f). The mean of the vapor pressure deficit (*d*VPD) showed a similar pattern as dT_{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_{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 uncut control (Fig.4. a–d). The highest dT_{soil} was measured in the clear-cuts and retention tree groups (approx. 1°C; Fig. 4. a), however, the latter treatment type induced less variable temperature (Fig. 4. b). The coolest soil environment with the lowest IQR was detected in the gap-cuts. dT_{soil} minima were significantly lower in gap- and clear-cuts than in preparation cuts and retention tree groups (Fig. 4. c).

The highest soil moisture was detected in gap-cuts (Fig. 4. e). *d*SWC 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 were relatively similar throughout the sampled growing seasons, however, significant year effects were also discovered in many cases (Table 1, Fig. 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_{air}, or *d*RH variables in most of the treatments Fig. 3.). However, the differences became more pronounced in the case of dT_{air} minima (Fig. 3. a). We found that light variables decreased in preparation cuts and retention tree groups during the three years, 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_{soil} mean, IQR and maxima, mainly in case of clear-cuts and retention tree groups (Fig. 4. a, b, d), while minima had a unimodal response (Fig. 4. c). Departures in *d*SWC enhanced over time in gap-cuts and clear-cuts (Fig. 4. e).

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 pattern before the treatments (F = 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. 5. a). The strongest separation could be detected in 2016 (F = 4.342, $P < 0.0001$), with 79.4% and 10.9% of explained variance by LD1 and LD2, respectively (Fig. 5. c). Separability power of the LDAs were high in 2015 (Fig. 5. b) and 2017 (Fig. 5.d) as well (F = 2.311, $P < 0.0001$ and F = 3.479, $P < 0.0001$, respectively). However, while separation of control and clear-cutting was more pronounced and the other three groups overlapped in 2016 (Fig. 5. c), all treatment types showed higher separation in 2015 and 2017 (Fig. 5. b and 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_{air}, VPD, T_{soil}) and principally their maxima and IQRs (Table 2). During the observed three years, only a slight realignment was observed. In the first year after the cuttings (2015), the IQR and maximum of T_{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_{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 three years 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 $d\mathrm{T}_{\mathrm{air}}$, *d*RH, *d*VPD and $d\mathrm{T}_{\mathrm{soil}}$ 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*PAR and *d*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 *d*SWC 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 detected 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 Kimmins 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 (tree species composition and structural heterogeneity mainly) (Aussenac 2000; von Arx et al. 2013; Ashcroft and Gollan, 2013; De Frenne et al. 2019). 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 Latid 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 it was present for air temperature values which concurs 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., 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-cuttings, 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 one year 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-cuts in different forest types typically based on chronosequence studies. For example, in northern hardwood forests, Dovčiak and Brown (2014) stressed that all microclimate variables differed from forest interior in five years old regeneration stands, while daily temperature minimum remained disparate for 15 years. 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 years 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 years while diurnal variances recover in 7 years. 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 three years, there is 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 years (Beaudet et al. 2004). Lewandowski and colleagues (2015) found differences in soil temperature between gaps and uncut control that lasted seven years. 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 yrs 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 three years. 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 (Aschroft and Gollan, 2013; Renaud et al. 2011; 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 falloff 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, Dovčiak and Brown 2014, Baker et al. 2014). Similarly to the results of Liechty and colleagues (1992), we did not have an unambiguous trend in the values of most variables but have between-years 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 minimum 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 three years 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, $d\mathrm{PAR}_{\mathrm{IQR}}$ 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 $d\mathrm{Tsoil}_{\mathrm{IQR}}$ 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 five years 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 pre-treatment 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 five-year-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 datasets from short term (typically 1–3 yrs) 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

Beside analyzing the treatment effects on microclimate variables, we aimed to identify those variables which are accountable 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 be emerged (De Frenne et al. 2013).

As in the case of the temporal analyses, after a more or less homogeneous pre-treatment 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 develop and the canopy closure evolve. However, the greatest separation was observed in the second year after the harvests. We detected two different phenomena according to the observational years: (i) 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; (ii) in the adjoining two years, the between-group separation was more pronounced and even. These could be addressed 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_{air} and T_{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, Ewers and Banks-Leite 2013, De Frenne et al. 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, Vanwalleghem 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 VPD_{max} than in VPD_{min} extremes (e.g., Chen and Franklin 1997, Vanwalleghem 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 three years after the forestry treatments, we can conclude that (i) the effect sizes among treatment levels were consistent throughout the first three years; (ii) the climatic recovery time for variables appears to be far more than three years – except for soil temperature – in all treatments and (iii) the applied silvicultural methods diverged mainly among the temperature maxima. The most drastic changes were observed in clear-cuts where retention tree groups could impinge 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 broadleaved 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, Tinya et al. 2019, Boros et al. 2019). Due to the high probability of extreme thermal events, clear-cutting enhances the frost damage, the heat stress as well as higher exposure of draught 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 broadleaved forests (like in this study, in oak–hornbeam stands), 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.

Acknowledgements

This research was funded by the Hungarian Scientific Research Fund (OTKA K111887), the National Research, Development and Innovation Fund of Hungary (GINOP-2.3.2-15-2016-00019, K128441), the Infrastructure Grant and the "Ecology for Society Project" of Hungarian Academy of Sciences (MTA KEP). B. K. was supported by the ÚNKP-17-3 New National Excellence Program of the Ministry of Human Capacities. F.T. was supported by the MTA Postdoctoral Fellowship Programme (PD-009/2017) and by the National Research, Development and Innovation Fund of Hungary (PD 123811).

The study site is legally protected; the experiment was approved by the Pest County Administration (permission number: KTF 30362-3/2014).

We are grateful for the cooperation and the joint efforts of the Pilisi Parkerdő Ltd., especially to Péter Csépányi, Viktor Farkas, Gábor Szenthe, and László Simon. The authors are thankful to Kristóf Kelemen for help in the database design and development and Beáta Biri-Kovács for editing the manuscript. Erika Guba played an essential role in the fieldwork in 2014–2015. We also thank the two anonymous Reviewers whose suggestions substantially improved the manuscript.

Author's contributions

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

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

Dependent variable	Model			Treatment		Year		Treatment:Year	
	Chi^2	*P*	R^2_{LR}	F	*P*	F	*P*	F	*P*
*d*PAR mean	363.0907	< 0.0001	0.489	**164.241**	< 0.0001	2.442	0.0880	1.683	0.1230
*d*PAR 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
*d*RH mean	85.8444	< 0.0001	0.385	**23.037**	< 0.0001	**6.058**	0.0025	1.681	0.1237
*d*RH IQR	173.6899	< 0.0001	0.289	**46.628**	< 0.0001	**26.824**	< 0.0001	1.441	0.1969
*d*RH min	137.6227	< 0.0001	0.348	**41.181**	< 0.0001	**11.305**	< 0.0001	1.362	0.2281
*d*RH max	35.9720	0.0002	0.261	**8.452**	< 0.0001	1.518	0.2203	1.334	0.2402
*d*VPD mean	85.1361	< 0.0001	0.267	**27.849**	< 0.0001	0.930	0.3951	0.854	0.5287
*d*VPD IQR	86.9652	< 0.0001	0.158	**24.073**	< 0.0001	**8.205**	0.0030	0.664	0.6788
*d*VPD min	23.2642	0.0162	0.192	**4.333**	0.0050	2.380	0.0936	0.914	0.4845
*d*VPD 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
*d*SWC mean	265.2427	< 0.0001	0.485	**103.042**	< 0.0001	**6.537**	0.0016	**2.337**	0.0309

Table 2. The results of linear discriminant analysis of variance performed for the individual growing seasons separately. Variables are coded as 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 typed in bold.

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**

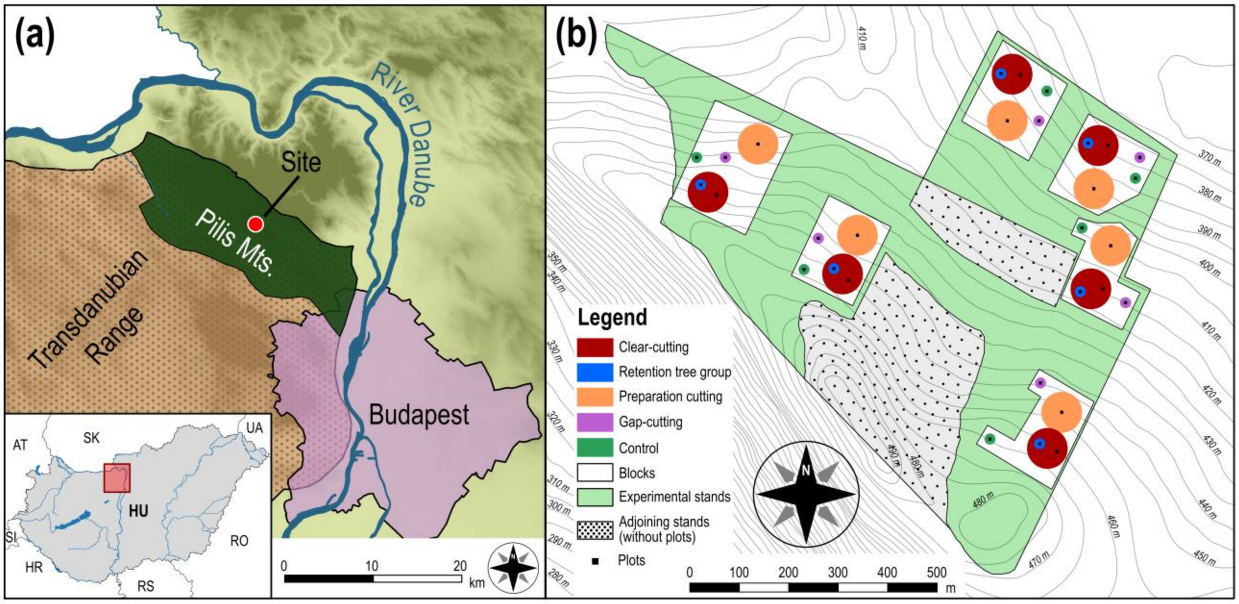

Figure 1. The study site of the "Pilis Forestry Systems Experiment" in Northern Hungary. (a) Site location (47°40′ N, 18°54′ E) in the Pilis Mountains (Transdanubian Range). (b) Experimental design showing the five treatments replicated within six blocks. Microclimate measurements were performed in the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

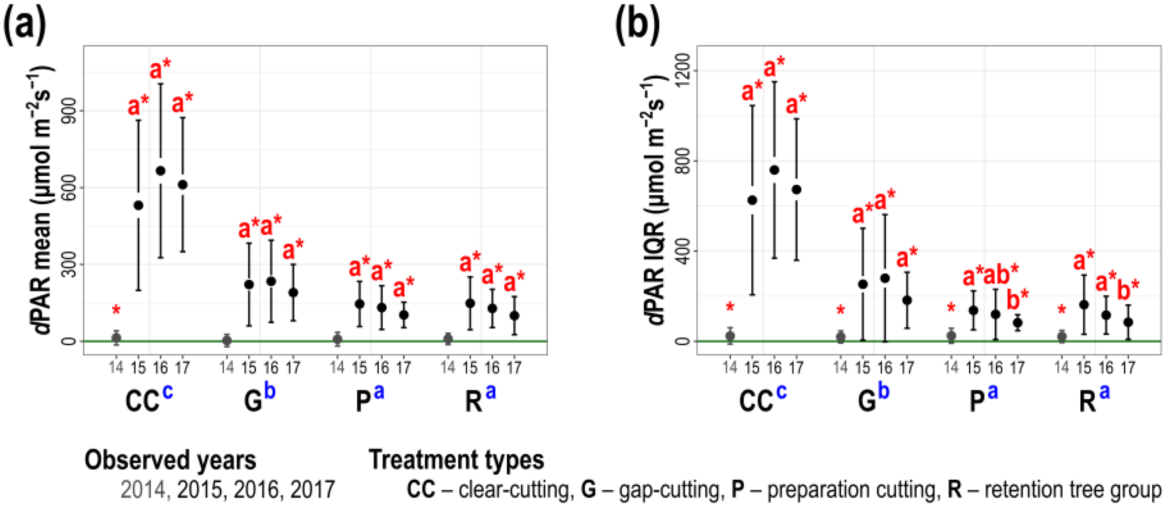

Figure 2. Means (a) and interquartile ranges (IQR, b) of the relative light (differences from the control; *d*PAR) among the applied silvicultural treatments throughout the observation years (2014–2017). The treatment types were CC – clear-cutting, G – gap-cutting, P – preparation cutting and R – retention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

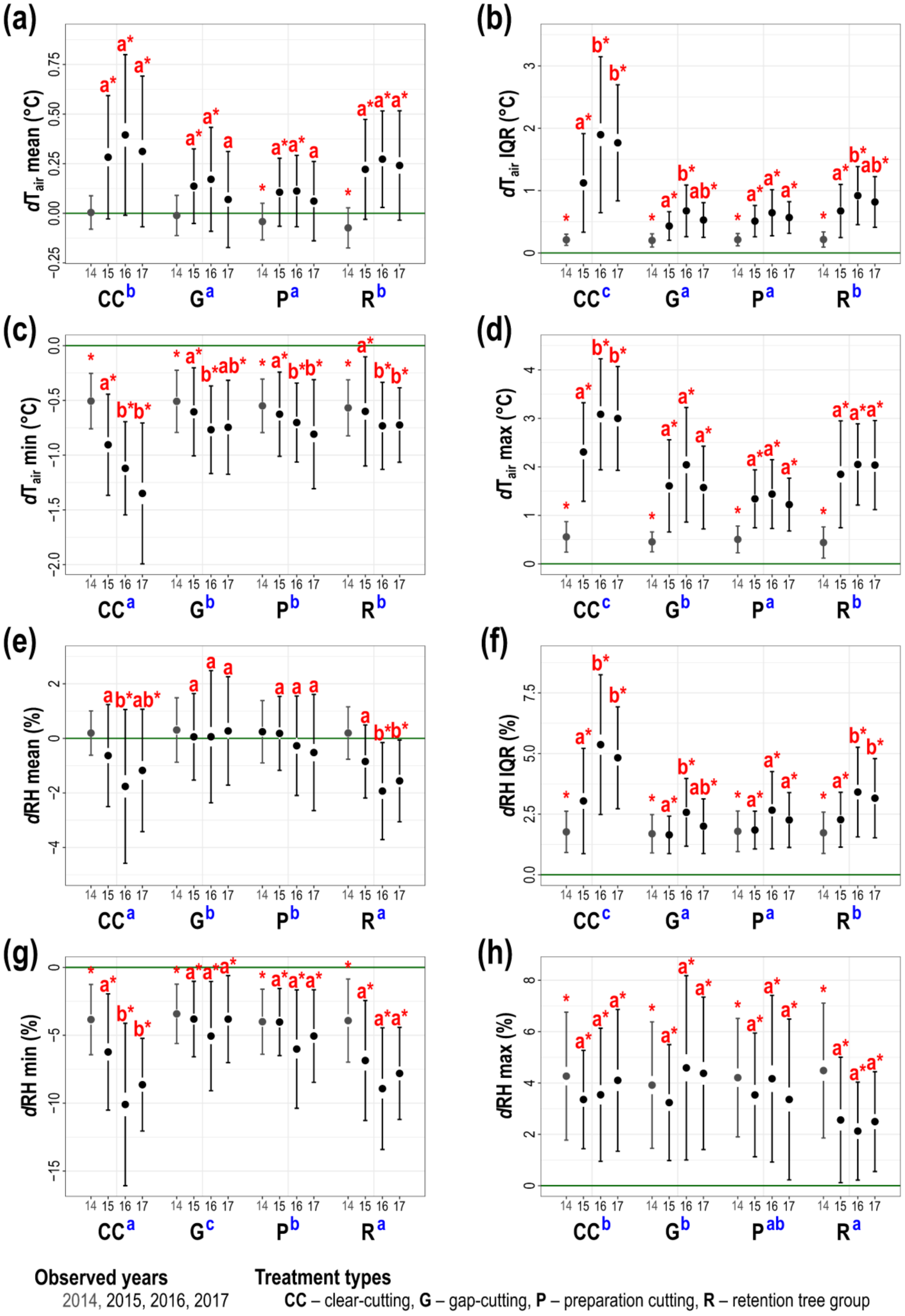
(a)
dTair mean (°C)
0.75
0.50
0.25
0.00
−0.25
a* a* a*
a* a* a
* a* a* a
* a* a* a*
14 15 16 17
CC b
G a
P a
R b
(b)
dTair IQR (°C)
3
2
1
0
* a* b* b*
* a* b* ab*
* a* a* a*
* a* b* ab*
14 15 16 17
CC c
G a
P a
R b
(c)
dTair min (°C)
0.0
−0.5
−1.0
−1.5
−2.0
* a* b* b*
* a* b* ab*
* a* b* b*
* a* b* b*
14 15 16 17
CC a
G b
P b
R b
(d)
dTair max (°C)
4
3
2
1
0
* a* b* b*
* a* a* a*
* a* a* a*
* a* a* a*
14 15 16 17
CC c
G b
P a
R b
(e)
dRH mean (%)
2
0
−2
−4
a b* ab*
a a a
a a a
a b* b*
14 15 16 17
CC a
G b
P b
R a
(f)
dRH IQR (%)
7.5
5.0
2.5
0.0
* a* b* b*
* a* b* ab*
* a* a* a*
* a* b* b*
14 15 16 17
CC c
G a
P a
R b
(g)
dRH min (%)
0
−5
−10
−15
* a* b* b*
* a* a* a*
* a* a* a*
* a* a* a*
14 15 16 17
CC a
G c
P b
R a
(h)
dRH max (%)
8
6
4
2
0
* a* a* a*
* a* a* a*
* a* a* a*
* a* a* a*
14 15 16 17
CC b
G b
P ab
R a
Observed years
2014, 2015, 2016, 2017
Treatment types
CC – clear-cutting, G – gap-cutting, P – preparation cutting, R – retention tree group

Figure 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). The treatment types were CC – clear-cutting, G – gap-cutting, P – preparation cutting and R – retention tree group. Full circles show the mean, vertical lines denote the standard deviation and white bands in between indicate standard error of the samples. Letters demonstrate the results of the pairwise multiple comparison (Tukey test, alpha = 0.05) based on the performed linear mixed effects models between treatments (related to the whole 2015–2017 period, blue letters) and between years (2015–2017) within treatment levels (red letters). Asterisks mark significant differences from the values measured at the control plots (linear mixed effects models without intercept, $P < 0.05$). The horizontal green lines demonstrate the 0-level of the control.

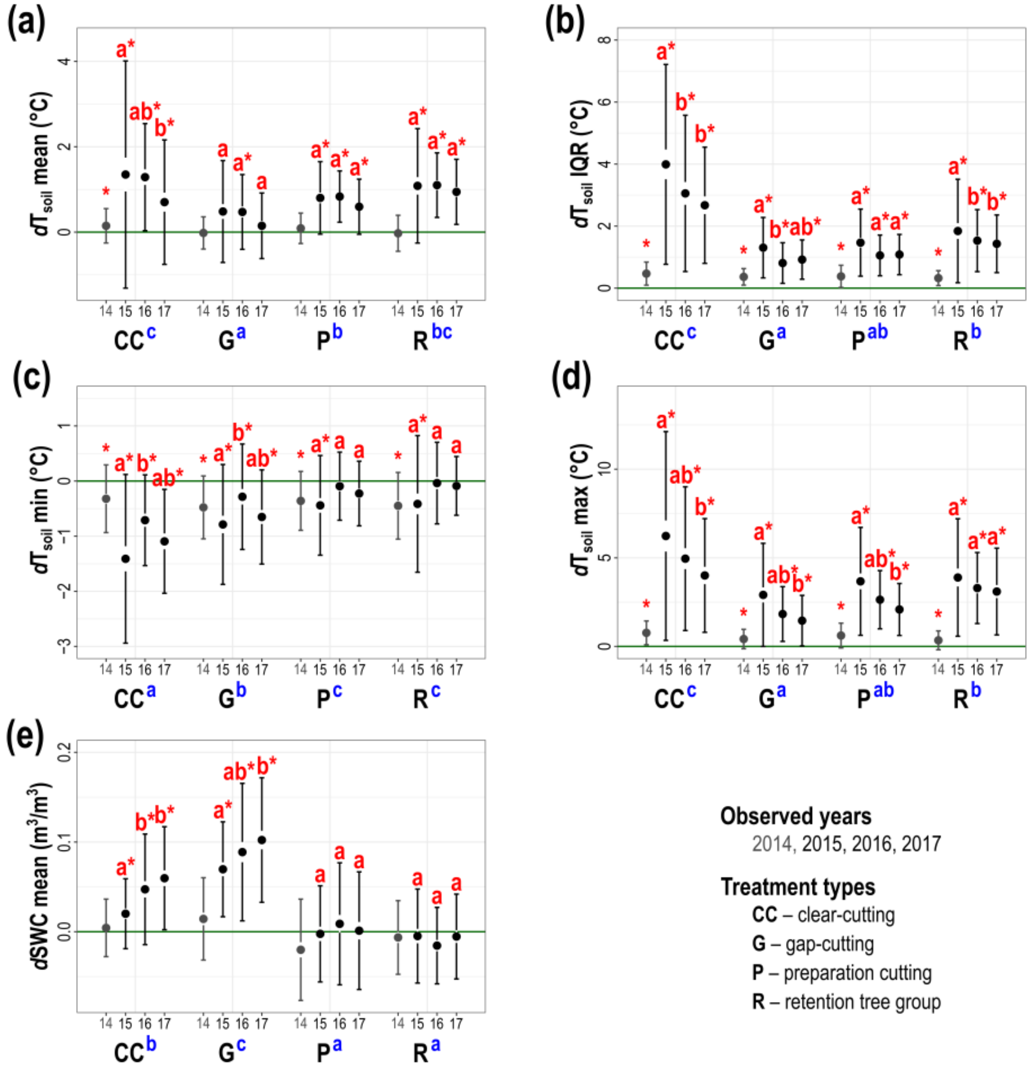

Figure 4. Means (a), interquartile ranges (IQR, b), minima (c) and maxima (d) of the relative values (differences from the control) of soil temperature (dT_{soil}) and (e) means of soil moisture (*d*SWC) among the applied silvicultural treatments throughout the observation years (2014–2017). The treatment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

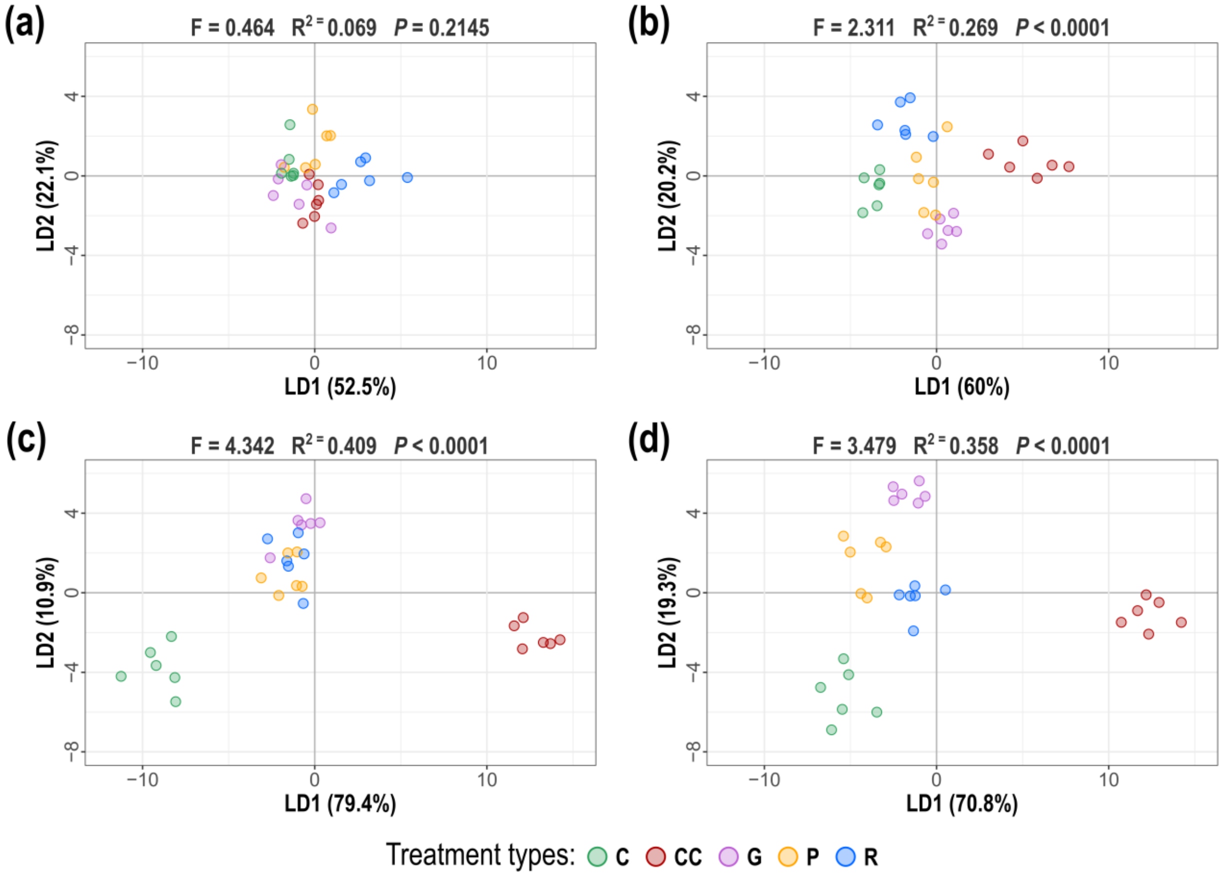

Figure 5. Ordination plots of the four treatment types and the control according to the linear discriminant analyses (LDA). LDAs were performed for the individual years separately: (a) 2014; (b) 2015; (c) 2016 and (d) 2017. Explained variance of the canonical axes (LD1 and LD2) are shown. Beside the results of the LDAs, the F-, pseudo-R^2- and p-values of the PERMANOVAs are also indicated for the observed years separately. Treatment types are coded as CC – clear-cutting; G – gap-cutting; P – preparation cutting; R – retention tree group.

Supporting information to the manuscript

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

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List of Appendices

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

					Pre-treatment (2014)			Post-treatment (2015)		
Treatment	DBH		Height		Basal area		Canopy closure	Basal area		Canopy closure
	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
	±5.8	±3.8	±1.5	±3.5	±0.12	±0.10	±2.6	±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
	±5.7	±4.2	±1.6	±3.8	±6.47	±4.66	±3.6			±2.1
G	27.3	12.5	20.5	11.2	29.53	9.33	88.4	0.00	0.00	44.8
	±5.3	±2.8	±1.1	±2.9	±9.03	±4.51	±4.4			±10.4
P	27.2	10.9	21.2	10.0	28.07	8.03	89.4	19.67	0.00	70.2
	±5.3	±4.1	±1.4	±3.5	±2.10	±1.33	±4.4	±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
	±5.8	±3.4	±1.9	±3.9	±3.73	±2.35	±3.2	±3.73	±2.35	±9.2

Figure S1 The stand structure and canopy closure (fish-eye photos) of the different treatment types created in the framework of the 'Pilis Systems Experiment': control, clear-cutting, retention tree group, preparation cutting and gap-cutting. The established treatments represent common forestry practices belonging to the rotation forestry system (clear-cutting, retention tree group, preparation cutting), while the recently introduced selection or continuous cover forestry system was also studied via gap-cutting. The photographs were taken in the first year after the interventions (in 2015). Means of the estimated canopy closure are also shown here. Superscripts refer to significant differences among treatments (pairwise Tukey comparisons, alpha = 0.05), based on linear mixed effect model.

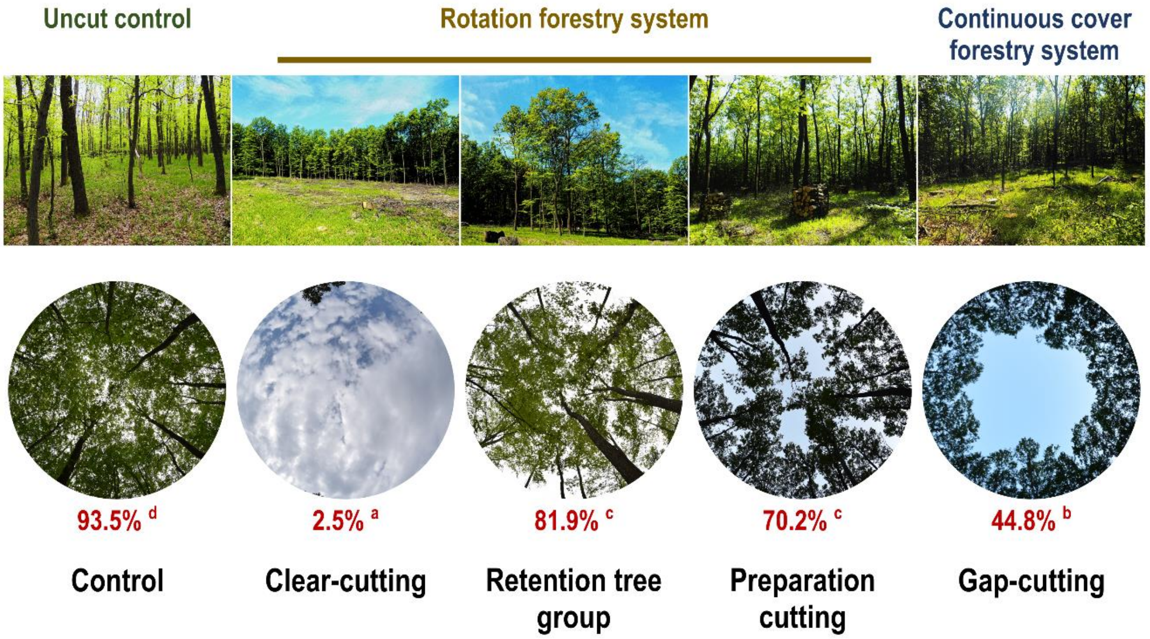
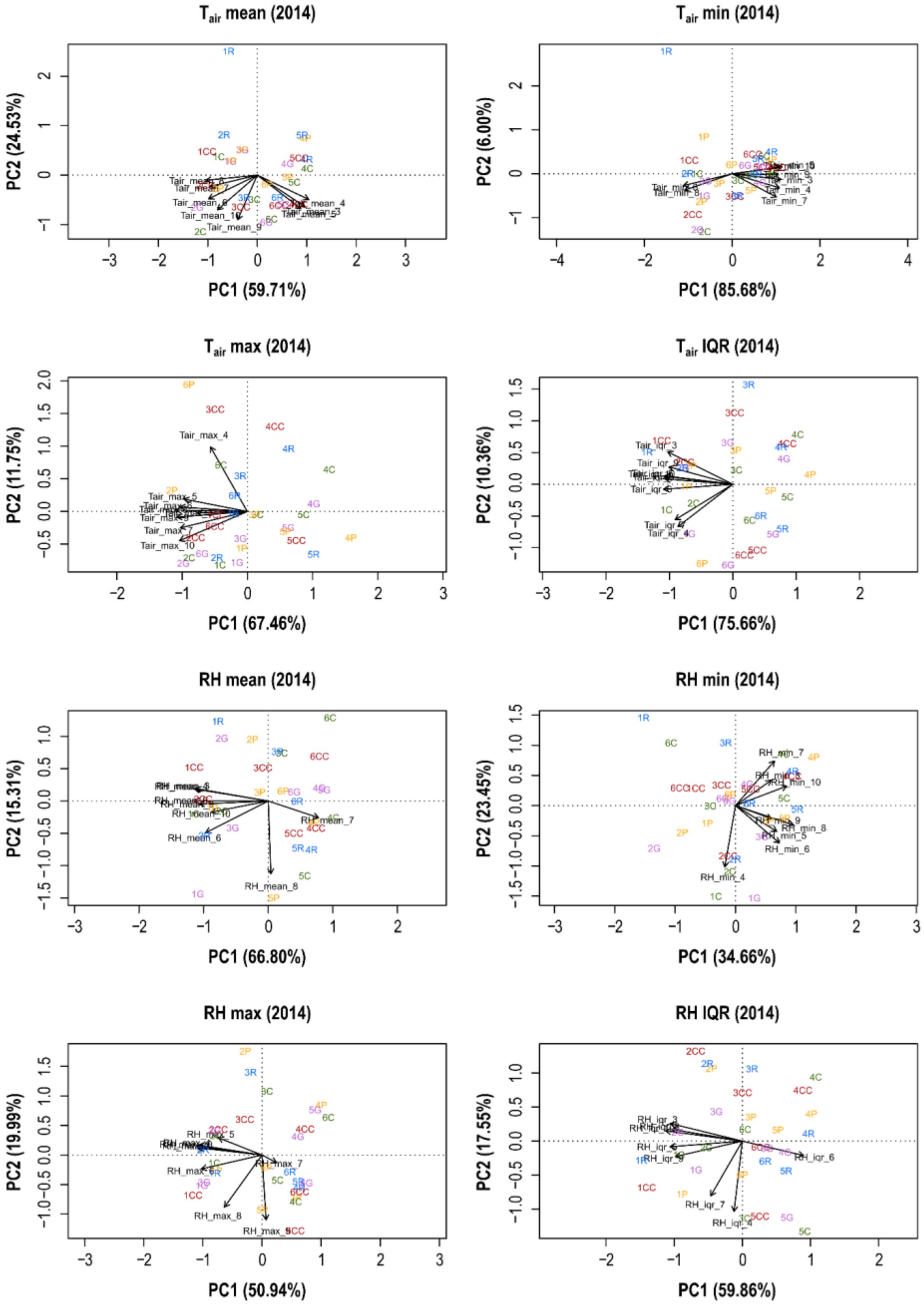
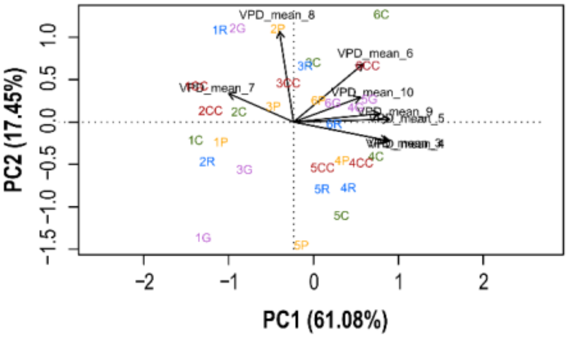


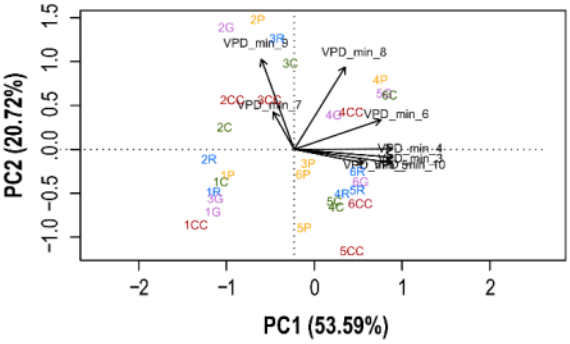
Table S2 Effect of treatments on microclimate, litter and soil variables in 2014 (pre-treatment year). The results of linear mixed effects models performed for relative values of the microclimate variables with the mean (± standard deviation) among the treatment levels in 2014. *d*PAR: photosynthetically active radiation; $d\mathrm{T}_{\mathrm{air}}$: air temperature; *d*RH: relative humidity; *d*VPD: vapor pressure deficit; $d\mathrm{T}_{\mathrm{soil}}$: soil temperature; *d*SWC: soil moisture. For modelling, 24-hour-means were used except in the case of PAR, where daytime (6:00-18:00 local time) means were calculated. Treatment was used as fixed while block as random factor. F and p values of the model statistics are presented. Superscripts refer to significant differences among treatments (pairwise Tukey comparisons, alpha = 0.05), treatment codes marked with bold indicates significant departures from control (alpha = 0.05).

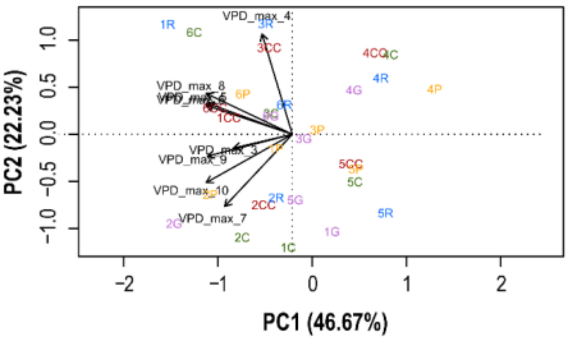
Dependent variable	F	p	Clear-cutting	Gap-cutting	Preparation cutting	Retention tree group
*d*PAR mean	2.217	0.0878	13.58 ± 27.64	3.09 ± 23.90	8.36 ± 26.72	9.22 ± 21.89
*d*PAR IQR	0.657	0.5794	23.94 ± 36.49	19.58 ± 26.72	24.63 ± 32.75	21.51 ± 26.93
$d\mathrm{T}_{\mathrm{air}}$ mean	**6.943**	**0.0002**	0.004 ± 0.084 ^{a}	-0.011 ± 0.101 ^{a}	-0.042 ± 0.093 ^{ab}	-0.074 ± 0.101 ^{b}
$d\mathrm{T}_{\mathrm{air}}$ IQR	0.234	0.8729	0.211 ± 0.090	0.201 ± 0.106	0.213 ± 0.099	0.216 ± 0.121
*d*RH mean	0.241	0.8677	0.194 ± 0.812	0.307 ± 1.181	0.243 ± 1.142	0.196 ± 0.961
*d*RH IQR	0.009	0.9608	1.770 ± 0.851	1.691 ± 0.791	1.793 ± 0.837	1.731 ± 0.853
*d*VPD mean	0.523	0.6671	-0.001 ± 0.018	-0.004 ± 0.024	-0.004 ± 0.022	-0.004 ± 0.021
*d*VPD IQR	0.078	0.9721	0.035 ± 0.023	0.033 ± 0.022	0.034 ± 0.021	0.035 ± 0.025
$d\mathrm{T}_{\mathrm{soil}}$ mean	2.529	0.0588	0.148 ± 0.402	-0.019 ± 0.377	0.089 ± 0.356	-0.027 ± 0.422
$d\mathrm{T}_{\mathrm{soil}}$ IQR	2.240	0.0852	0.467 ± 0.373	0.363 ± 0.266	0.379 ± 0.358	0.322 ± 0.240
*d*SWC mean	**7.404**	**0.0001**	0.004 ± 0.032 ^{ab}	0.014 ± 0.046 ^{b}	-0.02 ± 0.056 ^{c}	-0.006 ± 0.041 ^{ac}

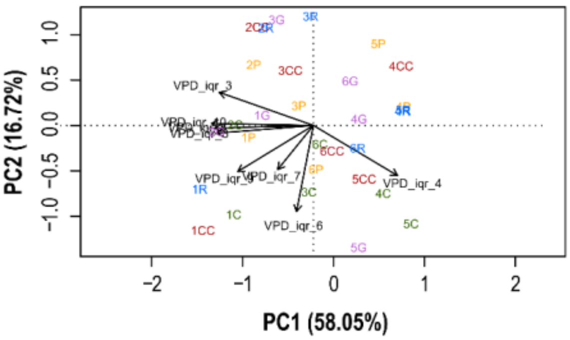
Figure S2 Correlation biplots based on the performed standardized principal component analysis for 20 microclimate variables (plot titles) analyzed by measurement years (in brackets) separately. Variables are abbreviated as PAR: photosynthetically active radiation (µmol $m^{-2}s^{-1}$) T_{air}: air temperature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

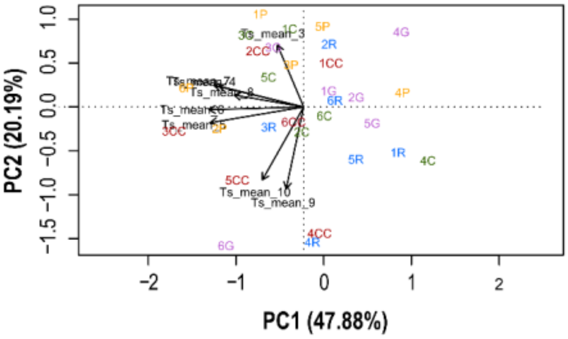

T_{air} mean (2014)
PC1 (59.71%)
PC2 (24.53%)
T_{air} min (2014)
PC1 (85.68%)
PC2 (6.00%)
T_{air} max (2014)
PC1 (67.46%)
PC2 (11.75%)
T_{air} IQR (2014)
PC1 (75.66%)
PC2 (10.36%)
RH mean (2014)
PC1 (66.80%)
PC2 (15.31%)
RH min (2014)
PC1 (34.66%)
PC2 (23.45%)
RH max (2014)
PC1 (50.94%)
PC2 (19.99%)
RH IQR (2014)
PC1 (59.86%)
PC2 (17.55%)

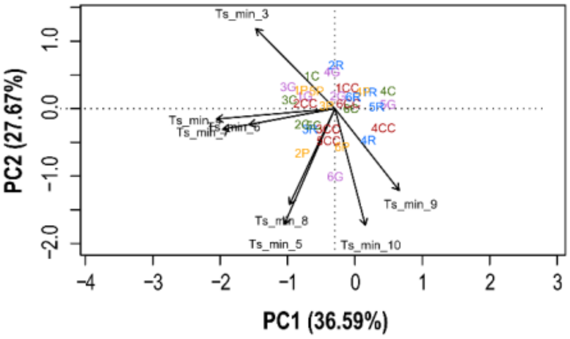

VPD mean (2014)

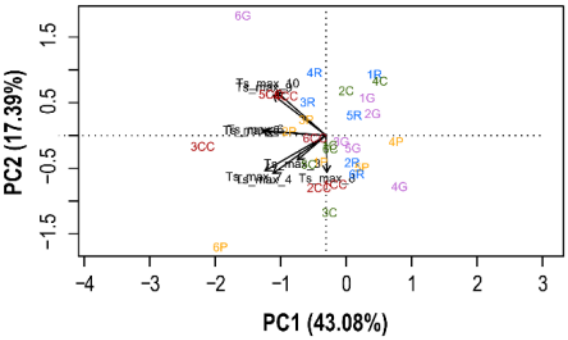

VPD min (2014)

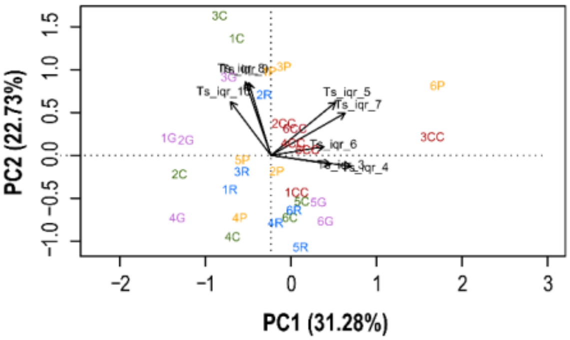

VPD max (2014)

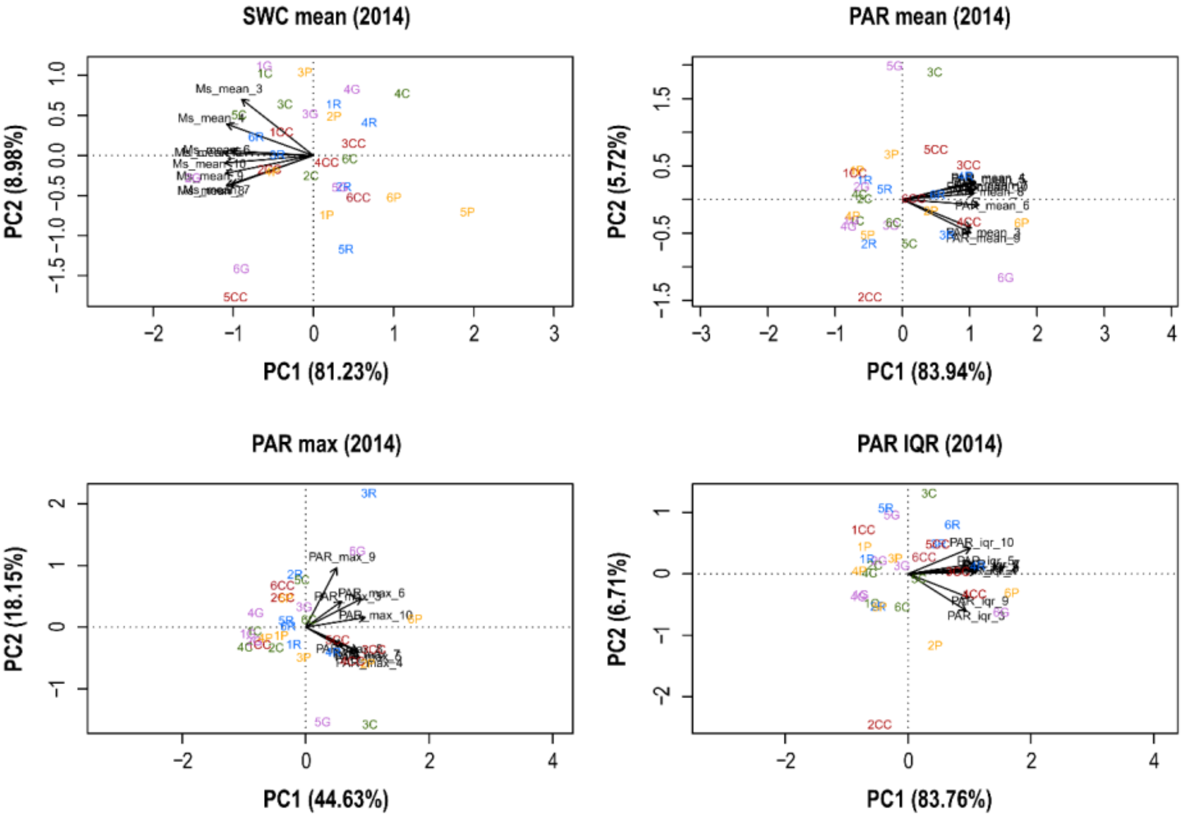

VPD IQR (2014)


T$_{soil}$ mean (2014)


T$_{soil}$ min (2014)


T$_{soil}$ max (2014)

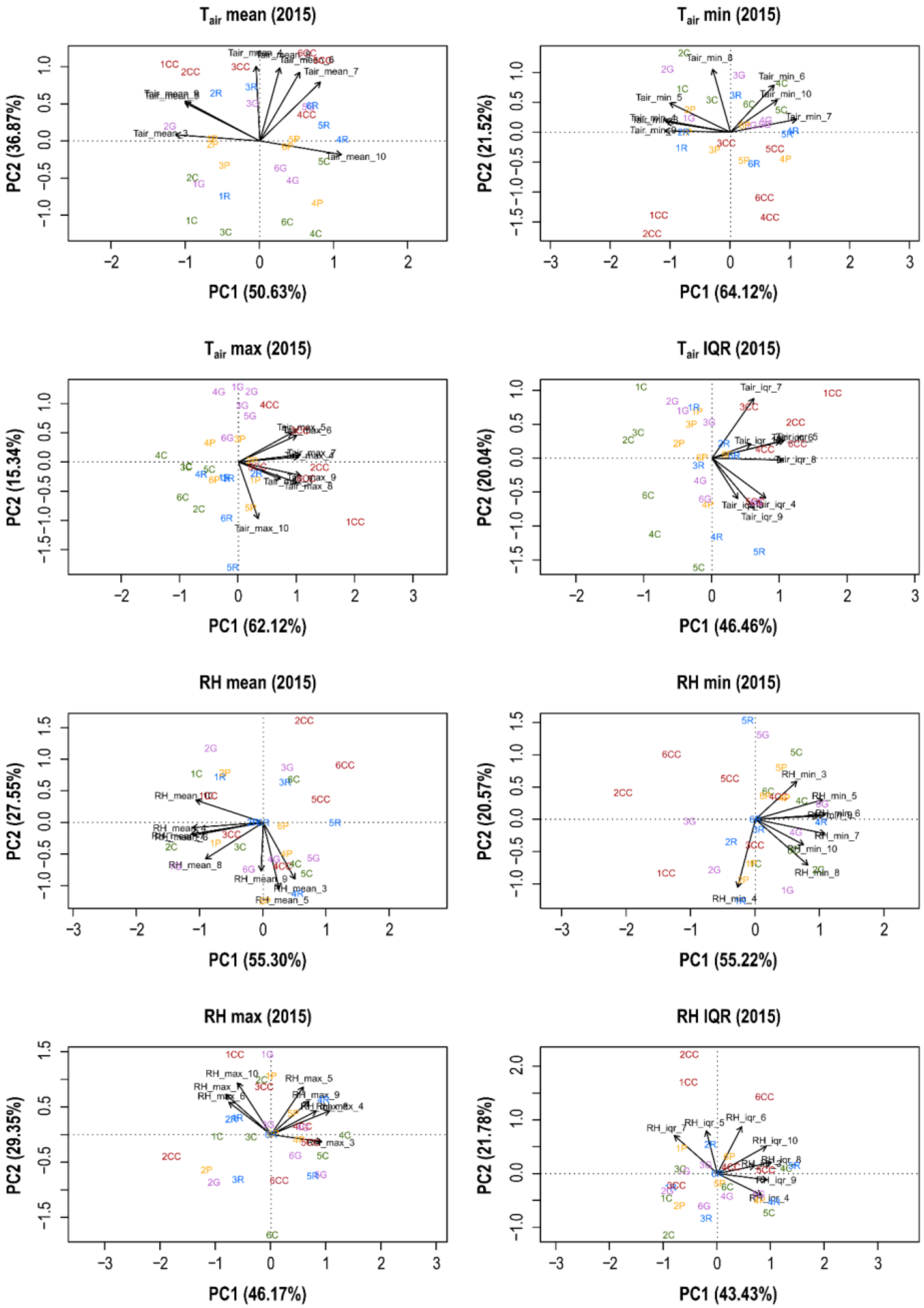

T$_{soil}$ IQR (2014)

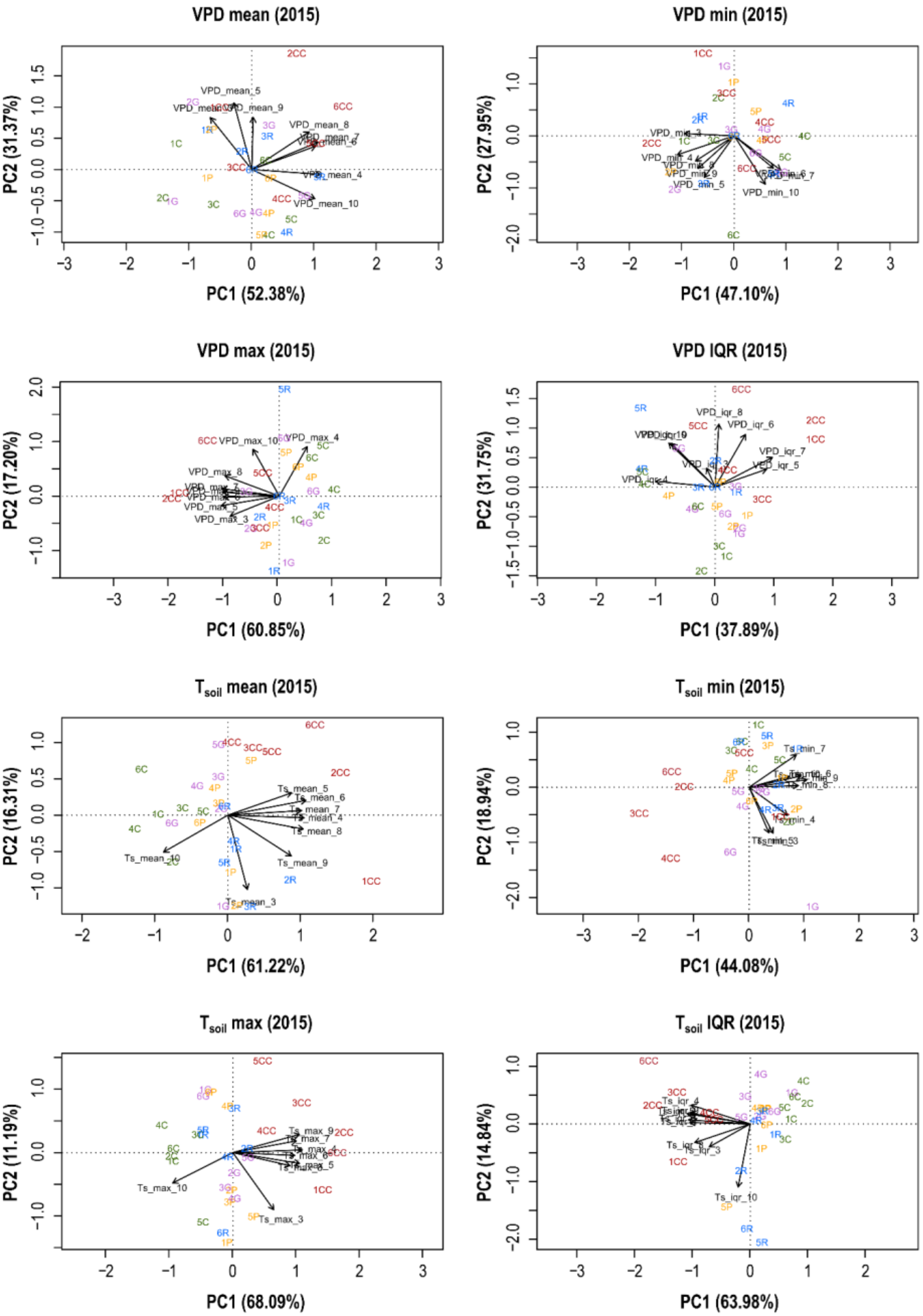

SWC mean (2014)

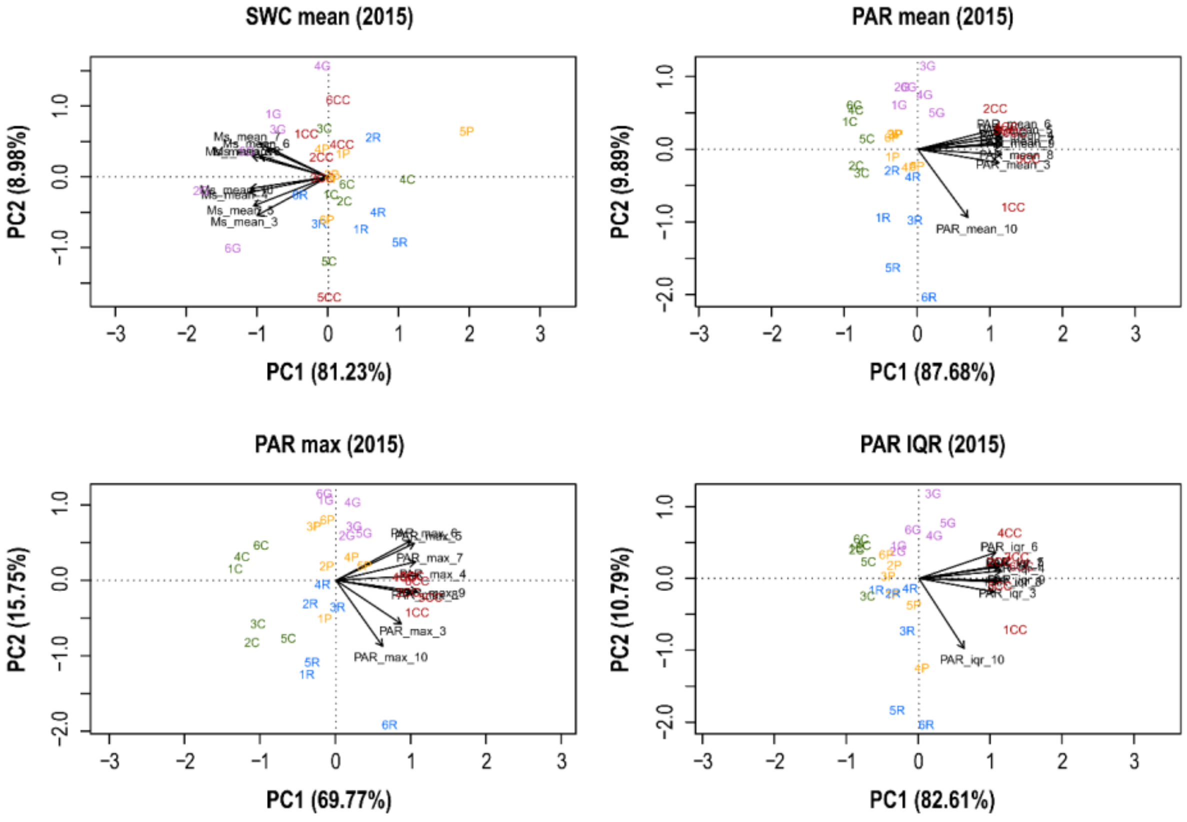
PAR mean (2014)

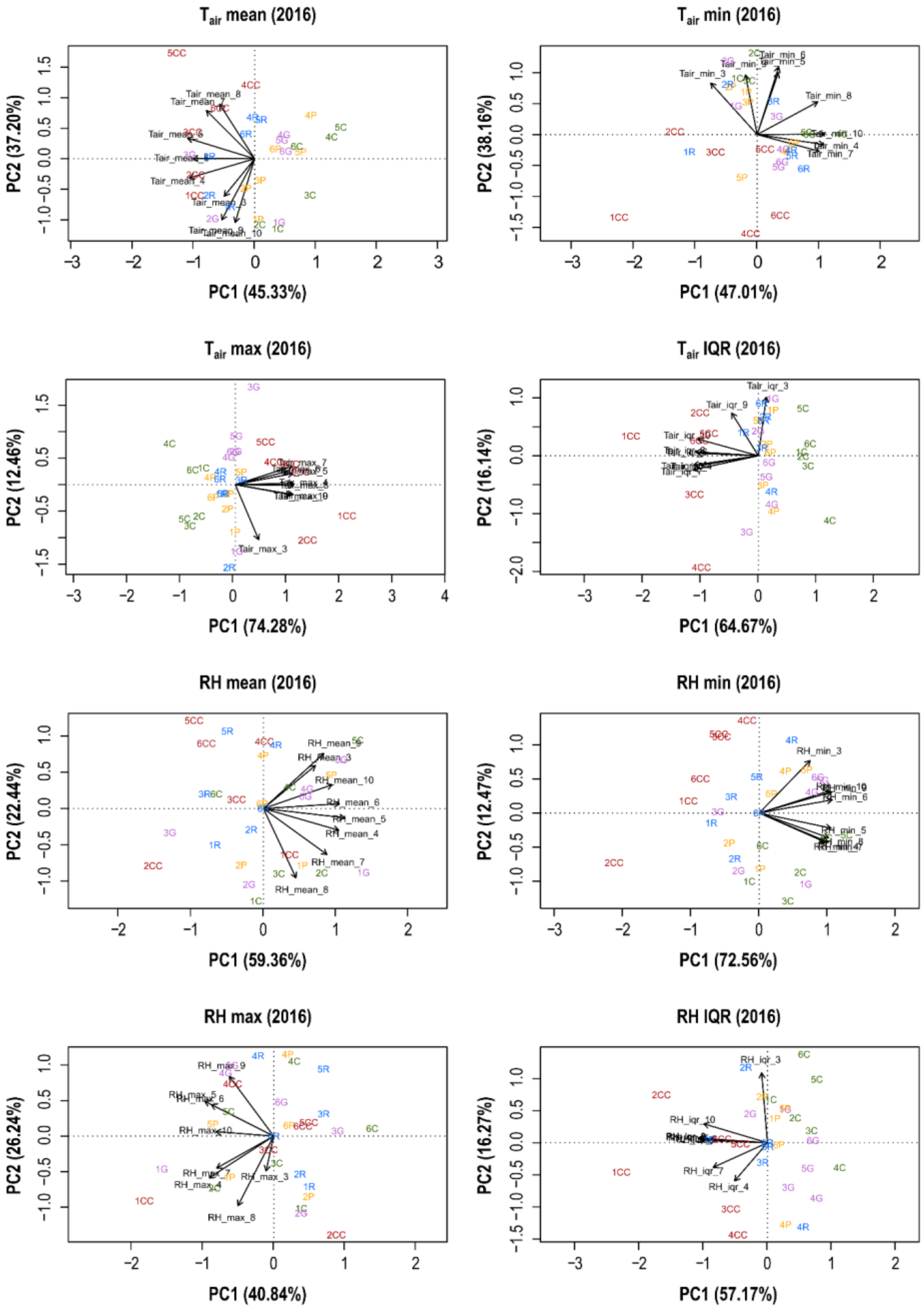
PAR max (2014)

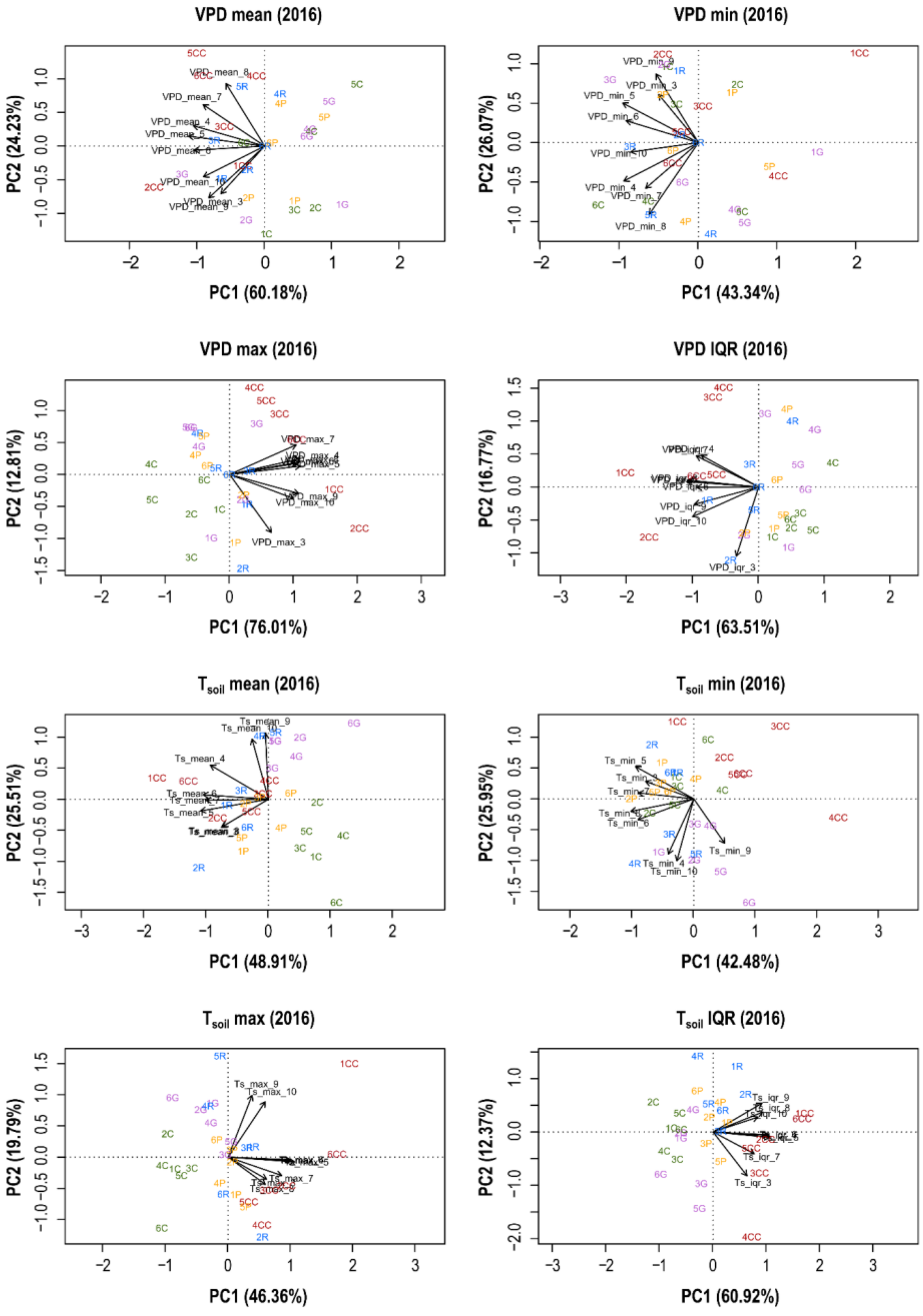
PAR IQR (2014)


T_air mean (2015)
PC1 (50.63%)
PC2 (36.87%)
T_air min (2015)
PC1 (64.12%)
PC2 (21.52%)
T_air max (2015)
PC1 (62.12%)
PC2 (15.34%)
T_air IQR (2015)
PC1 (46.46%)
PC2 (20.04%)
RH mean (2015)
PC1 (55.30%)
PC2 (27.55%)
RH min (2015)
PC1 (55.22%)
PC2 (20.57%)
RH max (2015)
PC1 (46.17%)
PC2 (29.35%)
RH IQR (2015)
PC1 (43.43%)
PC2 (21.78%)
Tair_mean_3
Tair_mean_7
Tair_mean_10
Tair_min_5
Tair_min_6
Tair_min_7
Tair_min_8
Tair_min_10
Tair_max_5
Tair_max_6
Tair_max_7
Tair_max_9
Tair_max_10
Tair_iqr_4
Tair_iqr_7
Tair_iqr_8
Tair_iqr_9
RH_mean_3
RH_mean_5
RH_mean_8
RH_mean_9
RH_mean_10
RH_min_3
RH_min_4
RH_min_5
RH_min_6
RH_min_7
RH_min_8
RH_min_10
RH_max_3
RH_max_4
RH_max_5
RH_max_6
RH_max_9
RH_max_10
RH_iqr_4
RH_iqr_5
RH_iqr_6
RH_iqr_7
RH_iqr_8
RH_iqr_9
RH_iqr_10
1CC
2CC
3CC
4CC
5CC
6CC
1C
2C
3C
4C
5C
6C
1G
2G
3G
4G
5G
6G
1P
2P
3P
4P
5P
6P
1R
2R
3R
4R
5R
6R


VPD mean (2015)
PC1 (52.38%)
PC2 (31.37%)
VPD min (2015)
PC1 (47.10%)
PC2 (27.95%)
VPD max (2015)
PC1 (60.85%)
PC2 (17.20%)
VPD IQR (2015)
PC1 (37.89%)
PC2 (31.75%)
T_soil mean (2015)
PC1 (61.22%)
PC2 (16.31%)
T_soil min (2015)
PC1 (44.08%)
PC2 (18.94%)
T_soil max (2015)
PC1 (68.09%)
PC2 (11.19%)
T_soil IQR (2015)
PC1 (63.98%)
PC2 (14.84%)


SWC mean (2015)
PC1 (81.23%)
PC2 (8.98%)
Ms_mean_7
Ms_mean_6
Ms_mean_10
Ms_mean_4
Ms_mean_5
Ms_mean_3
PAR mean (2015)
PC1 (87.68%)
PC2 (9.89%)
PAR_mean_6
PAR_mean_8
PAR_mean_3
PAR_mean_10
PAR max (2015)
PC1 (69.77%)
PC2 (15.75%)
PAR_max_6
PAR_max_5
PAR_max_7
PAR_max_4
PAR_max_9
PAR_max_3
PAR_max_10
PAR IQR (2015)
PC1 (82.61%)
PC2 (10.79%)
PAR_iqr_6
PAR_iqr_3
PAR_iqr_10


T_{air} mean (2016)
PC1 (45.33%)
PC2 (37.20%)
Tair_mean_8
Tair_mean_5
Tair_mean_6
Tair_mean_4
Tair_mean_3
Tair_mean_9
Tair_mean_10
T_{air} min (2016)
PC1 (47.01%)
PC2 (38.16%)
Tair_min_3
Tair_min_6
Tair_min_5
Tair_min_8
Tair_min_10
Tair_min_4
Tair_min_7
T_{air} max (2016)
PC1 (74.28%)
PC2 (12.46%)
Tair_max_7
Tair_max_5
Tair_max_4
Tair_max_10
Tair_max_3
T_{air} IQR (2016)
PC1 (64.67%)
PC2 (16.14%)
Tair_iqr_3
Tair_iqr_9
RH mean (2016)
PC1 (59.36%)
PC2 (22.44%)
RH_mean_9
RH_mean_3
RH_mean_10
RH_mean_6
RH_mean_5
RH_mean_4
RH_mean_7
RH_mean_8
RH min (2016)
PC1 (72.56%)
PC2 (12.47%)
RH_min_3
RH_min_10
RH_min_6
RH_min_5
RH_min_8
RH_min_4
RH max (2016)
PC1 (40.84%)
PC2 (26.24%)
RH_max_9
RH_max_5
RH_max_6
RH_max_10
RH_max_7
RH_max_4
RH_max_3
RH_max_8
RH IQR (2016)
PC1 (57.17%)
PC2 (16.27%)
RH_iqr_3
RH_iqr_10
RH_iqr_7
RH_iqr_4


VPD mean (2016)

VPD min (2016)

VPD max (2016)

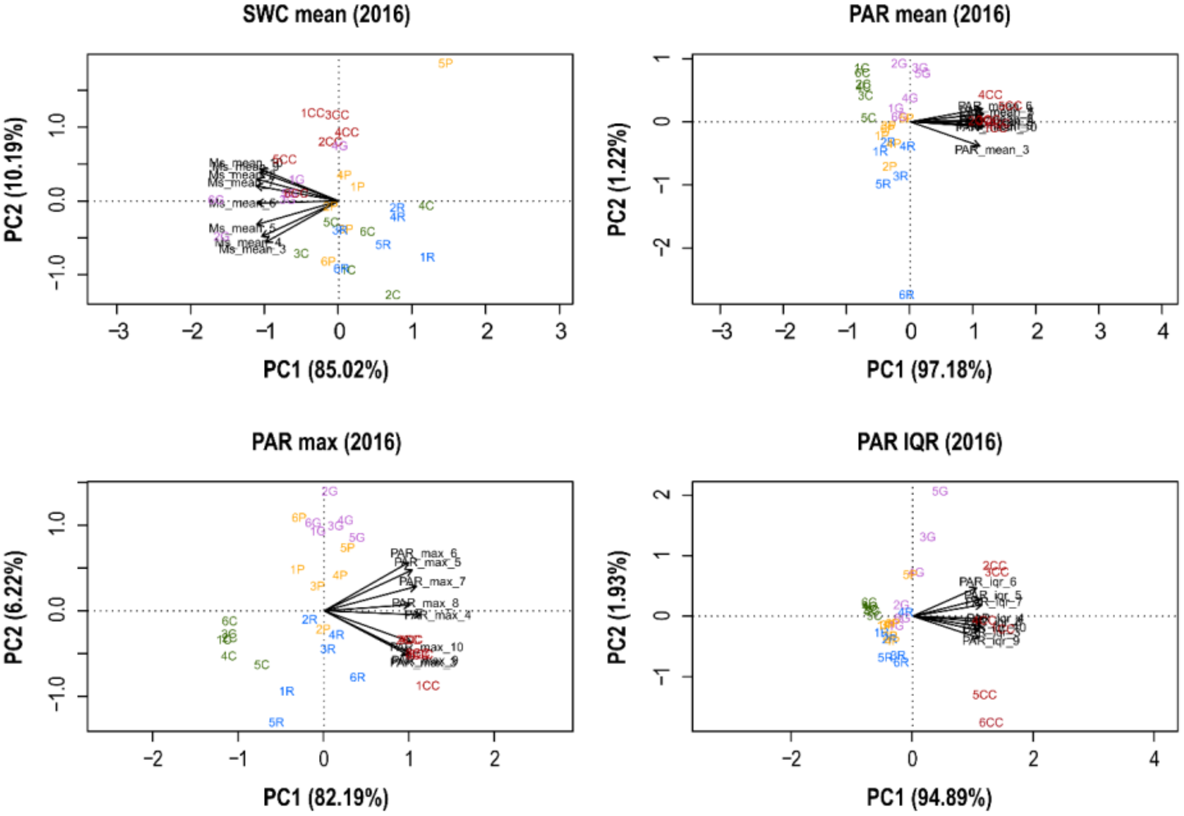
VPD IQR (2016)

T_{soil} mean (2016)

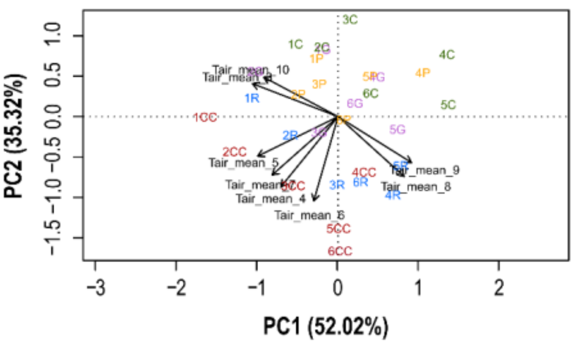
T_{soil} min (2016)

T_{soil} max (2016)

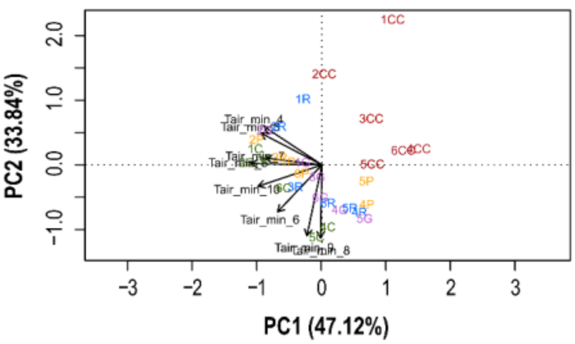
T_{soil} IQR (2016)


SWC mean (2016)
PC1 (85.02%)
PC2 (10.19%)
Ms_mean_3
Ms_mean_4
Ms_mean_5
Ms_mean_6
PAR mean (2016)
PC1 (97.18%)
PC2 (1.22%)
PAR_mean_3
PAR max (2016)
PC1 (82.19%)
PC2 (6.22%)
PAR_max_4
PAR_max_5
PAR_max_6
PAR_max_7
PAR_max_8
PAR_max_10
PAR IQR (2016)
PC1 (94.89%)
PC2 (1.93%)
PAR_iqr_5
PAR_iqr_6
PAR_iqr_7
PAR_iqr_9

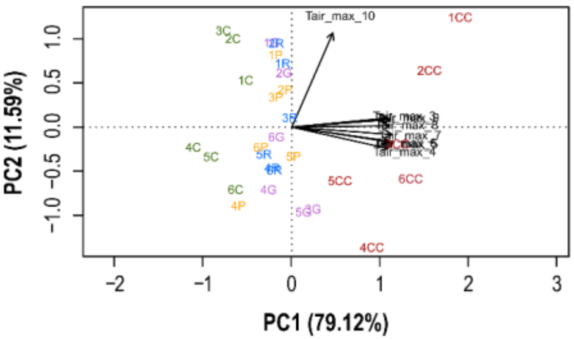
T_{air} mean (2017)



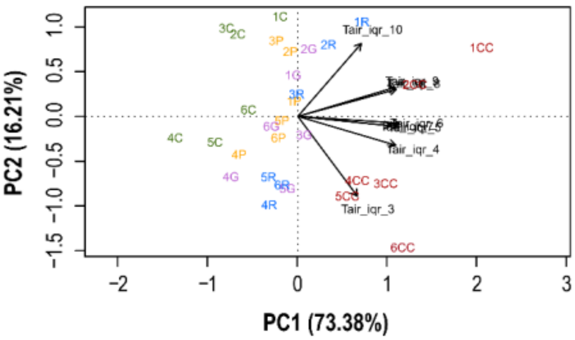
T_{air} min (2017)



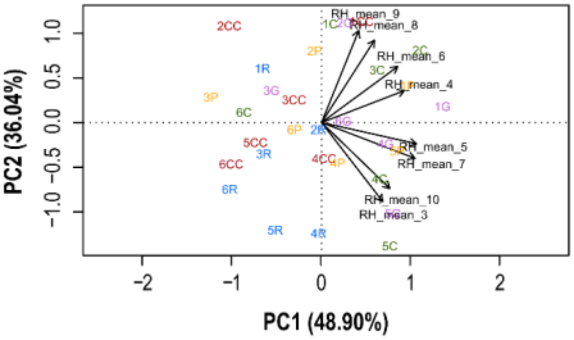
T_{air} max (2017)



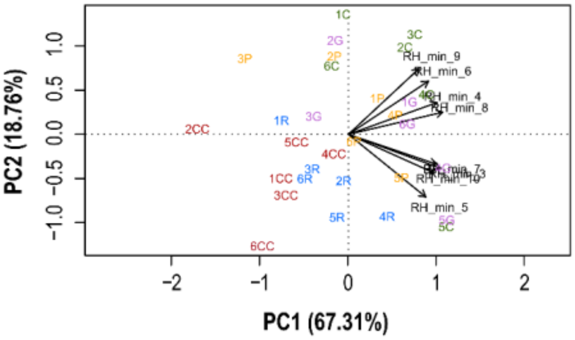
T_{air} IQR (2017)



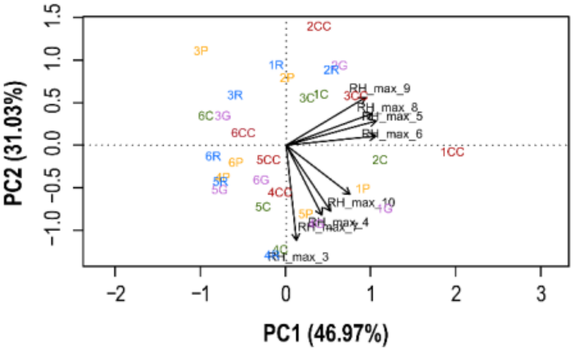
RH mean (2017)



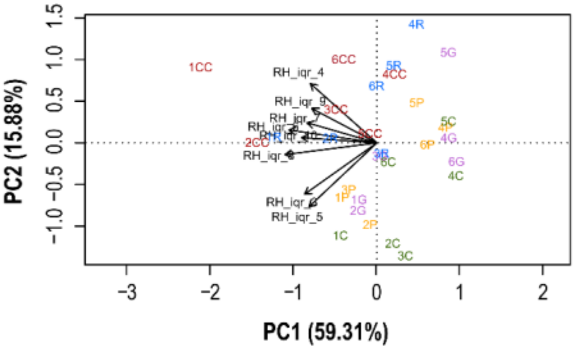
RH min (2017)

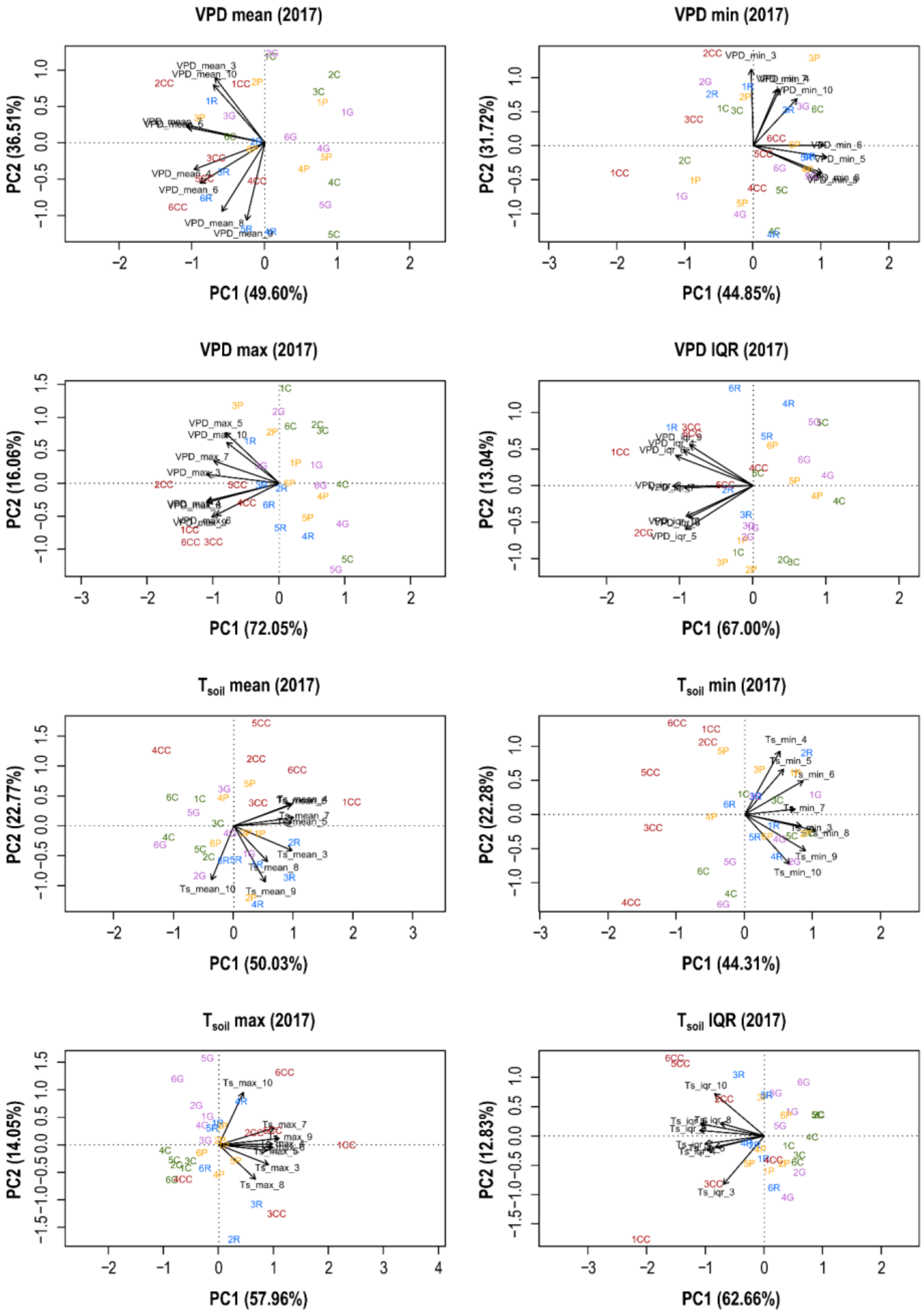


RH max (2017)

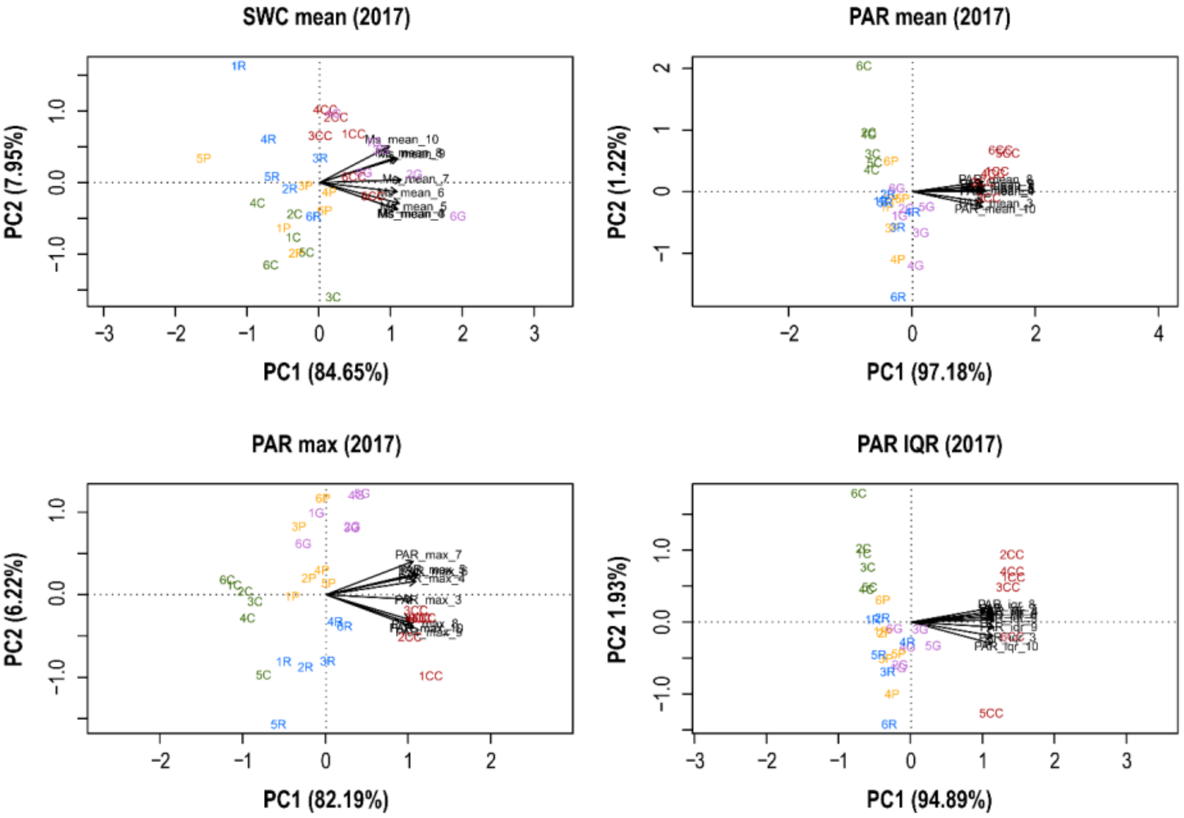


RH IQR (2017)





VPD mean (2017)
PC1 (49.60%)
PC2 (36.51%)
VPD_mean_3
VPD_mean_10
VPD_mean_4
VPD_mean_6
VPD_mean_8
VPD_mean_9
VPD min (2017)
PC1 (44.85%)
PC2 (31.72%)
VPD_min_3
VPD_min_10
VPD_min_6
VPD_min_5
VPD max (2017)
PC1 (72.05%)
PC2 (16.06%)
VPD_max_5
VPD_max_10
VPD_max_7
VPD_max_3
VPD IQR (2017)
PC1 (67.00%)
PC2 (13.04%)
VPD_iqr_5
T_{soil} mean (2017)
PC1 (50.03%)
PC2 (22.77%)
Ts_mean_7
Ts_mean_5
Ts_mean_3
Ts_mean_8
Ts_mean_9
Ts_mean_10
T_{soil} min (2017)
PC1 (44.31%)
PC2 (22.28%)
Ts_min_4
Ts_min_5
Ts_min_6
Ts_min_7
Ts_min_3
Ts_min_8
Ts_min_9
Ts_min_10
T_{soil} max (2017)
PC1 (57.96%)
PC2 (14.05%)
Ts_max_10
Ts_max_7
Ts_max_9
Ts_max_5
Ts_max_3
Ts_max_8
T_{soil} IQR (2017)
PC1 (62.66%)
PC2 (12.83%)
Ts_iqr_10
Ts_iqr_8
Ts_iqr_3


SWC mean (2017)

PAR mean (2017)

PAR max (2017)

PAR IQR (2017)

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

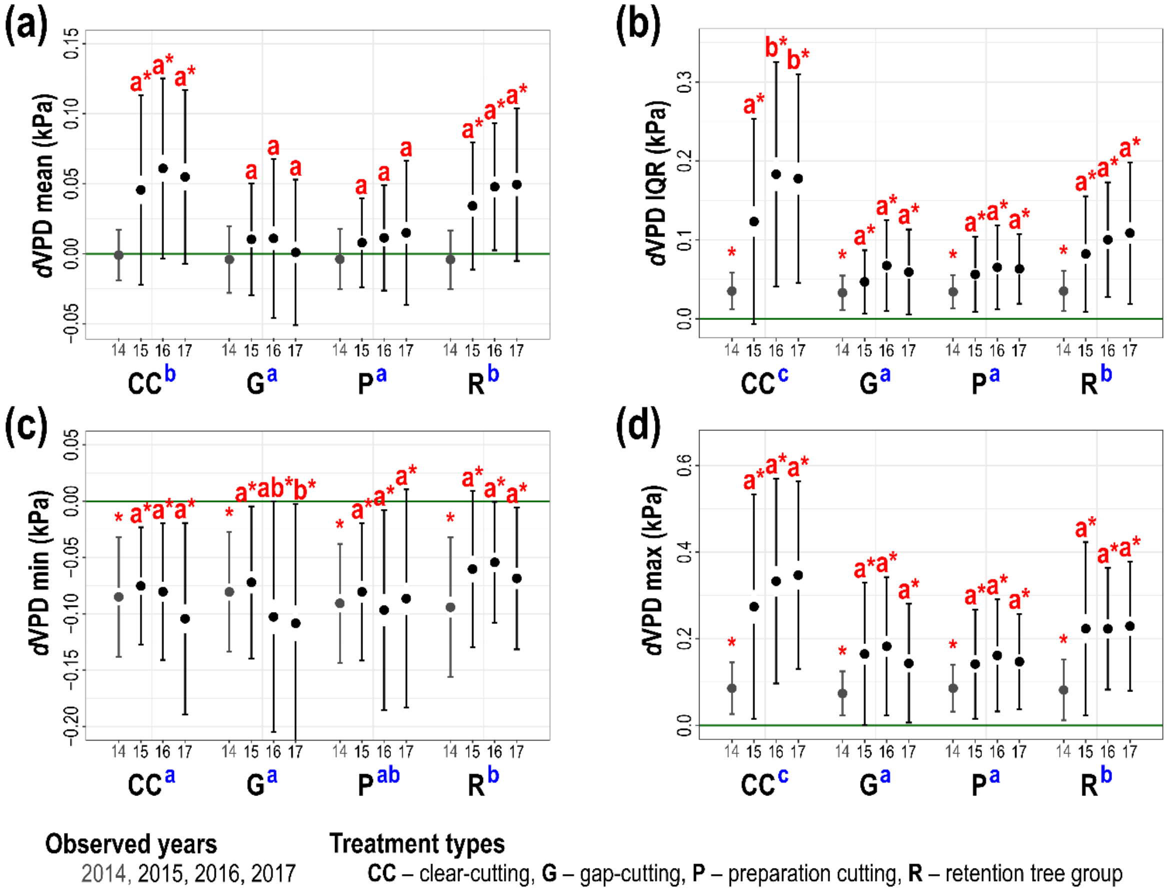
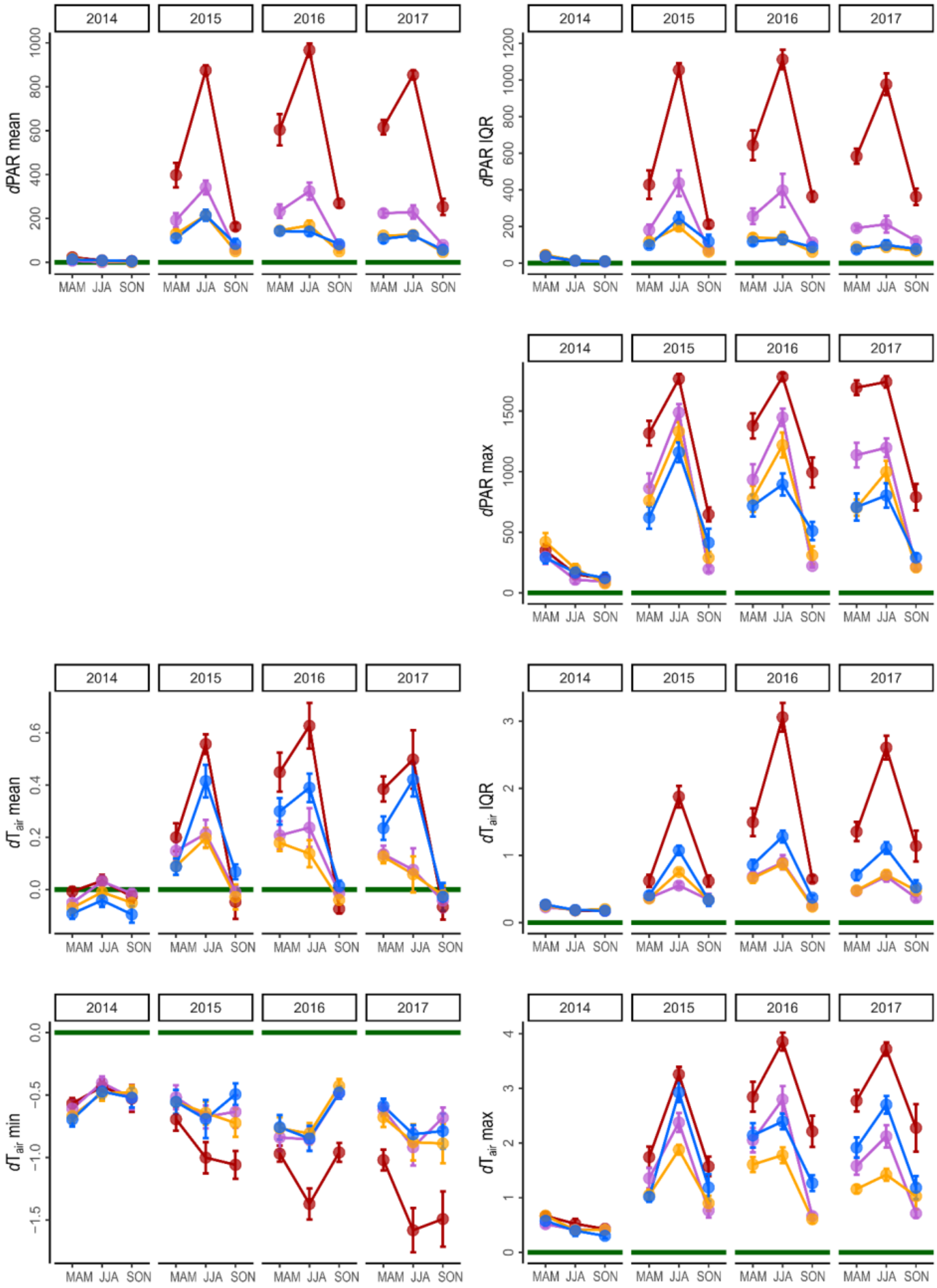
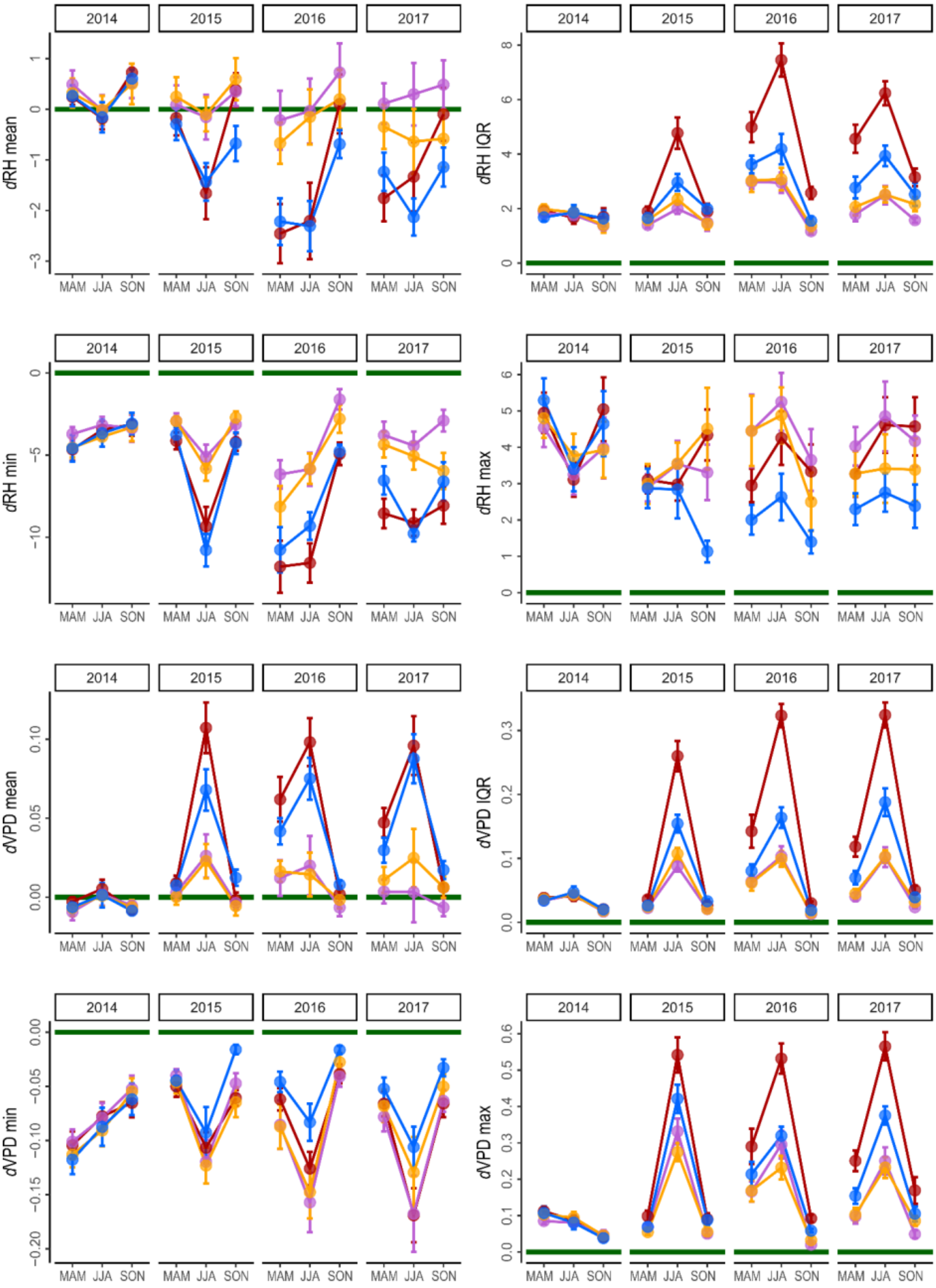
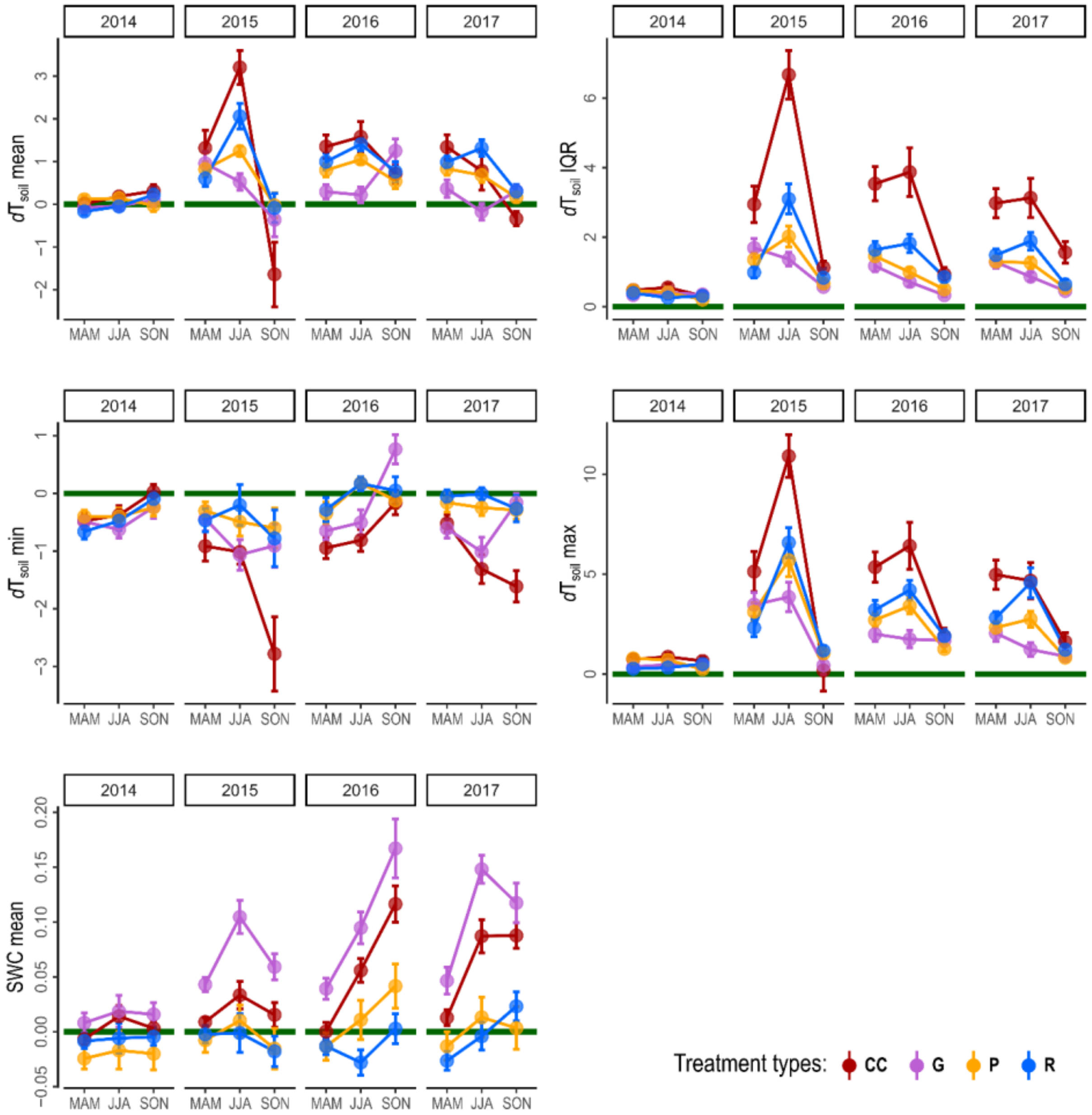


Figure S4 Means, interquartile ranges (IQR), minima and maxima of the relative values (differences from the control) of the microclimate variables among the applied silvicultural treatments throughout the seasons of the observation years (2014-2017). The first letters of the months refer to the seasons (MAM – Spring, JJA – Summer, SOP – Autumn). Variables are coded as: *d*PAR – photosynthetically active radiation (μE m^{-2} s^{-1}); *d*T_{ai} – air temperature (°C); *d*RH – relative humidity (%); (g) mean and (h) IQR of vapor pressure deficit (*d*VPD; kPa); (i) mean and (j) IQR of soil temperature (*d*T_{soil}; °C); (k) mean of soil moisture (*d*SWC; m^3/m^3). Treatment types are depicted by different colors: deep red – clear-cutting; purple – gap-cutting; orange – preparation cutting; blue – retention tree group. Circles show the mean, vertical lines denote the standard error of the samples. The horizontal green lines demonstrate the 0-level of the control.


2014
2015
2016
2017
MAM
JJA
SON
dPAR mean
0
200
400
600
800
1000
dPAR IQR
0
200
400
600
800
1000
1200
dPAR max
0
500
1000
1500
dT_{air} mean
0.0
0.2
0.4
0.6
dT_{air} IQR
0
1
2
3
dT_{air} min
0.0
−0.5
−1.0
−1.5
dT_{air} max
0
1
2
3
4


2014
2015
2016
2017
MAM
JJA
SON
dRH mean
1
0
−1
−2
−3
dRH IQR
8
6
4
2
0
dRH min
0
−5
−10
dRH max
6
5
4
3
2
1
0
dVPD mean
0.10
0.05
0.00
dVPD IQR
0.3
0.2
0.1
0.0
dVPD min
0.00
−0.05
−0.10
−0.15
−0.20
dVPD max
0.6
0.5
0.4
0.3
0.2
0.1
0.0


2014
2015
2016
2017
MAM
JJA
SON
dT_{soil} mean
3
2
1
0
−1
−2
dT_{soil} IQR
6
4
2
0
dT_{soil} min
1
0
−1
−2
−3
dT_{soil} max
10
5
0
SWC mean
0.20
0.15
0.10
0.05
0.00
−0.05
Treatment types:
CC
G
P
R