A matter of size and shape: Microclimatic changes induced by experimental gap openings in a sessile oak–hornbeam forest

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HIGHLIGHTS

- Scientifically based multipurpose forestry needs comparative studies on canopy gaps.
- We studied the microclimate of two gap size and shape types at two spatial scales.
- Light increment was driven by gap size, and shape determined soil moisture patterns.
- Daily means of air temperature increased at 1.3 m yet decreased near the ground.
- Gaps up to one tree height per diameter ratio can maintain forest conditions.

GRAPHICAL ABSTRACT
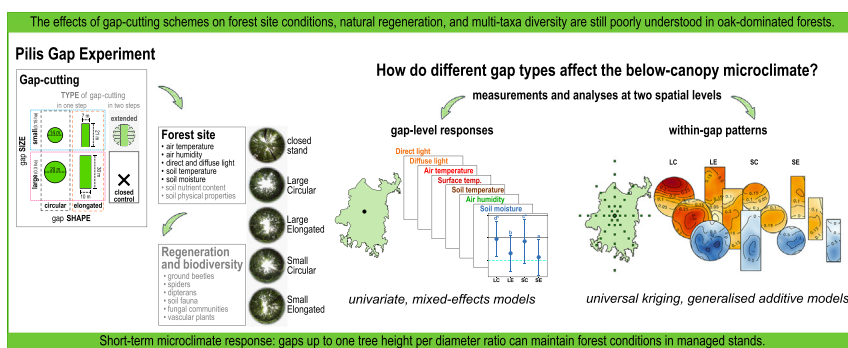
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ABSTRACT

Forest management integrating nature conservation aspects into timber production focuses increasingly on small-scale interventions. However, the ecological consequences of gap cuttings remain ambiguous in oak-dominated forests. In the Pilis Gap Experiment, we analyze how combinations of different gap shapes (circular and elongated), and gap sizes (150 m² and 300 m²) affect the microclimate and biota of a mature sessile oak-hornbeam forest in Hungary. We first report the changes in direct and diffuse light, soil moisture, daily air and soil temperatures, and relative air humidity in the experimental cuttings in the vegetation season directly following their implementation. Diffuse light had a central maximum and a concentric pattern. Direct light was distributed along a north-south gradient, with maxima in northern gap parts. Soil moisture was determined by gap shape: it increased significantly in the center of circular gaps, with multiple local maxima in the southern-central parts of large circular gaps. Its pattern was negatively related to direct light, and larger spatial variability was present in elongated gaps. The daily mean air temperatures at 1.3 m increased in all, especially in large gaps. Soil and ground-level temperatures remained largely unchanged, reflecting on light and soil moisture conditions affecting evaporative cooling. Relative humidity remained unaltered. Even though the opening of experimental gaps changed microclimatic conditions immediately, effect sizes remained moderate. Gap size and gap shape were both important determinants of microclimate responses: gap size

markedly affected irradiation increase, gap shape determined soil moisture surplus, while soil and air temperatures, and air humidity depended on both components of the gap design. We conclude that 150–300 m² sized management-created gaps can essentially maintain forest microclimate while theoretically providing enough light for oak regeneration; and that the manipulation of gap shape and gap size within this range are effective tools of adaptive management.

1. Introduction

Due to the extensive historical human impact, the proportions of primary forests and forests designated for biodiversity conservation are both low in Europe, while the area of forests managed for production is the highest among the continents (FAO, 2020; Sabatini et al., 2018). Forested habitats are nonetheless hosting a substantial part of Europe's terrestrial biodiversity, compelling conservation, and timber production efforts to be intertwined (Bastrup-Birk et al., 2016; Storch et al., 2020). Besides the preservation of biodiversity, and the production of timber and other commodities, the most widely recognized ecosystem services of forests include the regulation of erosion and water runoff, the sequestration and storage of carbon, the regulation of air and water quality as well as recreation (Biber et al., 2015; Sing et al., 2018; Shvidenko et al., 2005). All these ecosystem services are based on processes that are intimately connected to the environmental conditions associated with the canopy layer, which affects energy and water fluxes near and below ground (Bonan, 2016; De Frenne et al., 2021; Geiger et al., 2009).

Tree canopies are the active surfaces of woodlands: by intercepting and absorbing daytime shortwave radiation, reducing the night-time longwave radiation loss, and limiting air mixing, the canopy layer acts as a thermal insulator (Oke, 1987). Reduced levels of direct sunlight and wind speeds create a special subcanopy microclimate, distinct from those of adjacent open areas, which can be described by two general characteristics as detailed by De Frenne et al. (2021). On the one hand, by a constant presence of offsets (i.e., a positive or negative difference) from the open conditions with a varying strength throughout the seasons, and on the other hand, by a buffering capacity dampening the extremities of the micrometeorological variables below the canopy (De Frenne et al., 2021). The most well-known consequences of this mitigating effect are cooler summer and warmer winter temperatures below the canopies, as well as lower daily temperature ranges compared to open conditions. The differences between daily mean subcanopy and adjacent open-air temperatures are 0.5 °C as reported by Zellweger et al. (2019) using a microclimate network in temperate stands across Europe. It is approximately 1 °C in the temperate biome, found empirically by De Frenne et al. (2019) in their global meta-analysis or even as large as 2 °C, modelled by Haesen et al. (2021) for European forests. Offsets are also prevalent in relative air humidity (RH): compared to open habitats, below-canopy RH is generally higher, while its temporal variability is lower due to the buffering capacity of the stand (Geiger et al., 2009; Von Arx et al., 2012). The local water balance and thus soil moisture availability in the topsoil are also influenced by the canopy layer due to the interception of precipitation determining the amount of throughfall, and by the evapotranspiration of the vegetation (Bonan, 2016).

Forest microclimate is chiefly determined by the stand structure and its complexity, and consequently, it is affected by both natural and management-induced disturbances that alter stand structural characteristics (Aussenac, 2000; Greiser et al., 2018; Kovács et al., 2017). Indeed, in managed forests, the silvicultural systems (e.g., rotation forestry, continuous cover forestry) and the associated treatment types creating canopy openings (e.g., clear-cutting, final-cutting, thinning, gap-cutting) are important anthropogenic disturbances that affect forest microclimates (Chen et al., 1999; De Frenne et al., 2021; Ehbrecht et al., 2019; Kovács et al., 2020; Thom et al., 2020).

Within the framework of even-aged forest management, clear-cutting and shelterwood cuts applied over a short period of time recurrently create large and homogenous reductions in canopy cover over extensive areas (Aszalós et al., 2022; Gresh and Courter, 2021), which induce substantial changes in microclimate conditions (Keenan and Kimmins, 1993; Kermavnar et al., 2019). The microclimate of cut areas is characterized by increased incident shortwave radiation, higher and more variable air and soil temperatures, increased vapour pressure deficit and wind speeds compared to adjoining closed stands (Chen et al., 1999). The subsequently regenerating secondary forests have a simplified structure that is associated with an impaired buffering capacity as compared to old-growth forests (Frey et al., 2016; Norris et al., 2012). Continuous cover forestry, as an increasingly used alternative to rotation forestry in Europe; however, emphasizes the protection of the canopy layer, and thus operates mainly with single-tree or group selections, creating small canopy openings, i.e., gaps (Gustafsson et al., 2020; Mason et al., 2022; Pommerening and Murphy, 2004).

Natural gaps in forests are discrete openings in the upper crown layer that are formed by the breakage of limbs, or by the death of one or a small group of canopy tree individuals (Denslow, 1980; Runkle, 1982); their typical area is smaller than 0.1 ha in the temperate region (Hobi et al., 2015; Zhu et al., 2015). The extent of a treefall gap can be defined as a "canopy gap" that is the area of the canopy opening, or as an "expanded gap" that is delineated by the neighbouring boles on the forest floor, i.e., the canopy gap plus the adjacent area to the bases of the surrounding canopy trees (Runkle, 1982). When a forest gap is opened, an immediate change in the light climate occurs, as more incident shortwave radiation reaches the understory level, which increase is driven by gap size, and is partitioned increasingly as direct rather than diffuse light (Muscolo et al., 2014; Oke, 1987). With a reduction in the canopy cover, the interception loss in precipitation decreases, whilst evapotranspiration is also reduced, as the root systems of the fallen or cut trees die off, and a so-called root gap evolves below the ground resulting soil moisture increment (Gálhidy et al., 2006; van Dam, 2001; Vilhar et al., 2015). As more energy reaches the surface layer, sensible heat accumulation leads to rising soil and air temperatures, with the largest increases in maximum values, as observed during the growing season in temperate deciduous forests (Kovács et al., 2020; Thom et al., 2020).

Compared with clear-cuttings, albeit characterized by comparable trends, the effects of gap-cuttings on the forest microclimate are less transformative, and more transient (Kovács et al., 2020; Mollinari et al., 2019; Ritter et al., 2005; Schliemann and Bockheim, 2011). Besides, as studies from the mountainous forests of Europe confirm, small to intermediate disturbances are also more prevalent in the natural disturbance dynamics of temperate forests than stand-replacing disturbances (Kulakowski et al., 2017; Aszalós et al., 2022). Therefore, the use of gap-cuttings remains a compelling and advocated management option across a multitude of forest ecosystems and management approaches, with its increased use expected to advance modern multifunctional forestry (Gresh and Courter, 2021; Kern et al., 2017; Mason et al., 2022).

Implementing continuous cover forestry with the use of gap-cuttings in *Quercus petraea* (Matt.) Liebl. (sessile oak) and *Quercus robur* L. (pedunculate oak) dominated stands, however, remains to be a challenge to date (Mölder et al., 2019). The successful oak regeneration is conditional on multiple factors, such as the level of browsing pressure by ungulates, site characteristics, competition with the understory vegetation, and mostly light availability, due to the low shade tolerance of the sessile and pedunculate oak saplings after the first years of establishment (Petersson et al., 2020). Current knowledge is mainly experience-based, focusing on the results of practitioners (see Appendix A summarizing Hungarian examples and best practices), while comparative studies are scarce (Mölder et al., 2019). Even though some studies have focused already on the effect of

gap-cuttings in oak-dominated stands, the results are ambiguous (Diaci et al., 2008; Modrow et al., 2020; Tinya et al., 2020). Thus, it remains unresolved if small-scale approaches are viable for oak silviculture, and necessary to analyze their effect on the microclimate and light environments of gaps, especially in consideration of the increasing incidence of extreme weather, heat and drought stress events imposed by climate change (Kohler et al., 2020).

To contribute to the knowledge available on the use of gap-cuttings in silviculture, its effects on forest biota and microclimate, and its adaptation to oak-dominated stands, we have established a forest ecology experiment in a mature, managed sessile oak-hornbeam (*Carpinus betulus* L.) forest in Hungary ('Pilis Gap Experiment', https://piliskiserlet.ecolres.hu/en). Within the experiment, we combined two gap shapes (circular and elongated) and two gap sizes (approx. 150 m² and 300 m²) to study their effect on multi-taxon biodiversity, sessile oak regeneration, and forest site conditions (including microclimate, litter, and soil characteristics). The study was established in collaboration with local foresters; therefore, the design was created in accordance with their interests (Appendix A).

Microclimatic changes induced by silvicultural interventions can drive biotic responses to the cuttings and are expected to be the most expressed in the years directly following the harvests (Kovács et al., 2020). Therefore, in this study, we focused on the effect of gap shape and gap size on the microclimate and soil characteristics in the first year after the creation of experimental gaps. We analysed and compared the responses of direct and indirect radiation, air and soil temperatures, air humidity, and soil moisture in the gap centers. We also evaluated how direct and diffuse light and soil moisture are distributed within the whole area of the gaps, and along closed-canopy – gap edge – gap interior gradients. We hypothesized, that in response to the gap-cuttings:

1. Light increases in all treatments, and this increment is primarily determined by gap size: large gaps are more illuminated. The treatment effect is more pronounced in the direct than in the diffuse component of light.
2. Soil moisture increases in all treatments. Soil moisture increment is determined both by gap size and gap shape: the soil in large gaps is more humid than that of smaller gaps, and circular gaps induce more humid conditions than elongated gaps. A larger spatial variability emerges in circular than in elongated, as well as in large than in small gaps due to the differences in the effective area of root gaps.
3. Relative air humidity slightly decreases in all treatments but remains similar to the uncut control levels. Relative humidity is primarily determined by gap size: small gaps are more humid. However, soil moisture can also influence its levels as the evaporation of soil and the transpiration by the herb layer are the main sources of water vapour in the near-ground layers.
4. Air and soil temperatures increase in all treatments, reflecting the increase in the incoming radiation. Treatment effects are the strongest in maxima among all temperature metrics, and effects are more buffered near and below the soil surface than higher above ground. Temperatures near the soil surface are affected by the evaporative cooling driven by excess soil moisture.

2. Materials and methods

2.1. Study area and experimental design

The experimental site is located on the Hosszú-hegy (Pilis Mountains, Transdanubian Range, Hungary 47°40′ N, 18°54′ E; Fig. 1.*A-B*), on moderate (18.2° ± 14.9°), northeast-facing slopes 390–460 m above sea level. The macroclimate is humid continental with a mean annual temperature of 9.0–9.5 °C (16.0–17.0 °C during the growing season) and a mean annual precipitation of 650 mm (Dövényi, 2010). The bedrock consists of sandstone with loess intermingled with limestone (Dövényi, 2010). Soils of the experimental area are slightly acidic (pH = 4.6 ± 0.2), soil types include Luvisols (mainly brown forest soil with clay illuviation) and Rendzic Leptosol, and the soil depth varies along the slight topographic gradient (70–150 cm) (Kovács et al., 2018).

A 9.7-ha-sized area was completely wired against ungulates to establish the experimental site in a managed, 90 years old, two-layered sessile oak–hornbeam forest stand (Natura 2000 code: 91G0; Council Directive 92/43/EEC, 1992). The initial stand structure was relatively uniform due to the formerly applied rotation forestry (shelterwood system), resulting in homogeneous tree species composition and canopy closure.

All tree individuals in the experimental area (DBH ≥ 0.05 m) were mapped prior to the treatments. The canopy was two-layered: the upper canopy layer was dominated by sessile oak (height: 22.8 ± 1.9 m, mean ± standard deviation; DBH: 0.38 ± 0.07 m; relative volume: 91.6 %), and the subcanopy layer was primarily formed by hornbeam (*Carpinus betulus* L., height: 14.2 ± 4. 5 m, DBH: 0.17 ± 0.06 m, relative volume: 5.6 %). Other woody species were rare, individuals of *Quercus cerris* L., *Fraxinus ornus* L., and *Sorbus torminalis* L. were occasionally found as admixing tree species. Before the experimental treatments, the shrub layer was scarce with aggregated patches of hornbeam and *Fraxinus ornus* L. regeneration, and a lower frequency of shrub species (e.g., *Cornus mas* L., *Crataegus monogyna* Jacq., *Ligustrum vulgare* L.). The understory layer was dense, often multi-layered (cover: 124 ± 39 %) and it was initially formed by general and mesic forest species (*Carex pilosa* Scop., *Melica uniflora* Retz., *Galium schultesii* Vest., *Parietaria officinalis* L., *Rubus fruticosus* agg. L.). More details on the experimental stand can be found in Appendix B.

Five treatment types were implemented following a randomized complete block design in six blocks as replicates that resulted in 30 plots (Fig. 1.*C*.). The boundaries of the artificial gaps were designed to be either circular or rectangular (1:3 ratio, north-south orientation), using the expanded gap concept (Runkle, 1982). Gaps were created in February 2019 by cutting and removing all tree individuals within the area between the bases of canopy trees forming the gap boundary (a detailed assessment of the created gaps can be found in Appendix C and pictures in Appendix D). Theoretically, (1) *large circular* gaps (LC) have an approximately 1:1 gap diameter per intact canopy height ratio (diameter: 20 m; area: 300 m²); and (2) *small circular* gaps (SC) have a 0.6 diameter per height ratio (diameter: 14 m; area: 150 m²); while (3) *large elongated* gaps (LE) were planned as 10 m × 30 m rectangles (area: 300 m²); and (4) *small elongated* gaps (SE) as 7 m × 21 m rectangles (area: approx. 150 m²). Additionally, one uncut *control* (CO) plot was established in each block, which represented the original closed, two-layered stand. Although realized canopy openings were rather heterogeneous compared to the theoretical gap shapes (see Fig. 1.*C*), significant and consistent differences in both gape shape and size categories were successfully created as planned (see detailed in Appendix C with results of the ANOVAs performed).

2.2. Data collection

In this study, we combined two levels and designs of data collection (Fig. 1.*C*). Microclimate was continuously sampled in the gap centers, providing an opportunity to characterize and compare how the different treatments influenced the newly created gap environments. This sampling was complemented with a fine-scale sampling of a greater spatial extent for selected microclimate variables (i.e., light and soil moisture) to reveal and compare their within-gap patterns. The fine-scale sampling was implemented only in four blocks out of six.

In the center of each of the 30 gaps, we recorded temperature at four different layers – 130 cm (T_{130}; °C) and 15 cm above the ground layer (T_{15}; °C); on the soil surface (T_0; °C); and 8 cm below ground level (T_{-8}; °C), relative humidity (RH; %) at 130 cm, and soil moisture as volumetric soil water content (VWC; %) in the depth between 8 and 14 cm of the upper soil layer. Data collection was carried out by simultaneously using Voltcraft DL-210TH (Conrad Electronic SE, Hirschau, DE) and TMS-4 (TOMST s.r.o., Praha, CZ) loggers with 15-min logging intervals. Voltcraft loggers were mounted on a wooden pole and equipped with passively ventilated white, plastic radiation shields, and TMS-4 units were also covered by white plastic shields (provided by the manufacturer, see Wild et al., 2019 and Fig. D.5 in Appendix D for pictures). All loggers were tested pairwise before the installation to ensure the comparability of the measured values. Only data collected
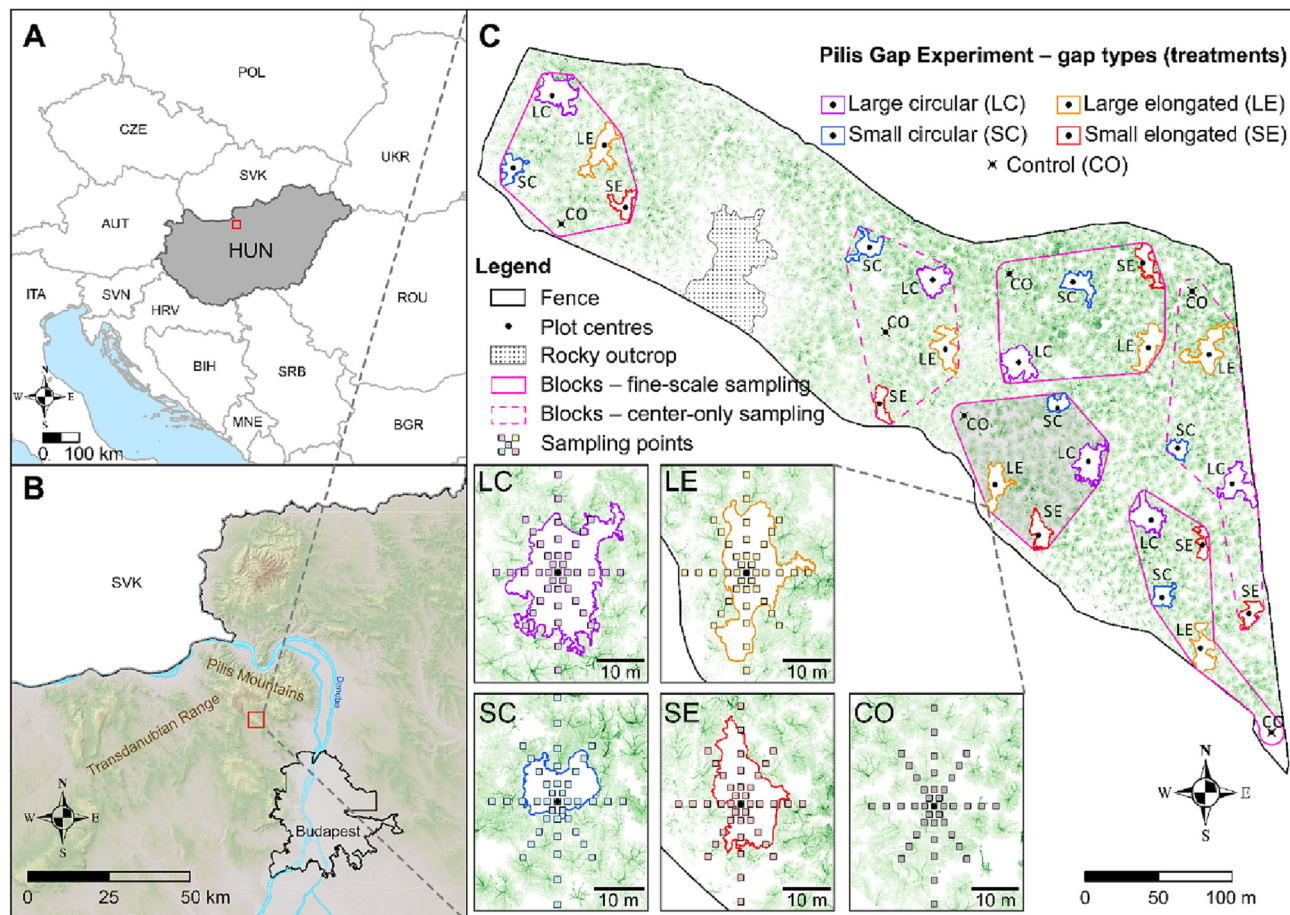
Fig. 1. Location of the experimental area in Hungary (A), on the Hosszú-hegy in the Pilis Mountains, Transdanubian Range (B). Map of the experimental area with the six blocks comprising five plots corresponding to five treatments (C). The area of the gaps is approx. 300 m² for large gaps and 150 m² for small gaps. Measurements were conducted on two levels: microclimate and soil properties were measured in all plot centers, while fine-scale sampling was conducted in four of the six blocks, in 41 points along transects ranging from the plot centers to under canopy areas. The green shading represents the canopy projections of the trees. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between 15 May and 15 September 2019 were used to show the most unambiguous microclimatic response to the treatments at the peak of the growing season. The manually screened microclimate data were imported into a SpatiaLite 4.3.0a database (Furieri, 2015) and split into 24 h subsets.

Light conditions in the gap centers were measured at the peak of the growing season (June) using hemispherical photographs taken at 1.3 m above ground with a KODAK PIXPRO SP360 camera. All photos were taken at dusk to minimize the bias due to the captured sun-disk or the reflectance of direct sunlight on the leaves. Direct and diffuse components of the incoming radiation were calculated by the WinSCANOPY 2019 software (Regent Instruments Inc., Québec, QC, CAN) and expressed as direct and indirect site factor (DSF and ISF, respectively; %). The applied time frame for the radiation analysis was the period between 01 May and 30 September.

For the spatial pattern analyses, a systematic sampling design with a finer spatial resolution was applied (Fig. 1.C). In four blocks (i.e., 4 × 5 plots), 41 sampling points per plot (altogether 820 sampling points) were established. The points were aligned along eight transects along the cardinal and intercardinal directions, which reached from the gap centers to under the closed canopies outside the gap boundaries. A detailed graphical representation of the applied sampling design can be found in Appendix E. In each sampling point, hemispherical photographs were taken following the same protocol as in the gap centers, and the direct and diffuse components of incoming radiation were calculated (as DSF and ISF, respectively; %) by WinSCANOPY 2019, the same way as for the gap centers. Soil moisture was measured by a FieldScout TDR 350 probe equipped with 7.5 cm

steel rods (Spectrum Technologies Inc., Aurora, IL, USA). Measurements were carried out once per month between June and early October 2019, altogether five times during the growing season, under various moisture conditions. Each monthly measurement lasted for two consecutive days of similar synoptic weather conditions. To minimize the effect of within-day changes, all measured values were related to spatially independent daily reference measurements conducted in a fixed location in a neighbouring closed stand. The soil moisture content of each point was then expressed as the difference between the measured and the reference values (VWC; %).

2.3. Data analysis

Microclimate variables collected in the gap centers were used for testing the treatment effects on the artificial gaps. Raw data were screened for obvious errors, and differences from the control were calculated separately in each block to exclude the effects of different site conditions and stand structure heterogeneity between the blocks. Relative values calculated this way (labelled with a "d" prefix) were subsequently synthesized as descriptive daily summary statistics (mean, minimum, maximum; Appendix F). We investigated the treatment effects on the daily statistics of dT_{130}, dT_{15}, dT_0, dT_{-8}, dRH, and dVWC using linear mixed effects models (random intercept models) with a Gaussian error structure (Faraway, 2006). Where it was necessary, the response variables were transformed to achieve the normality of the model residuals (Peterson and Cavanaugh, 2019): according to the best available fit, square root, Yeo-Johnson or ordered quantile transformation was applied (see more details in Appendix F). Only the daily means were

analysed in the case of dRH and dVWC, and besides the means, minima and maxima were also tested in the case of the thermal conditions. In all models, treatment type (four levels: LC, LE, SC, SE) was used as fixed factor, while block was specified as random term. As we used relative values (differences from the corresponding control), the control treatment itself was not applied as a level, thus zero values represent the control. The models' goodness-of-fit values were measured by a likelihood-ratio test-based coefficient of determination (R^2_{LR}; Bartoń, 2020), and the explanatory power of the treatments was evaluated by analysis of deviance (F-statistics; Faraway, 2006). Differences among the treatment levels were determined using Tukey's multiple comparisons procedure (alpha = 0.05) for all pairwise comparisons based on the post hoc general linear hypothesis test (Bretz et al., 2010). The significance of the differences between the control and the treatment levels were tested by linear mixed effects models without intercept (Zuur et al., 2009).

For the analysis of the spatial distribution of light (DSF and ISF) and soil moisture (VWC; %) within the gaps we conducted a spatial interpolation process with regression kriging, accounting both for treatment-related external drifts and for the spatial autocorrelation structure of the data (Dale and Fortin, 2014; Oliver and Webster, 2014). Relative values were calculated for each point as differences from the arithmetic mean of the corresponding 41 control points in each of the four blocks (hereafter dDSF, dISF and dVWC; %). Regression kriging was done separately for each variable in each individual gap, based on linear regression and variogram models fit to the empirical data from the 41 systematically placed sampling points within the given gap (Appendix G). For the deterministic part, we defined and calculated three factors influencing the responses: the distance of the point from the closest tree canopy boundary, the easting, and the northing geographic coordinates (CRS: EPSG:23700). Canopy boundaries defining actual gap polygons were delineated in QGIS 3.8 (QGIS Development Team, 2019) based on the crown projection of the trees in the adjoining stand (see Appendix C). Kriging was carried out over an interpolation grid shaped and sized according to the applicable theoretical gap geometry, centered in the centroid of the actual gap polygon. For the visualization of the general patterns across treatments, mean values were calculated for each grain cell of the theoretical gap grid across interpolation grids of the four blocks belonging to each treatment. The details of the spatial analysis, including the models, model diagnostics and variograms, can be found in Appendix G. Moreover, for the comparison of within-gap and under-canopy patterns of dDSF, dISF and dVWC, we selected the points along the transects on the main cardinal directions (north-south and west-east), and fit generalized additive models with integrated smoothness estimation to predict the variables along these main gradients.

The data analyses were performed using R version 4.0.1 (R Core Team, 2020). Add-on package 'bestNormalize' was used for data transformations (Peterson, 2021), 'lme4' was applied for the linear mixed effects models (Bates et al., 2015), *glht* function of the 'multcomp' package for multiple comparisons (Hothorn et al., 2008) and 'MuMIn' package for pseudo-R^2 values (Bartoń, 2020). The 'gstat' package was used for variogram modelling and regression kriging (Gräler et al., 2016; Pebesma, 2004), and the 'ggplot2' package for the comparison of smoothed conditional means along directions (Wickham, 2016).

3. Results

3.1. Responses in DSF, ISF, SWC, temperatures, and RH in the gap centers

The descriptive statistics of the studied relative variables in each treatment are found in Appendix F. dDSF did not differ significantly across the gap treatments in the gap centers, yet it was higher than the control in all gaps except for the SC (Fig. 2.*A*). dISF; however, was significantly different across the treatments and was linked to gap size. It was higher in LC gaps than in small gaps, while LE gaps had intermediate values (Fig. 2.*B*). dVWC was affected by gap shape (Fig. 2.*C*): it did not differ significantly from the control in elongated gaps, but it was significantly higher in circular gaps, independently of their size. Mean RH at 1.3 m remained similar to the
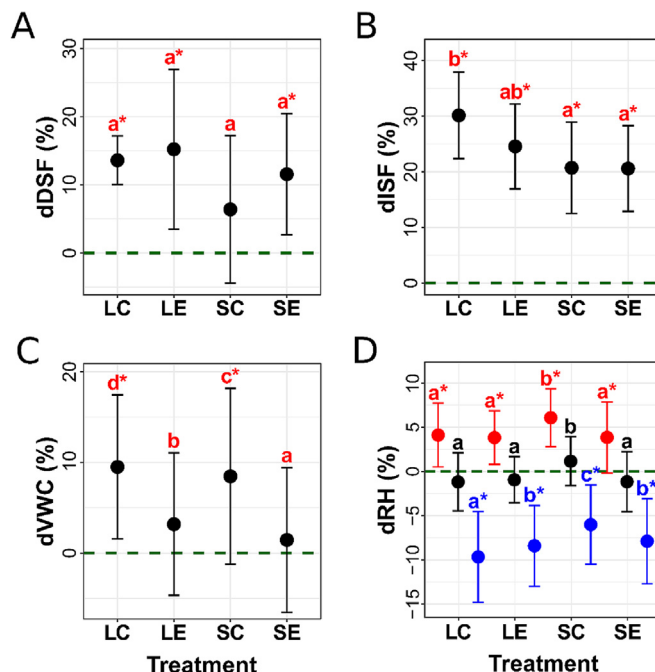
Fig. 2. Differences from the control (dashed green lines) in the gap centers in A: direct light (dDSF), B: indirect light (dISF), C: soil moisture (dVWC) 8–14 cm below ground, and D: daily mean (black), daily maximum (red) and daily minimum (blue) relative humidity (dRH) at 1.3 m above ground. Treatments: LC = large circular, LE = large elongated, SC = small circular, SE = small elongated gaps. Different letters indicate significant differences from pairwise multiple comparisons between treatments (Tukey's test based on the performed linear mixed effects models, alpha = 0.05). Asterisks mark significant differences from the values measured at the control plots, represented as zero values (alpha = 0.05). Full circles show the mean and vertical lines denote the standard deviation of the samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

control levels in all gaps, while maxima increased, and minima decreased in all gaps. However, dRH values were significantly higher in the SC gaps than in the other gaps, indicating a slightly, yet non-significantly elevated RH in SC gaps (Fig. 2.*D*).

Air temperature responses were different depending on the measurement levels: the gap-cuttings induced a significant warming effect in temperature means at 130 cm (with an increase of approx. 0.2 °C in mean temperatures, Fig. 3.*A*), yet a cooling effect at 15 cm (significant only in circular gaps, with a decrease of approx. 0.3 °C in mean temperatures, Fig. 3.*B*). Mean dT_0 (Fig. 3.*C*) and dT_{-8} (Fig. 3.*D*) did not differ significantly from that in the controls. However, above-ground diurnal temperature variability was significantly higher in all gaps than that in the control plots: minima were lower, and maxima were higher with larger effect sizes in the case of the latter variable type. dT_{130} was the largest in large gaps, where minima and maxima were also the most divergent from the control. Furthermore, dT_{130} mean and dT_{130} max were both higher in the LC than in the LE gap centers (Fig. 3.*A*). Nearer to the soil surface, however, the effect of gap shape became apparent, too. dT_{15} mean revealed that near the ground, circular gaps were significantly cooler than the controls, while elongated gaps remained unaffected, regardless of gap size (Fig. 3.*B*). Despite non-significance when compared to the control, this trend is also apparent in dT_0 mean (Fig. 3.*C*). Moreover, dT_{15} max and dT_0 max both showed that the circular gaps attenuated surface temperature maxima better than the elongated gaps, which effect was the strongest in SC gaps, where it was apparent even in dT_{-8} max. dT_0 means and ΔT_{-8} means did not differ significantly from the control; however, there were significant contrasts between the treatments (Fig. 3.*C-D*). dT_0 mean was significantly lower in circular than in elongated gaps, and the LE was cooler than the SE. The across-gap differences in dT_{-8} mean despite their significance, were small, the SC
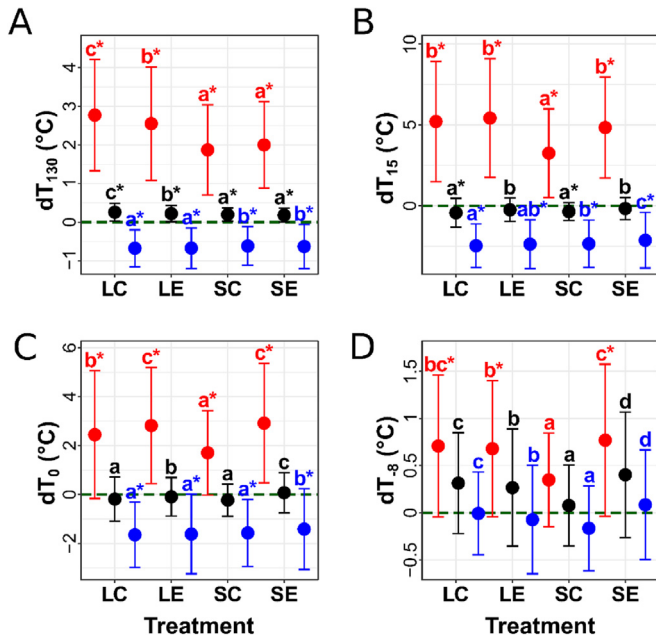
Fig. 3. Differences from the control (dashed green lines) in the gap centers in daily mean (black), daily maximum (red) and daily minimum temperatures (blue). A: 130 cm above the ground (dT_{130}), B: 15 cm above ground (dT_{15}), C: at ground level (dT_0) and D: 8 cm below ground (dT_{-8}). Treatments: LC = large circular, LE = large elongated, SC = small circular, SE = small elongated gaps. Different letters indicate significant differences from pairwise multiple comparisons (Tukey's test based on the performed linear mixed effects models between treatments, alpha = 0.05). Asterisks mark significant differences from the values measured at the control plots as zero values (linear mixed effects models without intercept, alpha = 0.05). Full circles show the mean and vertical lines denote the standard deviation of the samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

treatments being the coolest, and remaining closest to the control (Fig. 3.D). Generally, at higher levels (1.3 m) temperatures were determined mainly by gap size (larger gaps were warmer), while near the ground mainly by gap shape (circular gaps were cooler, and SC gaps were the coolest).

Since slightly different temperature responses were found to the treatments according to the measurement heights (Fig. 3.) that reflect both the gap-induced changes in light and soil moisture, supplemental models were created to test the combined and opposite effects of these two variable groups on temperature values. As it was expected, indirect and direct light had an overall warming effect on temperatures while soil moisture lowers this heating. The buffering effect of soil moisture was the strongest at 15 cm (i.e., the height of the understory layer) and on the soil surface, which might result in the negative and significantly lower dT_{15} means in LC and SC gaps compared to the control or being dT_{15} max lower in LC than that in SE gaps. Incoming radiation on dT_{130} and soil temperatures had higher relative importance than soil moisture, which was reflected by the clear difference among gap sizes. For more details on the supplemental models see Appendix H.

3.2. Spatial distribution of DSF, ISF and SWC within the whole area of the treatments

The interpolation maps shown here for each treatment were created to represent the treatment-level average values of the individual gap-level interpolation maps (Appendix G). In the case of dDSF, they revealed a markedly decreasing north–south gradient. This was present in all gaps, and it was the most pronounced in LC gaps, which received the highest amount of direct light in the greatest area. All other gaps were comparable in their dDSF maxima; however, the area of the patch receiving a considerable amount of direct light was larger in the SC than in the SE. It was even larger

in the LE gaps, though their southern parts were comparable with the control (Fig. 4.A). As opposed to the gap centers, in the northern parts of the gaps there were marked differences in dDSF between gap types.

Indirect light increased concentrically in all gaps. dISF levels were the highest in the LC gaps. There were considerable areal differences between the large gaps, as a substantial indirect light increment expanded to the whole area of the LC, while accordingly high values were contained only within the central area of LE gaps (Fig. 4.B). The small gaps were similar regarding the magnitude of change, yet the area characterized by increased dISF levels was greater in the circular gaps than in the elongated ones. It was also apparent that the maximum central dISF values of small gaps (0.15–0.2) occurred at the edge of the large gaps.

Soil moisture generally increased in all gaps, particularly in the central and southern parts (Fig. 4.C). dVWC levels were the highest in the LC gaps, where multiple local maxima developed around, and slightly south from the gap center. The second largest increment was found in the SC gaps; however, here only one maximum emerged close to the gap center. Regardless of gap design, the dVWC levels in the northern part of the gaps were equivalent to or decreased compared to the control levels.

By fitting trend lines based on generalized additive models to the points located exclusively on the north-south and west–east transects, we could quantify and compare gap interior–gap exterior gradients of light and soil moisture along these two main geographical directions (Fig. 5.). dDSF maxima were reached close to the northern gap edge in all gaps (Fig. 5.A). Increased dDSF levels were detectable under the closed canopy areas north from the gaps until about 20 m from the gap center. Even though dDSF values in the large gaps were comparable at the centers, the northern halves of the LC gaps were considerably more illuminated. Similar trend lines characterized the elongated gaps, while the gradient in SC gaps was more flattened than that of the LC gaps. Along the west–east transect, even though the dDSF levels were increased in the small gaps, they did not show a trend. There was however a characteristic symmetry in the large gaps, with a slight westward shift in the maximum of the LC and an eastward increment in the case of LE. The distribution of dISF was generally concentric and symmetric along both transects, and under-canopy areas received an indirect irradiation surplus in all gaps (Fig. 5.B). The trend lines of dVWC along the north-south transect were counterpointing the according trend lines of direct light (Fig. 5.C). In the SC gaps this southward shift in the distribution of dVWC surplus within the gap area was less characteristic since the highest values were found surrounding the center. Whilst soil moisture was increased under the closed canopy far beyond the southern edge of the gaps, it returned to the control levels at the northern gap edge already and decreased further under the closed canopy. In the elongated gaps, soil moisture levels were higher than in the control, but their distribution along the west-east transect was even. In the circular gaps, however, there was a bell-shaped trend, and values were slightly higher at the eastern gap edges than at the western ones.

4. Discussion

4.1. Light responses vary depending on the diffuse vs. direct component and within-gap position

Incoming solar radiation increased in all treatments: in our study, direct light increased in the gap centers by 6–15 %, and even more in the northern gap sides (30–50 %), while indirect light maxima were located in the gap centers, where the increase was 20–30 %. Light increases as the canopy layer is more opened, and 150–300 m^2 sized gaps are generally found to receive significantly more radiation compared to closed stands: on average, 1–6 % more diffuse and 1–8 % more direct light reaches the ground over the whole area of the gaps, and 11–13 % diffuse and approx. 8 % direct light surplus is found in gap centers (Diaci, 2002; Diaci et al., 2020; Gálhidy et al., 2006; Gray et al., 2002).

Light increment was primarily determined by gap size, as differences between the treatments were the most expressed in large gaps for both light components. The determinative effect of gap size on light increase
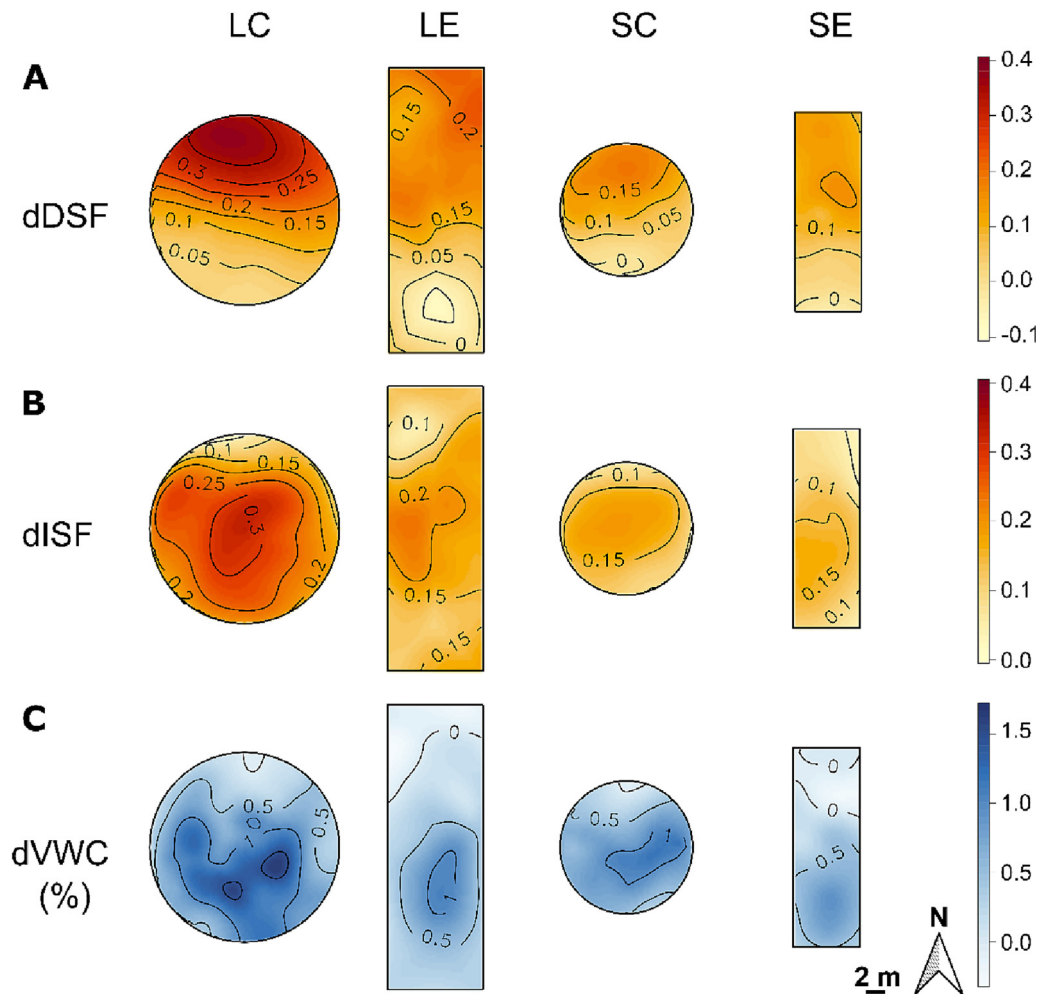
**Fig. 4.** The average interpolated spatial distribution of the differences from the control levels in A: direct light (dDSF), B: indirect light (dISF) at 1.3 m, and C: soil moisture (dVWC; %) at 7.5 cm below ground. Treatments: LC = large circular, LE = large elongated, SC = small circular, SE = small elongated gaps.

was suggested already by Canham et al. (1990), and has been proven in temperate forests by several case studies (Bagnato et al., 2021; Gálhidy et al., 2006; Reuling et al., 2019; Vilhar et al., 2015).

While the gap size–irradiance relationship is quite universal across forest types and studies, the effect of gap shape on irradiance is much less studied (Lima et al., 2013); however, narrow, elongated gaps are expected to receive less radiation than circular gaps (Muscolo et al., 2014). At the gap centers, the shape did not influence the increment neither in the indirect nor in the direct light components of incoming radiation. Nevertheless, gap shape clearly affected the patterns of direct light and the variability of within-gap positions. Due to the course of the sun, circular gaps can receive more light, as radiation reaches the surface from multiple directions (SE, S, SW, in the northern hemisphere) and for a longer duration throughout the day (Carlson and Groot, 1997). In elongated gaps, however, increased illumination is limited to a shorter timeframe, which is determined by the orientation of the main axis (Brang, 1998). Thus, larger within-gap light differences emerge in circular gaps; while elongated gaps are characterized by smaller maxima and a more balanced light environment. These findings align with the theoretical considerations and findings on the spatial variability of light within gaps outlined by Canham et al. (1990) and corroborated by Diaci et al. (2008). Differences between circular and elongated gaps were the most expressed along the north-south axis, and both tested shape types resulted in similar patterns along the west-east axis, suggesting a significant shading by neighbouring trees even in the case of large circular gaps.

In the gap centers, the treatment effect was more pronounced on the diffuse than on the direct component of light. Differences in direct light across the treatments evolved in the northern gap sides, according to the asymmetrical distribution of direct light along a north-south gradient. When the total incoming radiation is partitioned into direct and diffuse components, it is generally true for the northern hemisphere that the northwestern parts of gaps receive more direct irradiation, resulting in a north-south light asymmetry, while the diffuse irradiation surplus is more concentric, as it is unrelated to the sun's position on the sky (Diaci et al., 2020; Gray et al., 2002; Ritter et al., 2005).

Artificial gap-induced changes in light regimes are important determinants of natural regeneration and are crucial in production forests dominated by light-demanding tree species such as oaks (Kohler et al., 2020; Mölder et al., 2019; Von Lüpke, 1998). After the first years of establishment, the shade-tolerance of 7–10 years old oak individuals decreases significantly and optimal height growth requires >20 % of light (Kohler et al., 2020; Mölder et al., 2019; Tinya et al., 2020; Von Lüpke, 1998). This is initially provided by all gap types applied in our experimental design, especially by the large ones (see Table F.3 but also Modrow et al., 2020). Light increment is also an important driver of the herbaceous vegetation (e.g., of its biomass, composition, or flowering intensity), which can act as an important competitor for oak regeneration (Kohler et al., 2020; Tinya et al., 2019). Light-induced vegetation changes also have significant effects on other trophic levels, further expanding the effect of gap size and gap shape on biodiversity (de Groot et al., 2016). In the more illuminated gaps, the probability of generative reproduction of surculose species and the relative abundance of flowering plants increase; moreover, with greater light availability, plants typically grow larger with larger floral displays which attract pollinator species and enhance zoochory (Eckerter et al.,
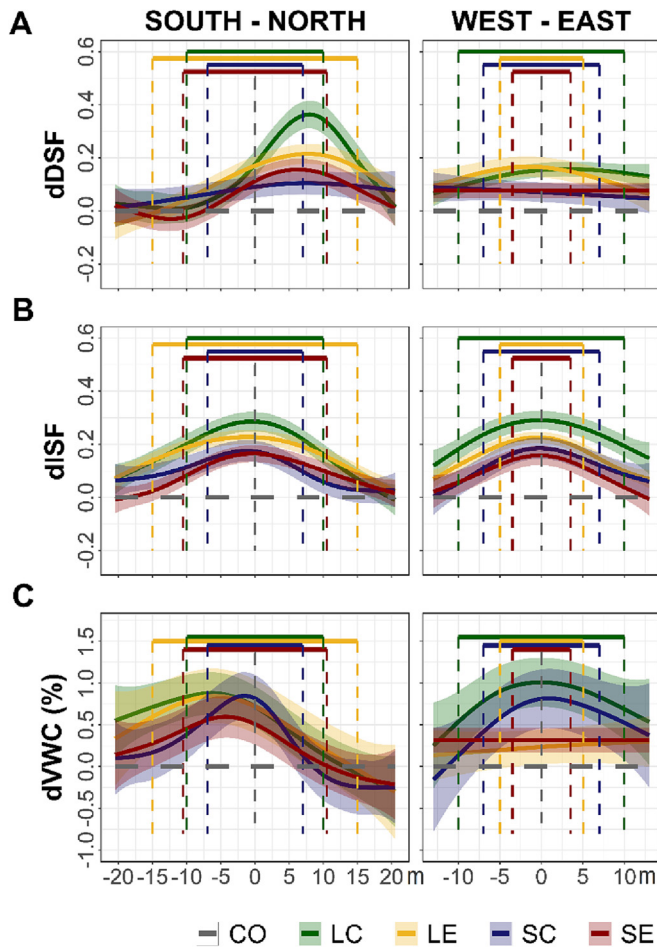
Fig. 5. GAM trend lines fit to A: relative direct light (dDSF), B: relative indirect light (dISF) and C: relative soil water content (dSWC) values against the distance of the sampling point from the gap center along the south–north (left) and west–east (right) transects, expressed in meters. Treatments: LC (green): large circular gap, LE (yellow): large elongated gap, SC (blue): small circular gap, SE (red): small elongated gap. Gap extents are indicated with horizontal lines, from which descending vertical dashed lines mark the gap edges. A gray-coloured vertical dashed line shows the gap center, and a horizontal one marks the control (zero) values. The coloured bands show confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2019; Kilkenny and Galloway, 2008; Proctor et al., 2012). Besides, light also has important effects on the thermoregulation of adult insects, their activity patterns, and the duration of larval development (Bouget and Duelli, 2004).

4.2. Soil moisture is affected the most by gap shape, and increases the most in the central area of large circular gaps

While soil moisture increased in all gap centers, the increment was significant only in the circular gaps (approx. 10 % increase for both gap sizes), clearly indicating a shape-driven response. In temperate forests, the increase of soil moisture after gap openings is a common response, although effect sizes highly depend on the topography, the soil texture, and weather conditions of the actual measurement years (Bigelow and North, 2012; Diaci et al., 2020; Gray et al., 2002; Lewandowski et al., 2015; Scharenbroch and Bockheim, 2007; Vilhar and Simončič, 2012; Zhu et al., 2003). Studies conducted in oak forests by Sariyildiz (2008), Tinya et al. (2019), Kollár (2017), and Abd Latif and Blackburn (2010) have also reported an increase in soil moisture in gaps, within the range of 2–36 % compared to the closed stand. This soil moisture increase is

generally driven by the decreased interception loss by the opened canopy, and by the decrease in transpiration with the loss of tree individuals (Bonan, 2016; Muscolo et al., 2014).

Both gap size and gap shape had a determinative effect on soil moisture, as the soil of large gaps was more humid than that of smaller gaps, and the soil of circular gaps was more humid than that of elongated ones; however, the effect of shape proved to be more important. There are studies demonstrating that soil moisture increases with gap size (e.g., Abd Latif and Blackburn, 2010; Gray et al., 2002). The effect of gap shape is less studied, in spite of its similarly key effect on the size of root gaps, i.e., the area within the gaps where the root system of the trees surrounding the gap cannot reach, and where evapotranspiration is consequently decreased (Gray et al., 2002; van Dam, 2001). In circular gaps, the area where tree roots are absent is expected to be larger than in elongated gaps, which explains the shape-related soil moisture differences found in our study (Schliemann and Bockheim, 2011; van Dam, 2001).

In our study, all gaps were characterized by a north–south asymmetry in soil moisture, negatively corresponding to that of direct light. Soil moisture is generally reported to have its maximum in the central-south area of the gaps, and to decrease towards the closed canopy from the gap center (Gray et al., 2002; Ritter et al., 2005). The lower soil moisture in the northern parts can be attributed to the enhanced drying effect of the increased incoming direct radiation, which affects transpiration and evaporation. Altogether, we found a greater spatial variability in the patterns of soil moisture in circular, especially in large circular gaps. We assume that this is linked to root gaps as well, as the absence of evaporation by trees can unfold soil moisture differences caused by microtopography, and by the fine-scale heterogeneity of vegetation and soil texture, which can contribute to spatial heterogeneity (Vereecken et al., 2014).

In mesic forests such as our experimental site, the elevated soil moisture availability induced by the opening of gaps is expected to support the original forest character of the gap vegetation, and to increase the biomass production (Gálhidy et al., 2006; Kermavnar et al., 2019; Tinya et al., 2019). Increased soil moisture induced by the opening of such small to intermediate gaps can also contribute to the diversity of soil meso- and macrofauna (Boros et al., 2019; Peng et al., 2022).

4.3. Relative humidity in gap centers remains close to that of the closed mature stands

We expected that gap creation reduces air humidity due to enhanced air mixing and insolation, but this effect can be somewhat mitigated by elevated soil moisture levels. Contrary to our hypothesis, we found that mean air humidity in the gap centers remained unaltered as compared to the controls, although its variability increased. Despite the rise in irradiation and thus incoming energy, in gaps, air mixing is still reduced by the surrounding stand, and elevated soil moisture levels act as an additional source of evaporation and evapotranspiration by understory vegetation (Abd Latif and Blackburn, 2010; Geiger et al., 2009; Kovács et al., 2018; Whitmore et al., 1993). Nevertheless, in small circular gaps, relative humidity was slightly exceeding that of all other gap types. The opposing effects of soil moisture and the desiccating power due to the incoming energy were the most noticeable in the comparison of large and small circular gaps. In larger openings, the increased light and air-mixing can reduce air humidity (Geiger et al., 2009; De Frenne et al., 2021), which can only partly be compensated by the increased soil moisture; while in the smaller gaps, vaporization due to elevated soil moisture can outweigh the drying capacity of incoming radiation.

Air humidity was proved to be an important driver of the diversity and community assemblages of many forest-dwelling organism groups such as plants (Lendzion and Leuschner, 2009), terricolous saproxylic fungi (Tinya et al., 2021), carabid beetles (Negro et al., 2014), spiders (Samu et al., 2014) or amphibians (Brooks and Kyker-Snowman, 2008). According to our results, mean conditions do not change regardless of the applied gap sizes and shapes (150–300 m^2), which suggests that gap-cutting up to one height-diameter ratio can maintain the original humid character of mesic

forests—contrary to clear-cuts (e.g., Kermavnar et al., 2020; Kovács et al., 2020)—and cryptogams might even benefit from increased maxima (Frahm, 2003; Heylen et al., 2005). Creating gaps therefore can be a beneficial forest management alternative in production forests that maintains original humidity conditions after the harvests. This is an important positive consequence both for forest biodiversity and forest regeneration – especially facing more frequent drought events under current climate change (Archaux and Wolters, 2006; Lendzion and Leuschner, 2008; Thom et al., 2020).

4.4. Temperature responses vary along measurement heights, revealing an intricate interplay between soil moisture and light

In general, we found that maximum temperatures increased and temperature minima decreased in all treatment types with the magnitude of change comparable to previous studies (e.g., Abd Latif and Blackburn, 2010; Carlson and Groot, 1997; Clinton, 2003; Kermavnar et al., 2020; Thom et al., 2020). However, the effect of gap-cuttings varied according to the measurement strata. At 1.3 m above ground, all temperature metrics showed a significant increase, with effect sizes comparable to, yet slightly smaller than demonstrated by previous studies (Gray et al., 2002; Kermavnar et al., 2020; Ritter et al., 2005; Whitmore et al., 1993). Gap size, however, was clearly linked to an increased air temperature only at this level, i.e., above the typical height (approx. 25 cm) of the herbaceous vegetation of the gaps.

Cooler conditions were detected in the 0–15 cm strata in all gap types than under the closed canopy with gap shape driven between-treatment differences in both means and maxima. Lower temperature regimes followed by canopy opening are rarely reported by previous studies (e.g., Abd Latif and Blackburn, 2010; Gray et al., 2002 – in small gaps only, and Špulák and Balcar, 2013 – at 30 and 60 cm), which might partly be due to the applied measurement heights.

Soil temperature means did not differ from the control levels in any of the gap types, only a slight, non-significant increment could be detected in the means ($dT_{-8} < 0.5$ °C), which however was much less than expected (compared to e.g., Abd Latif and Blackburn, 2010; Gray et al., 2002; Ritter et al., 2005). We hypothesized that an irradiance-induced increase in T_0 and T_{-8} would be counteracted by the evaporative cooling driven by excess soil moisture (De Frenne et al., 2021; Von Arx et al., 2013). Indeed, this was reflected in the vertical pattern of temperature offsets near the ground (up to 15 cm above the ground).

Gap size is the major determinant of the near-ground temperature pattern, as it is closely related to the amount of incoming solar radiation, which is the main source of heat load (Bonan, 2016; Gray et al., 2002; Whitmore et al., 1993). However, temperature responses are also affected by the moisture of a given site, and thus by gap shape, since soil water content reduces local temperatures by transforming incoming energy into latent heat through evaporative cooling (Davis et al., 2019; Von Arx et al., 2013). The effect of the latent heat of vaporization is primarily driven by soil evaporation and the evapotranspiration of understory vegetation, and thus it has a significant effect on temperatures measured nearer the ground (Landuyt et al., 2019; Von Arx et al., 2013). The combined and opposite effects of incoming radiation and soil moisture on temperatures were tested (Appendix H), and we found a consistent relationship—reduced buffering capacity when gaps are more illuminated and drier—with light being the overall stronger predictor.

Our results suggest that in mesic forest stands, artificial gaps induce moderate changes in the near-ground temperature if their size is not larger than 1:1 gap diameter per tree height ratio, thus we can suppose that they do not act as detrimental to the forest-dwelling communities and to biological processes as larger clearings (e.g., Elek et al., 2018; Keenan and Kimmins, 1993). As one important driver of the thermal regimes of artificial gaps found here is soil moisture levels increasing or remaining similar to those under the closed forest, artificial gaps might be favorable to the less mobile soil organisms, especially in the cores zones and the more shaded and southern parts (Boros et al., 2019; Elek et al., 2018). Within-

gap thermal patterns can also reinforce the gap partitioning of herbaceous vegetation by influencing germination success or mortality rates (Fahey and Puettmann, 2007). Our findings suggest that the slight increase in the maximum temperatures and in general, the local removal of canopy trees, and a more open forests on the landscape level can also lead to thermophilization in understory plant communities (Thom et al., 2020; Zellweger et al., 2020).

5. Management implications

5.1. Microsite heterogeneity and biodiversity

The north-south asymmetry in direct light, complemented by a reverse trend of soil moisture, and a disparate trend of diffuse light creates microsite heterogeneity within gaps, which is higher in case of circular than in elongated, and in case of large than in small gaps. Ultimately, a larger microsite heterogeneity might lead to a greater diversity in the herb layer, and thus a greater diversity in other trophic levels, too. However, the recording of biotic responses is an ongoing task since the start of the experiment, and our extensive multi-taxon approach will only enable us to draw a comprehensive overview of community ecology changes during the coming years.

5.2. Microclimatic buffering capacity

Even though the observed effects linked to the gap-cuttings induced significant changes in most microclimate variables, as opposed to effect sizes typical in clear-cuts, the effects were moderate in general (Carlson and Groot, 1997; Kermavnar et al., 2020; Kovács et al., 2018). In the face of recent and predicted macroclimatic changes, it is important to see how the buffering capacity of the opened stands is altered, and whether the emerging conditions provide suitable microenvironments for tree regeneration (Thom et al., 2020; Blumröder et al., 2021). All applied gap types were able to sustain the relative humidity and temperatures near the ground characteristic to closed stands. However, larger gaps experienced a more intense heat effect above ground, and circular gaps could buffer relative humidity and temperatures more via evaporative cooling, which might gain critical importance with regard to heat and drought stress, especially in the face of predicted climate change. Based on our present results however, by opening gaps of 150–300 m^2 size, forest managers can maintain the buffering capacities of forests on the local scale, while they can also govern the site conditions to be favorable for the regeneration and growth of the target oak species by considering gap size, shape, or direction (Diaci et al., 2020; Kollár, 2017).

6. Conclusions and further perspectives

We demonstrated that experimental gap-cuttings change microclimatic conditions significantly in the first year after their creation in an oak-dominated stand. Light is affected mostly by gap size. Soil moisture is mostly influenced by gap shape as a consequence of drying by the incoming radiation and root systems of the neighbouring tree individuals. Temperatures depend on both factors, while mean air humidity shows insignificant changes. Temperature responses vary according to the measurement heights: above the understory vegetation, the temperature is influenced mainly by incoming radiation, i.e. gap size; however, soil moisture levels through buffering by evaporative cooling become also important nearer the ground, which is mainly governed by gap shape (circular gaps remain cooler environments). Distinct spatial microclimatic patterns emerge within the gaps, driven both by gap shape and gap size: the northern parts of the gaps receive the highest amount of direct irradiance but become also the driest, while increment in diffuse light and soil moisture are typical characteristics of core zones. We also demonstrated the most pronounced patterns (concentric for diffuse light, north-south gradient for the direct component and soil moisture) can emerge in the large circular gaps, nonetheless, our approach has provided a universalized overview of these

patterns in all applied gap types, by studying patterns based on averaged effect sizes. We conclude that 150–300 m² sized management-created gaps can maintain forest microclimate in line with providing enough light for oak regeneration; and that the manipulation of gap shape and gap size within this range are effective tools of adaptive forest management.

Gap-cutting is widely used in the framework of continuous cover forestry in oak-dominated stands, but the appropriate size, shape and whether the gaps should be progressively opened, remains ambiguous. Thus, as a continuation of our study, we plan to enlarge small elongated gaps in the following years, to evaluate how gap extension affects oak regeneration and the decisive environmental factors driving its response. Our sampling approach will provide a chance to evaluate the link between light and soil water content and regeneration responses of oaks not only within the area of the gaps but also in the edge environments, potentially revealing species-specific regeneration responses to resource heterogeneity within and around the area of gaps.

CRediT authorship contribution statement

Csenge Veronika Horváth: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Visualization. **Bence Kovács:** Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Visualization. **Flóra Tinya:** Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing. **Julia Schadeck Locatelli:** Investigation, Writing – review & editing. **Csaba Németh:** Investigation, Writing – review & editing. **Lorenzo Crecco:** Investigation, Writing – review & editing. **Gábor Illés:** Investigation, Methodology, Writing – review & editing. **Péter Csépányi:** Conceptualization, Writing – review & editing. **Péter Ódor:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

Data is available on the Open Science Framework (https://osf.io/kn3eu/).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Supplementary material associated with this article can be found online at doi: https://doi.org/10.1016/j.scitotenv.2023.162302. Appendix A: General observations and common knowledge gained by Hungarian foresters focusing on the possibilities of CCF in oak forests. Appendix B: Tree species composition and forest structure data of the experimental stand. Appendix C: Specification of the hypothetical and realized gaps and the comparison of their size and shape. Appendix D: Pictures of the gaps and the microclimate loggers. Appendix E: Overview of the systematic design used for fine-scale sampling. Appendix F: Raw aggregated microclimate data, summary statistics and model tables. Appendix G: Comprehensive documentation for the spatial analyses performed. Appendix H: The relationship between light (direct and indirect site factor separately), soil moisture and temperature measured at different heights.

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