Eötvös Loránd University

Faculty of Natural Sciences

Centre of Environmental Studies

Effects of gap size and shape on the understory vegetation in an oak-hornbeam forest

THESIS

Made by:

JULIA SCHADECK LOCATELLI

Environmental Sciences MSc

Supervisor:

Dr. Péter Ódor

Centre for Ecological Research

Budapest

2020

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1. Introduction

Nature conservation of forests is a global challenge due to direct and indirect negative human interference, such as climate change. Forests comprise high biodiversity of plants and animals, control soil erosion, affect the water sources, act as climatic regulators and fix carbon dioxide from the atmosphere. In addition, forests have important social and economic roles as well.

In Europe, according to a report on the state of the continent's forests published by the Ministerial Conference on the Protection of Forests in Europe (Forest Europe, 2015) the area of forests undisturbed by human intervention is only around 4% of the continent's forested area. In the continent, the forested area has increased in the last 25 years, due to afforestation and the expansion of forests (Forest Europe, 2015). Although the increase in the forested area is good news, not only the extent of forests needs to be assessed, but their state of naturalness too. Regarding this, it is reported that almost 70% of the forested areas in Europe are even-aged (Forest Europe, 2015). In Hungary, 100% of the forested area is subject to management plans (Anonymus, 2016), out of which 62.4% has as production as a primary function (Anonymus, 2014). In this country, approximately 21% of the forested area is protected either on the national or on the local level, 85% of which are managed by state-owned forestry companies (Anonymus, 2016).

In this way, forest management has an immeasurable responsibility for forest conservation, especially in European countries. Coates and Burton (1997, p. 338) emphasize that silvicultural systems are challenged to "(…) evolve beyond their traditional emphasis on timber production to include the broader objectives of protecting sensitive species, sustaining ecosystem functions (diversity, productivity, nutrient cycling and resilience) and identifying sustainable levels of use for a broad range of renewable resources".

Forest stands presenting uniform structures and species composition are not sufficiently fulfilling nature conservation purposes, thus forest management needs to take these factors into account and increase the use of close-to-nature silvicultural systems (Angelstam, 1996). Consequently, forestry experiments are indispensable to comprehend how forest management practices affect forest site conditions, regeneration and biodiversity, as stressed by Kovács et al. (2018).

The forest investigated in this study is a mesophytic deciduous forest (European Environment Agency, 2006), a typical example of the sessile oak-hornbeam forests of Hungary, which are important from both economical and conservational aspects in the country. It is even-aged and composed mainly by sessile oak (*Quercus petraea* Liebl.) and hornbeam (*Carpinus betulus* L.). The aim motivating this study is to convert this type of stands to more diverse, uneven-aged, continuous woodlands. This is supported by the new directives in silviculture in Hungary, which are calling for a management shift to nature-based silvicultural methods (Anonymus, 2016).

European temperate oak woodlands have a great value for biodiversity conservation, particularly relevant for their relation to saproxylic species (Mölder et al., 2019). Equally, sessile oak has a very good quality of wood and has high economic value, which makes it more significant to develop management methods able to maintain the economic targets and protect the oak forests ecosystems (Mölder et al., 2019).

The provision of vital oak regeneration is one of the main challenges of continuous cover forestry in oak-dominated stands, as sessile oak saplings are especially light-demanding (Lüpke, 1998; Mölder et al., 2019). The hornbeam, beech (*Fagus sylvatica* L.) and lime tree (*Tilia cordata* Mill.) are commonly used as admixture species in oak forests to avoid the presence of knots on the lower trunk and the formation of epicormic branches, which decrease the quality of the wood (Lüpke, 1998). But, despite these advantages of the second canopy layer, these other tree species can outcompete for light and hamper oak regeneration.

Regarding hornbeam, which can regenerate easier and faster than oak (Sikkema et al., 2016), even though it is a shade-tolerant species, the light incidence also interferes in its regeneration, which appears to be enhanced in gaps (Salamon-Albert et al., 2018). In the case of pedunculate oak (*Quercus robur* L.), one study on gap openings showed a big challenge in regenerating this oak species in bigger gaps because of the higher solar irradiance and consequently the better understory development of other species (Diaci et al., 2007). Other studies suggest that small scale forestry management methods favor the development of shade-tolerant species, which changes considerably the composition of the forest ecosystem (Knapp et al., 2019). So, the application of continuous cover forestry and the management of light availability in oak forests are more complicated compared to other European temperate tree species, such as beech and fir (*Abies alba* Mill.) (Schütz et al., 2016).

Other conditions that interfere with the natural regeneration of oaks are the availability of seeds, as acorns have limited dispersion abilities in forest openings and oaks have irregular seed production between years (Tinya et al., 2020), and intensive predation by wild animals (Lüpke, 1998).

Besides the importance of understanding how natural regeneration of oak occurs under continuous cover forestry, the herbaceous layer is the most biodiverse component of the forest

(Gilliam, 2007), which drives our attention to how silvicultural practices affect the understory vegetation and how this forest stratum interferes in the regeneration of tree species after the implementation of forest treatments.

Muscolo et al. (2014) suggest gap cutting as a useful tool to secure sustainable forest development. Likewise, the case study of Tinya et al. (2019) in an oak-hornbeam stand reported that gap cutting provided appropriate light conditions for natural regeneration, but it maintained the moderated forest microclimate and understory conditions compared to larger scaled clear-cuttings. Kovács et al. (2018, 2020) also suggest small scale forestry treatments in this forest type, in order to maintain higher ecosystem functionality and contribute to nature conservation.

To convert Hungarian oak-hornbeam forests to the continuous cover forestry system it is critical to choose the ideal size and shape of gap openings that should be applied in order to have enough light to enable oak regeneration and prevent other species to outcompete oak. Different gap designs cause different effects in multiple conditions of the forest ecosystem such as light, soil moisture, temperature, and nutrients, which consequently affect the understory vegetation and forest regeneration (Muscolo et al., 2014).

1.1. Objectives

The Pilis Forestry System Experiment has started in 2014 to compare the effects of different silvicultural treatments in an oak-hornbeam forest, within a broad range of variables: microclimatic conditions, the soil and litter characteristics, different animal groups (ground beetles, spiders, enchytraeid worms, flies), the understory vegetation and the woody regeneration (Elek et al., 2018; Kovács et al., 2018, 2020; Boros et al., 2019; Tinya et al., 2019, 2020). The following treatments were used in this experiment: clear-cutting, preparation cutting, retention tree group, gap cutting, and mature closed forest as control.

The Pilis Gap Experiment was initiated in 2018 with the aim of identifying which kind of gap should be created to simultaneously guarantee the natural regeneration of the forest, the preservation of the forest microclimate and the soil conditions, and thus the conservation of the biodiversity. In this research project we study the effects of gap size (small, 150 m^2 and large, 300 m^2), gap shape (circular and elongated) and the methodology of the creation (gaps created in one step or a gap created in two steps: a small elongated gap enlarged some years later to large circular). This second, extended gap type is currently the same as the small elongated gap, so this is excluded from the current analysis.

This thesis work is a preliminary study of the Pilis Gap Experiment and comprises the environmental and vegetation responses recorded in the first growing season after the creation of the gaps. We aim to compare how the different gap designs affect the understory vegetation, soil moisture, canopy openness and incident light. Besides, we intent to verify the patterns of changes in each gap type, considering three zones within the gaps – center, edge and under canopy.

1.2. Hypothesis

We hypothesized that:

(1) the vegetation will not yet be affected by the gaps in the first growing season;

(2) larger gaps will show a greater increase in the soil moisture content, especially in the center of the gap, and the pattern of soil moisture will be different in elongated and circular gaps;

(3) the incident light will be greater in larger gaps, with different light patterns between elongated and circular gaps.

2. Literature review

2.1. Temperate forest dynamics

Ecosystems are continually changing, even without human interference. In the case of forests, a variety of disturbances occur in different frequencies and intensities, and their outcome depends on the state of the community preceding the disturbance (White & Picket, 1985). The work of Picket and White (1985) has been one of the most influential pieces describing natural disturbance and related patch dynamics. The authors define disturbance as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment" (White & Picket, 1985, p.7). The causes of disturbance are varied and are dependent on the type of the forest (e.g. evergreen or broadleaved deciduous), therefore natural disturbances should be studied in each forest type to determine which are characteristic in each of these ecosystems (White & Picket, 1985).

In the case of temperate forests, mainly small-scale disturbances are occurring, which are characterized by the death of individual trees (White & Picket, 1985). The same authors complement that these disturbance regimes are related to the age of the trees and the longevity of the species present in the area, as older trees are more susceptible to be affected by disruptive events, such as windthrows.

On the landscape level, disturbances can create different patch types, dependent on the kind of disturbance and its impact. When many adjacent trees are affected, the patches created can be larger, and in case of scattered trees, they can be smaller (White & Picket, 1985).

Understanding natural forest dynamics is very important for forest conservation and management, as it can form the basis of and inspire the development of nature-based silviculture and the assessment of the ecological impacts of forestry (Parviainen et al., 2000).

2.2. Intermediate disturbance hypothesis

The intermediate disturbance hypothesis infers that higher species diversity is obtained by disturbance events with intermediate frequency or intensity, as these keep the community in a non-equilibrium state where succession can occur constantly (Connell, 1978). Connell (1978) initially proposed this hypothesis for the tropical forests and coral reefs, however, it has also been applied for other ecosystems.

In this hypothesis, Connell (1978) explains that too frequent or too immense disturbances will only generate suitable circumstances for species with higher dispersion ability to colonize the opened area. Long-term stability, on the other hand, would favor good competitors and drive the community to competitive exclusion and thus finally to a monospecific composition. The intermediate state, where early successional species and late colonizer species coexist, would result in higher species richness on a local scale.

Some authors criticize the unrealistic simplicity of the intermediate disturbance hypothesis, based on the fact that any disturbance event is dependent on the type of vegetation found in the area, therefore the frequency and extent of intermediate disturbances are specific to each ecosystem (Lindenmayer & Burgman, 2005). Another argument is that for biodiversity conservation it is not enough to analyze species richness alone (Lindenmayer & Burgman, 2005).

In their analysis of tree fall disturbances in tropical forests, Sheil and Burslem (2003) stressed that as in these forests tree fall disturbances do not increase significantly the light incidence, the regeneration of the forest occurs due to the sprouting of the stumps present or due to the growth of advanced regeneration, and so the disturbance does not actually affect the species richness. Therefore, the intermediate disturbance hypothesis is being tested and, in some cases, refuted.

Although the intermediate disturbance hypothesis is criticized in some aspects, according to a meta-analysis by Paillet et al. (2010), the species richness of vascular plants tends to be higher in managed forests than unmanaged ones due to management related disturbances. Small-scale silvicultural practices can increase the heterogeneity in forests, generating diverse patches and regeneration stages, creating an opportunity for a wide range of plant species to thrive. The challenge for forest managers is to resemble the frequency and intensity of disturbances ideal for each ecosystem type.

2.3. Forest management

Forest management practices are known to interfere with the stand structure and species composition of forest ecosystems (Márialigeti et al., 2016) and can change the natural disturbance regimes of the forests for large periods of time (Paillet et al., 2010). Human societies make use of forest products as building material, fuel, raw material for paper production, among other uses. Therefore, forest management needs to implement plans that meet the objectives for supplying these goods, considering economic factors as well as social and ecological aspects (Bettinger et al., 2017).

How forest management affects the environmental conditions and the species diversity depends on the type of management strategy used, especially on the intensity of harvesting. Considering the effect of silvicultural practices on forest structure, the following classification exists:

1. Rotation forestry systems: harvesting is carried out on the stand scale, and the following regeneration of the stand is achieved by either artificial or natural regeneration methods, creating even-aged and structurally homogenous forest stands (Matthews, 1989). Stand replacement harvesting methods are used, such as:
    a. the clear-cutting system: all mature trees in an area are removed in one step, and regeneration occurs mainly artificially;
    b. the shelterwood system: part of the mature trees remains to provide a source of seeds for the establishment and shelter for the growth of saplings; the remaining trees are removed gradually in a stepwise manner;
    c. the coppice system: all or part of the mature trees in an area are removed, and the regeneration occurs by the regrowth from the remaining tree stems.
2. Selection forestry systems: harvesting is carried out on a smaller scale, based on single tree selections and group selections, resulting in uneven-aged and structurally more heterogeneous forest stands. There are various implementations of this silvicultural system (Pommering & Murphy, 2004); the term we use in this work is continuous cover forestry. In this system there are no definitive rotation cycles affecting whole stands, as harvesting and regeneration are occurring concomitantly (Schültz et al., 2012). As the system is characterized by single tree selections or group selections, the structure of the forest is maintained so that biotic and abiotic disturbances can be kept to a minimum (Schütz et al., 2012).

This study is focused on gap cutting, which belongs to the continuous cover forestry system. Managing for continuous forest cover is not a new management strategy, but the interest in it is increasing due to growing concerns about environmental problems affecting forest ecosystems (Pommering & Murphy, 2004).

As continuous cover forestry is based on the imitation of natural disturbance regimes, the implementation in Europe is especially challenging due to the lack of primary forests which could be used as references (Kenderes et al., 2008). Therefore, continuous cover forestry experiments, fostering the observation and analysis of the effects of management related disturbances on the forest ecosystem, have a great significance to the implementation of continuous cover forestry methods and the substitution of even-aged forestry systems.

2.4. Gap environment

Forest gaps have been widely studied lately, as gap cutting has gained increasing interest as a forest management method. Scientific research has been mainly focusing on the understanding of how canopy gaps affect the forest environment and its regeneration, and the findings have been summarized in multiple review articles (e.g., Coates & Burton, 1997; Muscolo et al., 2014; Zhu et al., 2014).

Natural gaps are formed in a forest by the death or fall of one or multiple trees, or in some cases a large branch only, resulting in an opening in the forest canopy of an area smaller than 0.1 ha (Yamamoto, 2000). These disturbances can be caused by a variety of events, such as diseases, insects, snowfall, wind, fire, acid deposition and climate change (Schliemann & Bockheim, 2011).

The gap promotes multiple changes in the forest ecosystems, as it affects the light, the nutrients, litter, and creates regeneration microsites associated with the affected trees (Muscolo et al., 2014). As a result to gap creation, open space is created in the forest, and resources become more accessible.

The opening of gaps by forest management is different from the natural gaps to some extent, e.g. in artificial gap openings the stump and root system remains in the ground and the deadwood is most often removed from the site (Muscolo et al., 2014). However, in general, both artificial and natural gaps change some characteristics of the forest similarly.

In temperate forests, multiple experiments have shown an increase in soil moisture in canopy gaps when compared to the under canopy areas (e.g., Zhu et al., 2003; Gálhidy et al., 2006; Kollár, 2017). According to Collins et al. (1985) this is explained by the decrease in the water interception by the forest canopy, resulting in a higher amount of rainfall reaching the forest floor. In addition to that, the absence of trees in gaps decreases transpiration and thus the loss of water from the soil to the atmosphere (Zhu et al., 2003).

With the deletion of canopy trees, light is one of the factors that change considerably in the gap area, as even in a deciduous forest during the absence of leaves the trees obstruct the passage of light (Collins et al., 1985). The size of the gap has a substantial impact on the light availability in gaps, as in larger gaps more light tends to reach the ground level (Gálhidy et al., 2006). The shape of the gap also has a major impact on light availability: based on Schliemann and Bockheim (2011), less photosynthetically active radiation reaches the ground level in narrow gaps, as compared to circular gaps with an equal extent.

Soil temperature has been reported to increase in the gap area as well (Ritter et al., 2005; Latif & Blackburn, 2010). Collins et al. (1985) stressed that gaps show a higher temperature variation and higher temperature maxima in summer, as compared to closed canopy. Nonetheless, this condition seems to vary depending on the size of the gap and on factors as wind, insolation and soil cover.

Nutrient availability tends to increase in gaps, due to the rise in soil temperature and therefore the intensification in the activity of soil microbiota, and a consequently accelerated decomposition of the soil organic matter (Muscolo et al., 2014). The same authors suggest that the rate of litter decomposition depends on the gap size, however, results of different studies remain contradictory.

In general, environmental conditions have a mosaic structure in each gap. Different patterns exist in different regions of the gap, varying from its center to beneath the closed canopy (Collins et al., 1985). In addition, these changes are highly dependent on the gap size, as reported previously, and impact the forest vegetation and regeneration, as it is described in multiple studies (Zhu et al., 2003; Diaci et al., 2007). The shape of the gap affects the forest ecosystem as well, but there is a lack of studies focusing on this aspect.

The changes in the site conditions and resources in the gap are transient, and after the establishment and growth of the plants, the environmental variables return to the state previous to the disturbance (White & Picket, 1985).

2.5. Regeneration in forest gaps

As mentioned previously, subsequently to gap creation there is, generally, an increase in the availability of resources and more suitable conditions for plant growth, which allow succession to occur (White & Picket 1985).

Gap dynamics is defined as the formation of small openings and the regeneration of the area over time, which is closely related to the surrounding forest (Runkle, 1985). Right after the canopy opens by gap formation, the branches of the surrounding trees start to grow, causing the closure of the canopy, the rate of which depends greatly on the size of the gap. Smaller gaps have a large ratio of edge to interior, thus the growth of the branches of adjacent trees is proportionally more significant than in large canopy openings (Runkle, 1985). Thereby, larger openings give seedlings and saplings more time to grow and reach the canopy before the surrounding trees close the canopy. This also means that seedlings and stem sprouts that are already present in the area at the moment of the disturbance have an advantage (Sheil & Burslem, 2003). After the canopy closure, it is very unlikely that saplings and seedlings can reach the canopy layer, as they grow very slowly under shade (Runkle, 1985).

So, the establishment of tree species is influenced by the gap size, as larger gaps open the canopy more and consequently allow a higher incidence of light on the ground level, enabling shade-intolerant species to develop, while smaller gaps are more favorable for shade-tolerant species (Muscolo et al., 2014). According to Zhu et al. (2014), although shade-intolerant species are especially favored by forest gaps, regeneration of all functional types of woody plants increase substantially as an effect of the disturbance.

One of the factors influencing which tree species will establish after a disturbance is the availability of seeds at the site. Canham and Marks (1985) relate this to:

(1) seed production and dispersion, which influence which location of the gap seeds can reach;
(2) seed storage and germination, which influence if there is a viable seed pool or if the germination occurs just after dispersion (meaning the time of seed production and the timing of dispersion must be in synchrony with the disturbance timing, in order for the species to establish);
(3) seed size, which seems to affect seed sensitivity to physical stress, as bigger seeds have greater reserves.

Competition plays an important role as well, as the occupation and utilization of the resources available after a disturbance is a race against time. The growth rate is an essential attribute in this case, where plant species with the highest growth efficiency under the environmental conditions available will be the most successful (Canham & Marks, 1985).

Due to the growth of the branches from the neighboring trees and the establishment and growth of seedlings and saplings within the gap, according to Zhu et al. (2014), the area of the gap diminishes over time and in approximately 25 years the differences in regeneration densities between the gap and the under-canopy areas disappear.

2.6. Forest conservation and continuous cover forestry

The conservation of forest ecosystems and biodiversity is an important topic of discussion worldwide. Based on Parviainen et al. (2000), two approaches must be considered for this purpose: the establishment of protected areas and the use of nature-based silviculture. As already mentioned, in Europe most of the forests are managed, with a very low area of primeval forest and a likewise low percentage of protected forests (12.2% of the European forest area) (Forest Europe, 2015).

Silvicultural systems which maintain even-aged stands (1 or 2 age classes), including plantations, are known to have a lower biodiversity and simpler structure than uneven-aged stands (O'Hara, 2014). In addition to low species diversity typical of even-aged silvicultural practices, most often trees are harvested when they reach an optimal size, which restricts the life cycle of the trees to the desired trunk diameter determined for each species. After a certain period in a tree's life, the increment in growth decreases so that it is considered to be the most profitable to cut the trees at this determined trunk diameter (Bauhus et al., 2009). This consequently leads to a loss of diversity and microhabitats associated with more mature and decaying trees, as trees in later life stages are essentially missing or are underrepresented in even-aged stands.

According to Pommering and Murphy (2004) some of continuous cover forestry's major components, among others, are:

(1) the conservation of old trees;
(2) the promotion of mixed age classes and tree species composition with the preference of native tree species;
(3) the maintenance of deadwood and protection of endangered plant and animal species;
(4) consideration of site limitations;
(5) emphasis on diverse vertical and horizontal structure.

Continuous cover forestry could possibly reproduce some attributes of old growth forests in managed forests. Old growth forests, according to Bauhus et al. (2009) are primary forests that have not experienced severe disturbances for a long time, and in this way have kept distinctive attributes in their structure and composition. Regarding their naturalness and conservational value, old-growth forests have been found to be associated with a higher richness of animal, plant, fungi and lichen species (Bauhus et al., 2009). Assessing how structural and compositional characteristics of old growth forests can be developed in managed stands is an important step for nature conservation, helping to maintain more heterogeneous and resilient forests and conserving their ecosystem functions.

3. Materials and Methods

3.1. Study area

The Pilis Mountains are located at the northeastern ridge of the Transdanubian Range, Hungary (47°40'N, 18°54'E). The area is managed by the state-owned Pilis Park Forestry Company Ltd. The study site involves a 90 years old deciduous forest, mainly composed by sessile oak (*Quercus petraea*) in the upper canopy layer and hornbeam (*Carpinus betulus*) in the sub-canopy layer. The site comprises a 10-ha stand that was historically managed with a shelterwood system, which explains its even-aged characteristics, and its relatively homogenous structure and composition.

The area has an elevation of 370-470 m above sea level, with a moderate north-facing slope of 15.6° (mean slope of the quadrats). Mean annual precipitation is 650 mm and the average annual temperature is 9.0-9.5°C and 16.0-17.0°C during the growing season. The bedrock is Daschsteinian limestone and Lattorfian sandstone with loess (Dövényi, 2010). The lower elevation parts of the area are characterized by brown forest soil with clay illuviation (Luvisol) and the higher parts by Rendzic Leptosol (Krasilnikov et al., 2009). The pH of the soil of the 0-20 cm layer is 4.6 ± 0.2.

The average height of the oak specimens is 22 m and for the hornbeams is 12 m. The basal area of the site was 29.2 m2/ha (before the experimental interventions).

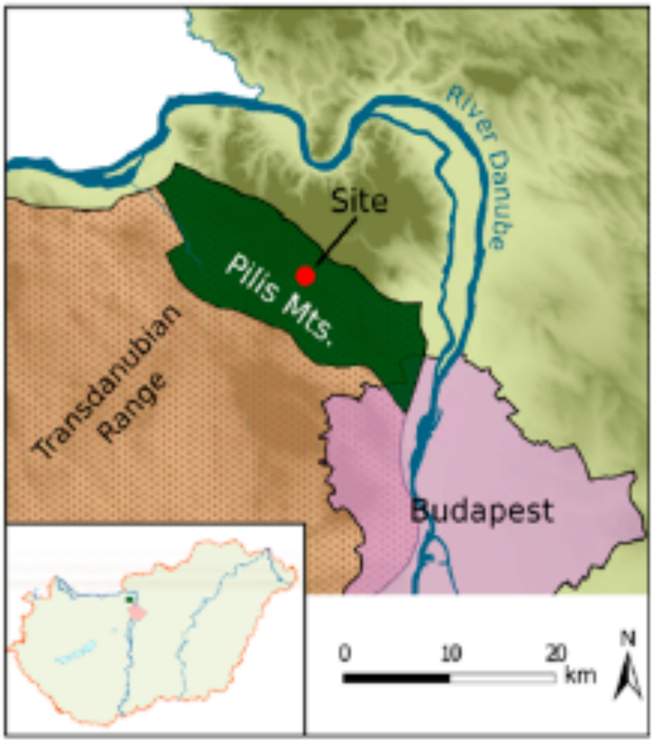

Figure 1: The location of the study area.

3.2. Experiment design

Artificial gap openings were created in February 2019. The whole area was fenced to avoid game interference. Six treatments were implemented following a randomized complete block design in six replicates. In this study we used five treatments and four replicates per treatment, resulting in a total of 20 gaps (*Figure 2*). All woody individuals have been cut in the gaps, which were created using the extended canopy gap concept (Schliemann & Bockheim, 2011). Therefore, this study comprises a total of 20 study plots, with 4 replicates for each of the following treatments:

1. Control (CO): mature closed stand with no treatment implemented;
2. Large circular gap (LC): a 20 m diameter gap, representing approx. 1 tree height/diameter ratio (size: ~ 300 m^2);
3. Small circular gap (SC): a 14 m diameter gap, representing approx. 0.7 tree height/gap diameter ratio (size: ~ 150 m^2);
4. Large elongated gap (LE): a 10 x 30 m rectangular gap with a north-south orientation (size: 300 m^2);
5. Small elongated gap (SE): a 7 x 21m rectangular gap with a north-south orientation (size: ~ 150 m^2);

In all elongated gaps the proportion of longer to shorter side was 3 : 1, and the longer side aligned with the north-south cardinal direction. The sixth treatment, the extended gap (small elongated gap to be extended to large circular after 4 years) is not included in this study.

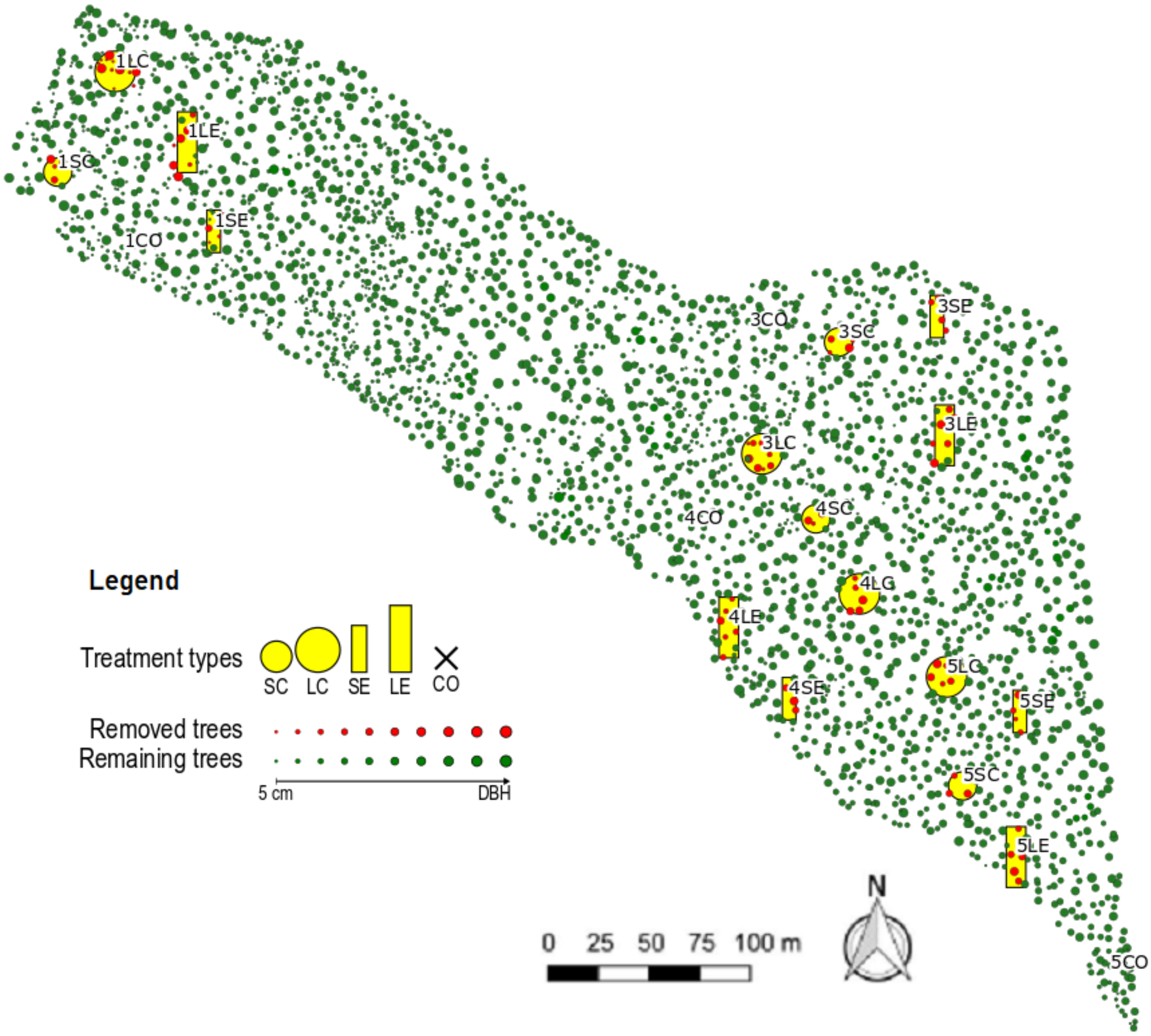

Figure 2: Map of tree individuals in the Pilis Gap Experiment. The schematic gap shapes (yellow) and cut trees (red) are marked.

The study plots established in each treatment consist of 41 50 x 50 cm quadrats, placed along four transects, arranged in the cardinal and intercardinal directions of the compass (*Figure 3*). Because of repeated measurements during the vegetation period, permanent and temporary sticks marked the position of the quadrats. The arrangement and the number of the quadrats were the same in each plot, independently from the size and shape of the gaps. However, because of the different gap sizes and shapes, the sampling design was not a regular grid, as the inner part and the south-north direction was more intensively sampled.

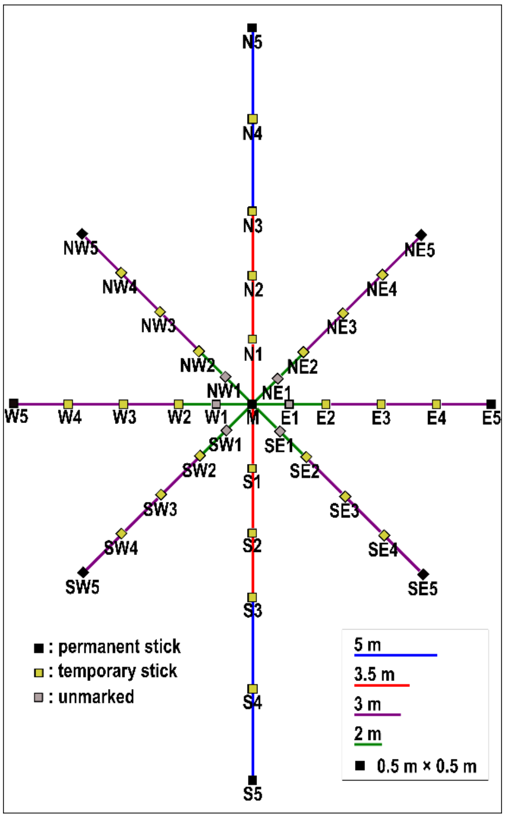

Figure 3: Quadrats disposition on the study plots.

3.3. Data collection

3.3.1. Vegetation

The understory vegetation survey was done during June and July of 2019. We identified all vascular plant species in the understory vegetation present in the quadrats and visually estimated their percentage cover. In this study, the variable cover will be referred to as the sum of all individual species cover values in each quadrat. Therefore, the value of this total cover can exceed 100%, because of the layered, overlapping structure of the understory vegetation. We used species nomenclature and characterized the functional groups according to the identification key for vascular plants by Király (2009).

3.3.2. Soil moisture

The soil water content (SWC) was measured using FieldScout TDR 350 (Spectrum Technologies Inc, 2017) with 7.5 cm rods. The Soil Moisture Meter determines the percentage of volumetric water content in the soil by measuring the soil's electrical conductivity, which is a function between salts and water content (Spectrum Technologies Inc, 2017). The equipment was set in standard mode. Where rocky and shallow soils necessitated it, we used shorter rods (3.8 cm). These values were later transformed to 7.5 cm rod length, based on a calibration equation developed by linear regression, using data of points measured with both rod lengths.

SWC was measured five times in the middle of each quadrat during the vegetation period, once per month, in June, July, August, September, and October of 2019. To establish a reference to which all quadrat level value could be related, we chose a location in a closed stand outside the experimental area, where we measured both before starting and after finishing the measurements on a day, in 5 points. To account for the expected variance in soil moisture conditions, we made multiple measurements in the middle of each quadrat, recording at least four values. This was repeated in all 20 plots in each measurement campaign in two consecutive days under similar environmental conditions, to avoid the temporary variances in the results. We calculated the relative soil moisture content for each quadrat by subtracting the average of the morning and the afternoon reference values from the average of the recorded values in each quadrat. Due to this procedure, the calculated relative soil water content values (dSWC) may be negative.

For the calculation of SWC from raw sensor readings we conducted a soil-specific calibration of the sensor. Calibration was done using gravimetric analysis by the determination of soil water content in soil core samples that were initially measured in situ on the field with the TDR. We used 30 soil samples for the calibration, acquired at two different measurement days representing different water content conditions. The actual water content of the samples was plotted against the according TDR raw sensor readings, and a calibration curve and equation were developed with linear regression.

3.3.3. Light

Hemispherical photographs were taken with a KODAK PIXPRO *SP360* Action Camera calibrated in Lens.Cal Regent VRCam10MP. The images were taken at 130 cm above ground, once during the growing season in the middle of each quadrat. The photos were taken after sunset, to minimize the error caused by the imaging of the sun-disk and by the reflection of direct sunlight on the canopies. To reach a proper exposure of the canopy (to avoid overexposure of the leaves), photos were taken at each point with -0.3 and -0.7 EV (exposure value) settings; for the analysis, the photos with -0.7 EV were used. In some cases, where direct sunlight reached the camera, the overexposure patch of the picture was manually masked before the analysis. The orientation and location data of each point were recorded.

For the analyses of the images we used the WinSCANOPY 2019a software (Guay & Déri, 2018) . The software analyzes each pixel of the photograph taken, and classifies them either as canopy or as sky, based on a threshold value of brightness and color. This thresholding process was done automatically by the software, however, in some cases, it was refined manually. Further examination was done by applying the canopy analysis theory to the pixels classified image, which includes canopy structure, LAI, and radiation analyses (Guay & Déri, 2018). During radiation analysis the program creates the sun track for the whole period of interest from one picture only and calculates both direct and indirect incident light values for the point where the photo has been taken. The time period of the radiation analysis was set to the period between 01 May and 30 September.

The following light variables were calculated for each quadrat: openness, direct site factor, indirect site factor and total site factor. Openness is the portion of open sky unobstructed by vegetation, in a specific region captured by the camera lens (in %). Direct site factor is the average proportion of daily direct radiation received under canopy compared with the over canopy radiation. The indirect site factor is the average amount of diffuse incident radiation below canopy relative to that of over canopy indirect radiation. The total site factor is the sum of both, direct and diffuse radiation, received under-canopy during the growing season relative to that of the over canopy during the same period. Direct, indirect and total site factors range was between 0 and 1.

3.3.4. Spatial data acquisition

The stand structure was mapped by Trimble TX 6 terrestrial laser scanner before the implementation of the treatments (January 2019) and a model of the stand was created by Trimble Realworks 11 and GreenValley Int. LiDAR 360 software. Based on the point intensity in the 10-30 m vertical layer, the crown projection of the trees was created by LiDAR (*Figure 4*). Based on these crown projections the actual shape and size of the created gaps was drawn in QGIS software (*Figure 4*).

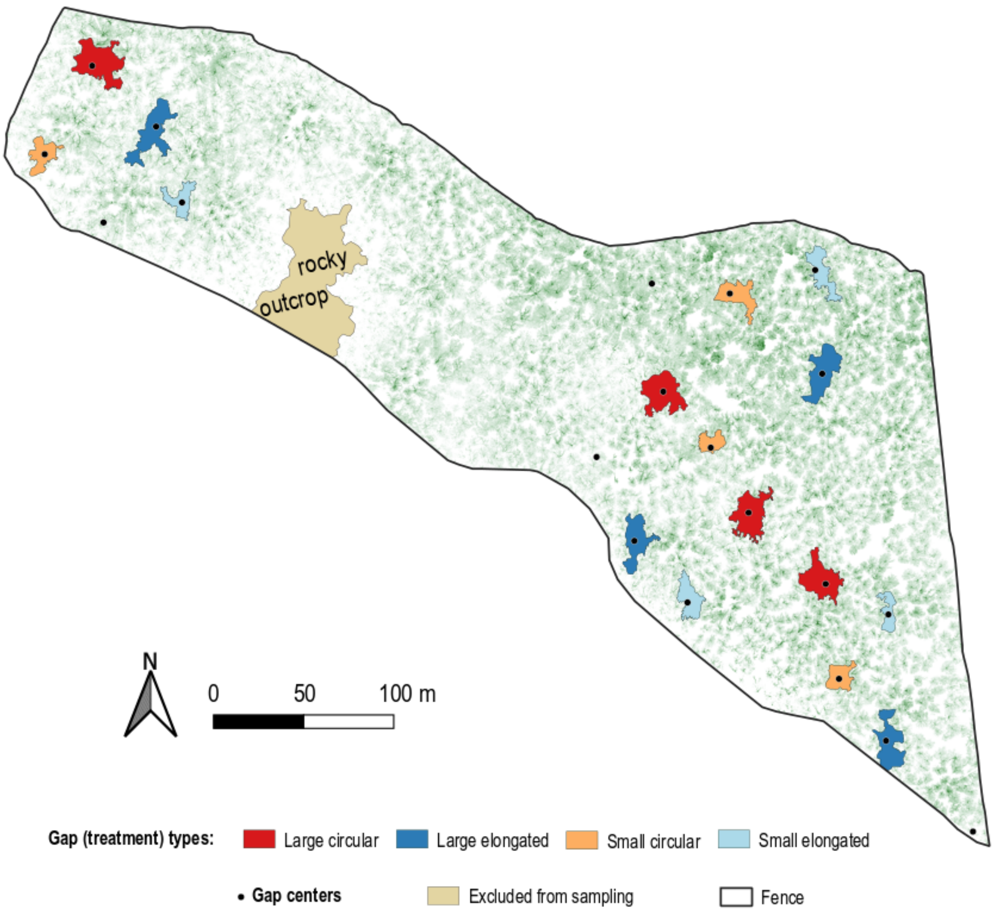

Figure 4: Actual size and shape of the gaps based on the crown projections created from LiDAR image (green layer). The green patches represent the crown projection of trees, based on LiDAR point intensities in the 10-30 m vertical layer.

3.4. Statistical analysis and visualization

QGIS 3.8 (QGIS Development Team, 2019) was used for mapping patterns of different variables on the plot level, as well as for the LiDAR data management and processing.

Based on the canopy boundaries projections on the ground, and the quadrats' minimum distance to the boundaries, the position of each quadrat in each plot has been classified either as center, edge or under-canopy. All quadrats that are within 1.5 m perpendicular distance from either side of the canopy projection line were classified as edge quadrats (ED). Quadrats within the gap area, but not closer to the canopy projection line than 1.5 m were classified as center (CE), and quadrats that are outside the gap and further away from the canopy projection line than 1.5 m were classified as under canopy quadrats (UC). The classification process was implemented in R, using the "rgdal" (Bivand, et al., 2019), "sp" (Pebesma & Bivand, 2005; Bivand et al., 2013), "pointdexter" (Nuno, 2019) and "sf" packages (Pebesma, 2018). The quadrat – canopy projection polygon distances were calculated with the “st_distance” function.

Because of the different gap sizes, the classification led to a slightly unbalanced number of quadrats in the zones, but the linear mixed models used for the analysis are robust to unbalanced data as well (Duursma & Powell, 2016).

All studied dependent variables (light variables expressed as total site factor, indirect site factor, direct site factor, and openness; dSWC; vegetation cover and species number) were analyzed by Generalized Linear Mixed Models using Poisson error structure for species number and Gaussian for all other variables (Zuur et al., 2009). For all analysis the variable treatment was tested as a fixed factor (5 levels), while the variables block and plot within the block were used as random factors. For the environmental variables the treatment effect was tested in the different zones separately. The distribution of the data was checked visually and tested for normality with Kolmogorov-Smirnov Normality Tests. In case of all models the residuals were visually checked for normality (quantile-quantile plots) and variance homogeneity (residuals and standardized residuals versus fitted values plots). The effect of the fixed factor was expressed as likelihood-ratio test-based coefficient of determination (Barton, 2019) and tested by log-likelihood Chi^2 test. The alpha level used in this study for all the statistical tests was 0.05. In the case of a significant treatment effect the levels were compared by Tukey-type multiple comparisons (Zuur et al., 2009).

R version 3.6.1 software (R Core Team, 2019) was used for the statistical analysis. The Generalized Linear Mixed Models were performed by the “lme4” package (Bates et al., 2015). The “lmer” function was used for the environmental variables and cover, while the "glmer" for species number. The fixed factor was tested by the “Anova” function of the “car” package in the case of environmental variables and cover (Fox & Weisberg, 2019), while the “anova” of the “nmle” package was used for species number (Pinheiro et al., 2019).

The package “MuMIn” and the function “r.squaredGLMM” was used to express the goodness-of-fit of the model (Barton, 2019). For multiple comparisons, the “cld” and “glht" functions of the “multcomp” package were applied (Hothorn et al, 2008).

To test the treatment effect on the species composition of the understory vegetation in the study plots, we used Permutational Multivariate Analysis of Variance (PERMANOVA, Anderson, 2001). For this we calculated the sum of cover for each species in a plot and used a square root transformation. We also performed Principal Component Analysis (PCA) ordination methods on this dataset for the visual comparison of understory composition of the different treatments (Podani, 2000). We used the R package “vegan” (Oksanen et al., 2019), and the function "adonis" to perform PERMANOVA based on dissimilarity measure Bray-Curtis (with permutation number set to 9999), and for Principal Component Analysis (PCA) we used the "rda" function.

4. Results

4.1. Descriptive statistics

The total number of species found in this study in the understory was 83, comprising herbs, grasses and woody species (seedlings and saplings smaller than 50 cm) (*Annex I*). The frequency (the percentage of quadrats where a species was present) of the ten most frequent species is shown in *Figure 5*. Two of the three most frequent species were *Melica uniflora* and *Carex pilosa*, both graminoids, which are dominant species in the studied area. The most frequent herb species were found to be *Galium schultesii, Stellaria holostea, Rubus fruticosus* agg.*, Melittis melissophyllum* and *Galium odoratum.*

The second most frequent species was *Quercus petraea*, as its seedlings and saplings were present in 98% of the quadrats, and showed a high cover as well (13.8%, see *Figure 6*). This is explained by the fact that the previous year (2018) was a mast year for the sessile oaks in the stand. *Carpinus betulus* was also among the ten most frequent species in the understory, which is explained by the fact that it is the dominant tree species in the secondary layer of the forest canopy. This species was found in 27% of the quadrats, but it's cover was small, only 1% (*Figure 6*).

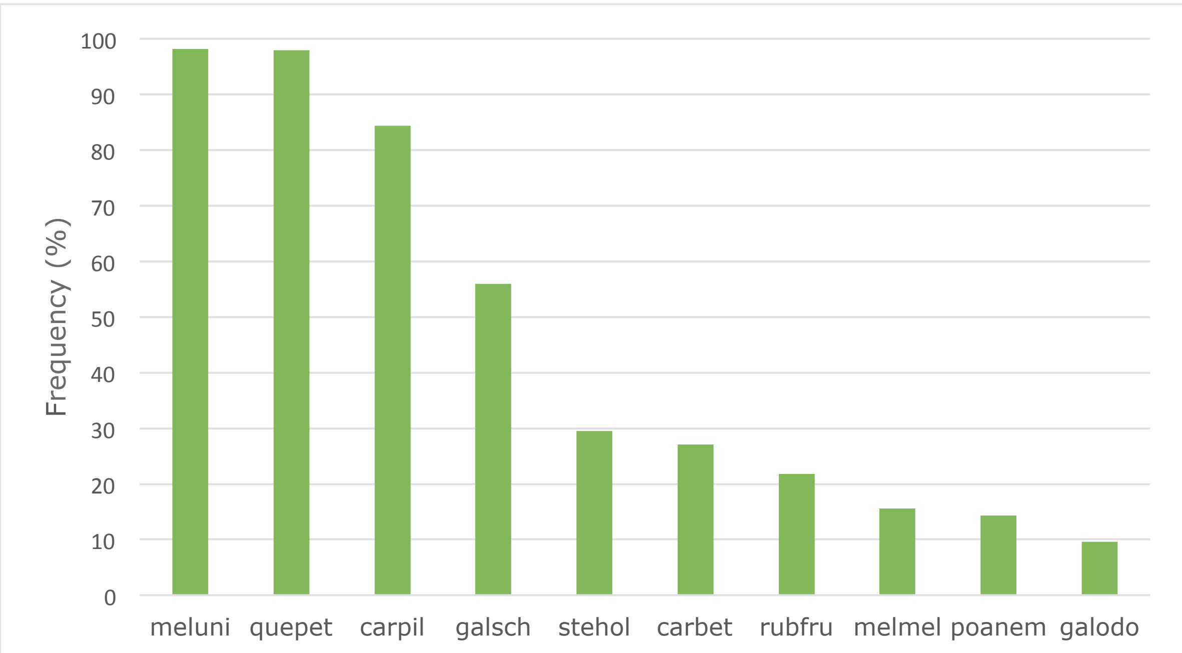

Figure 5: Frequency of the ten most frequent species (meluni: *Melica uniflora*; quepet: *Quercus petraea*; carpil: *Carex pilosa*; galsch: *Galium schultesii*; stehol: *Stellaria holostea*; carbet: *Carpinus betulus*; rubfru: *Rubus fruticosus* agg.; melmel: *Melittis melissophyllum*; poanem: *Poa nemoralis*; galodo: *Galium odoratum*). Frequency is the percentage of quadrats where the species were present out of all the 820 quadrats surveyed.

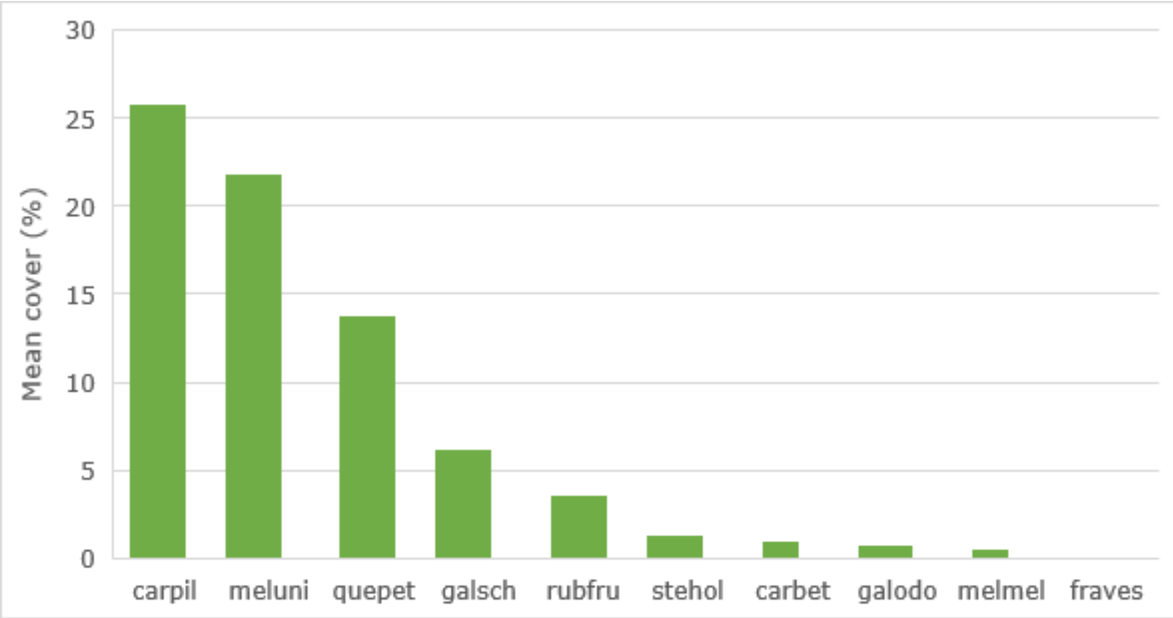

Figure 6: Mean cover of the most abundant species (carpil: *Carex pilosa*; meluni: *Melica uniflora*; quepet: *Quercus petraea*; galsch: *Galium schultesii*; rubfru: *Rubus fruticosus* agg.; stehol: *Stellaria holostea*; carbet: *Carpinus betulus*; galodo: *Galium odoratum*; melmel: *Melittis melissophyllum*; fraves: *Fragaria vesca*).

The absolute soil water content (SWC) values were generally quite low during the whole vegetation period. The mean and standard deviation for the growing season of the closed stand (control) were 4.06 % ± 0.50%. The values presented in *Table 1* describe the conditions of the five separate soil moisture measurement campaigns performed. From that, we verify a big variation between the measurement times.

Table 1: Mean and standard deviation (*SD*) values of absolute soil water content (SWC) in the control plots in each of the measurement campaigns.

	Measurement campaigns				
SWC (%)	**June**	**July**	**August**	**September**	**October**
Mean	5.80	3.76	3.97	3.63	2.91
SD	0.83	0.52	0.62	0.56	0.45

The openness of the closed stand was 11.22 % ± 3.26 %. Considering the light condition, the total site factor and direct site factor had similar values, 0.15 ± 0.07, and the indirect site factor was 0.17 ± 0.06.

4.2. The effect of gap treatments on the vegetation

Based on the generalized mixed effect model the treatments did not influence the number of species in the plots (*Chi*^{2}=3.54, *P*=0.472, R^2m=0.024, *Figure 7*). However, there was a weak, but significant treatment effect on the vegetation cover (*Chi*^{2}=10.52, *P*=0.032, R^2m=0.089, *Figure 7*). The cover was higher in the large elongated gap than in the control, while other treatments had intermediate values.

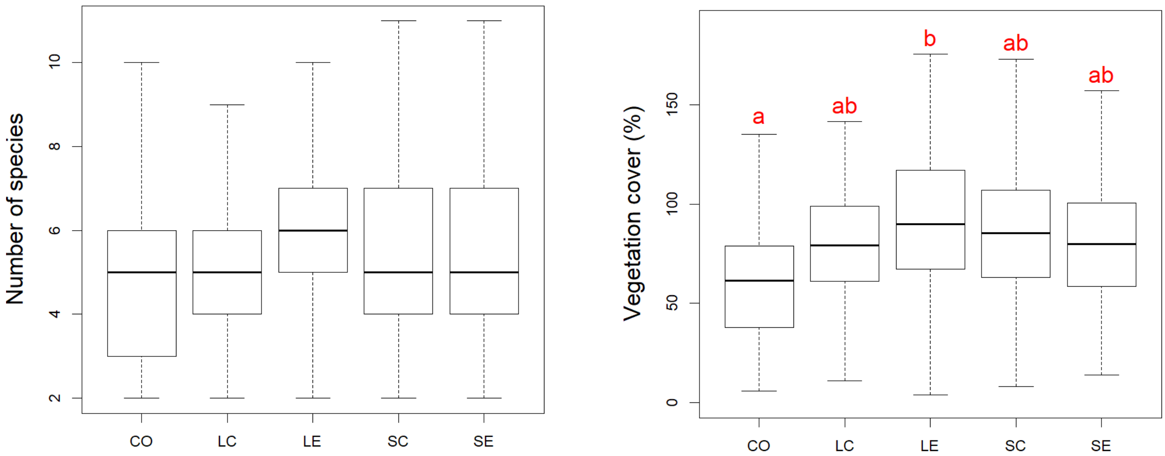

Figure 7: The effect of treatments on the number of species (left) and on the cover (right). The thick lines represent the median, the box the interquartile range, while whiskers the range (without outliers). Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated. Letters (a and b) designate the significant pairwise differences among the treatments (Tukey-test, alpha=0.05).

Permutational analysis of variance (PERMANOVA) has not revealed significant treatment effect regarding the understory species composition (*F*=0.51, *P*=0.824). This result corroborates with the principal component analysis (PCA) (*Figure 8*). The position of the plots along the first and second PCA axes did not show any separation according to the treatment types. Non-metric multidimensional scaling (NMDS) has also confirmed these results (analysis not shown). Therefore, we can conclude that there is no substantial difference in the species composition between the treatment types in the first year after treatment.

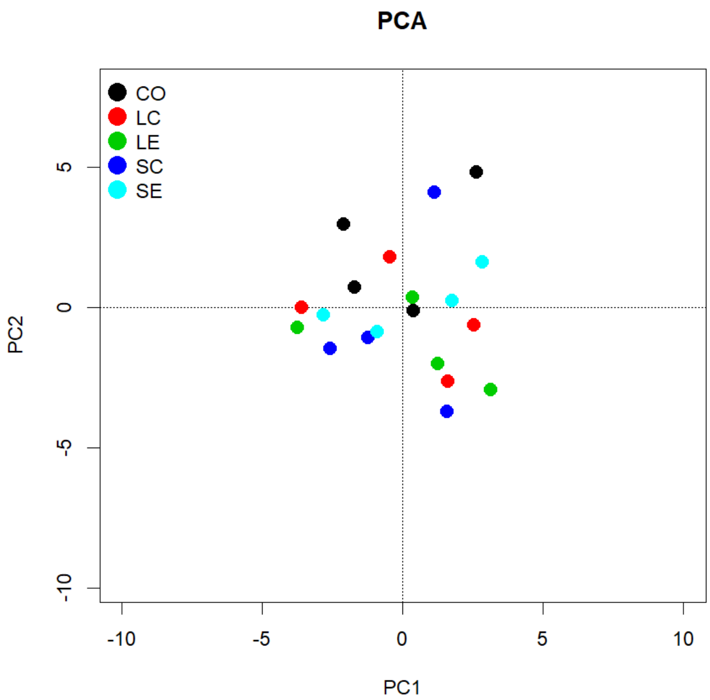

Figure 8: Principal component analysis with squared root transformed cover data of the 83 species in each study plot (N=20). Colors show the type of the treatments. The axes PC1 and PC2 are explaining 7% and 5% of the variance respectively. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

Although there was not any treatment effect on the mean species richness, the two-dimensional pattern of the mean of the four replicates for each treatment showed some heterogeneity within the gap types and control (*Figure 9*). While the pattern appears to be irregular in the control, the species richness was higher mainly in the quadrats located in the central part of the gaps.

This pattern was more pronounced for vegetation cover (*Figure 10*). Looking at the south-north and west-east gradient of vegetation cover separately, there is a pronounced increment in the central part of the circular gaps (bell-shaped pattern) and the northern part of the elongated gaps (*Figure 11*). These increments were more intensive in case of the large gaps than for the small ones.

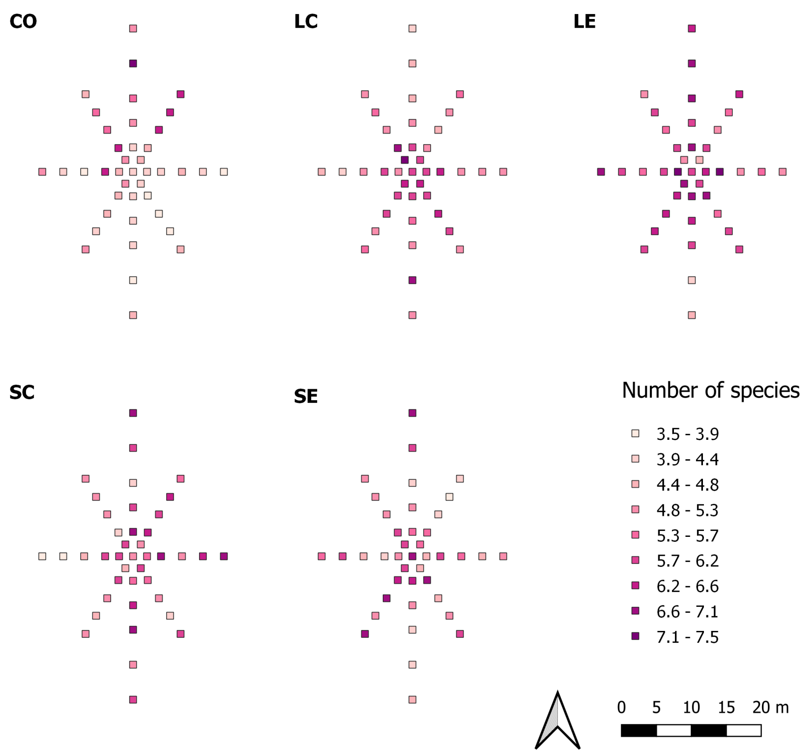

Figure 9: The average species number of the quadrats within the gaps. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

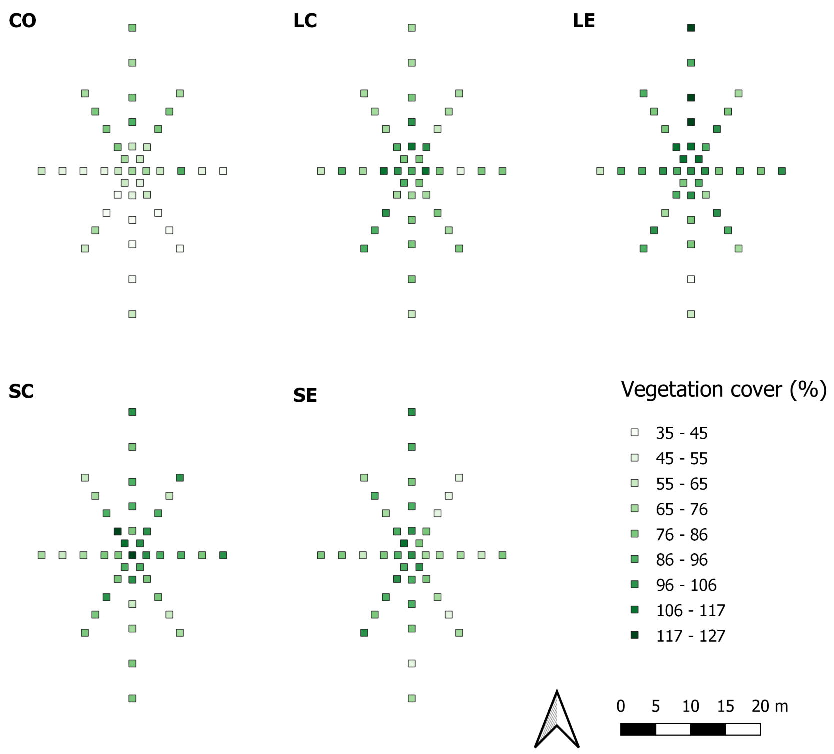

Figure 10: The average vegetation cover of the quadrats within the gaps. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

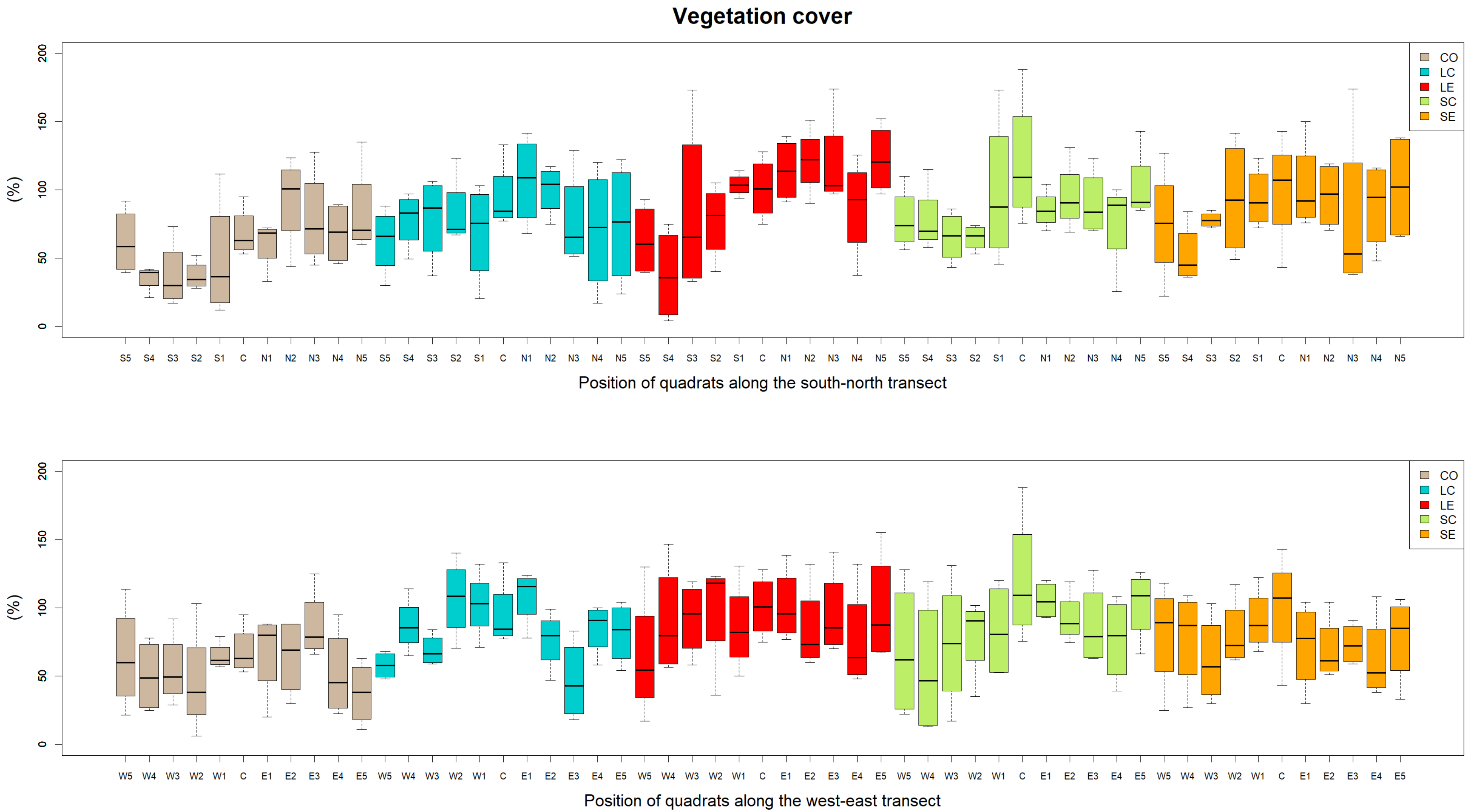

Figure 11: Pattern of the vegetation cover in quadrats along the south-north (top) and west-east transects (bottom). The treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated

4.3. The effect of gap treatments on the environmental variables

The response of the environmental variables to the treatments was characteristic of the different gap types (*Table 2*).

Due to the low values for the absolute soil water content, the calculated relative soil water content (dSWC) values and the differences in them among the treatments were also small. Relative soil water content was calculated by subtracting the average of the day reference from the average of the recorded values in each quadrat. This means that control treatments can also be characterized by negative dSWC% values, as it can be any treatment that was drier than the reference.

Table 2: Mean and standard deviation (*SD*) values for the investigated gap designs (CO: control; LC: large circular; LE: large elongated; SC: small circular; SE: small elongated) for the environmental variables: relative soil water content (dSWC), canopy openness, total site factor, direct site factor and indirect site factor.

	TREATMENTS									
	CO		**LC**		**LE**		**SC**		**SE**	
Variables	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
dSWC (%)	**-0.63**	0.38	**0.05**	0.75	**-0.36**	0.72	**-0.18**	0.84	**-0.42**	0.52
Openness (%)	**11.22**	3.26	**22.56**	4.93	**19.17**	3.70	**16.84**	5.10	**16.02**	4.38
Total site factor	**0.15**	0.07	**0.31**	0.12	**0.27**	0.08	**0.23**	0.10	**0.22**	0.08
Direct site factor	**0.15**	0.07	**0.30**	0.13	**0.26**	0.09	**0.22**	0.11	**0.22**	0.09
Indirect site factor	**0.17**	0.06	**0.37**	0.10	**0.32**	0.08	**0.28**	0.10	**0.26**	0.09

All environmental variables were significantly affected by the treatments (*Table 3*), with the openness and indirect site factor having the most variance explained by the treatments as the fixed effect ($R^2m = 0.41$ and $R^2m = 0.37$ respectively).

Table 3: The results of the linear mixed effects models testing the effect of the treatments on the environmental variables: relative soil water content (dSWC), canopy openness, total site factor, direct site factor and indirect site factor. R^2m – Marginal proportional explained variance of the treatments (excluding the effect of the random factor).

	Goodness-of-Fit	**ANOVA**	
Variables	R^2m	*Chi*^{2}	*P*
dSWC (%)	0.10	18.57	< 0.001
Openness (%)	0.41	64.27	< 0.001
Total site factor	0.23	25.10	< 0.001
Direct site factor	0.19	20.87	< 0.001
Indirect site factor	0.37	74.63	< 0.001

Multiple comparisons revealed that dSWC was significantly higher in the large circular gap than in the control (*Figure 12a*). The dSWC increments were apparently higher in the circular gaps than in the elongated ones, even though the differences are only significant in the case of the large circular gap compared to the small elongated one.

The canopy openness (*Figure 12b*) was significantly greater in all of the gap treatments than in the control, and the highest values were observed in the large circular gap. The average openness in the large circular gap was 22.56%, twice as high as in the control, where it was 11.22%.

In case of light results, total site factor (*Figure 12c*) and direct site factor (*Figure 12d*) showed very similar trends. In the large circular and the large elongated gaps both variables were significantly higher than in the control, but the effect was not significant in the case of the small gaps. The indirect light (*Figure 12e*) was the most affected by the treatments, with all of the treatments showing significantly higher indirect site factor values than the control. Its result was very similar to the Openness (*Figure 12b*). Indirect light has been the highest in the large circular and large elongated gaps.

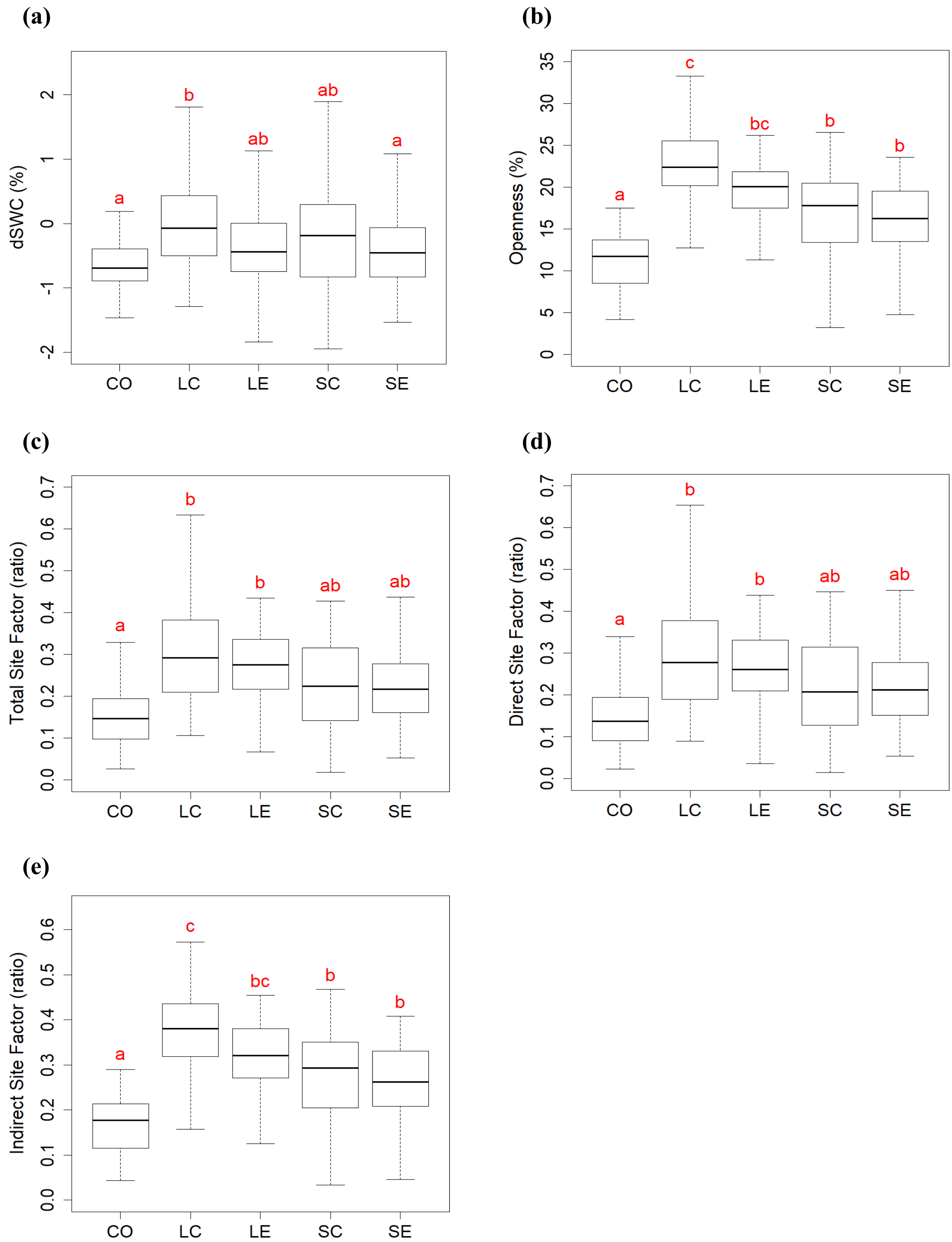

Figure 12: Boxplot of environmental variables in the gap treatments (line: median, box: interquartile range, whiskers: range without outliers). (a) relative soil water content (dSWC, %) (b) canopy openness (%) (c) total site factor (d) direct site factor and (e) indirect site factor. Letters designate the significant pairwise differences among the treatments (Tukey-test, alpha=0.05). Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

Table 4: The results of the linear mixed effects models testing the effect of the treatments on the environmental variables within each gap zone separately (CE - center; E - edge; UC - under-canopy). Relative soil water content (dSWC), canopy openness, total site factor, direct site factor and indirect site factor.

		Goodness-of-Fit		ANOVA	
Variables	**Zone**	R^2m	R^2c	X^2	P
dSWC (%)	CE	0.24	0.46	29.60	<0.001
	E	0.08	0.29	10.40	0.034
	UC	0.02	0.32	2.74	0.602
Openness (%)	CE	0.67	0.88	81.45	<0.001
	E	0.45	0.56	65.14	<0.001
	UC	0.17	0.35	16.13	0.003
Total site factor	CE	0.33	0.63	27.35	<0.001
	E	0.23	0.38	29.91	<0.001
	UC	0.07	0.31	5.53	0.237
Direct site factor	CE	0.27	0.57	21.54	<0.001
	E	0.19	0.33	24.81	<0.001
	UC	0.06	0.29	4.97	0.287
Indirect site factor	CE	0.69	0.89	102.61	<0.001
	E	0.42	0.5	81.63	<0.001
	UC	0.11	0.3	9.75	0.045

The results of the linear mixed models applied for the testing of the effect treatment on the different environmental variables in the three different zones (center of the gaps, edge of the gaps and under-canopy zones) are shown in *Table 4*. As an effect of the treatments, the soil moisture increased significantly in the quadrats located in the center zones of the gaps (Chi^2=29.60, $P<0.001$) and the ones in the edge zones (Chi^2=10.40, $P=0.034$), while soil moisture has not been affected significantly by the treatments in the quadrats located in the under-canopy zones (Chi^2=2.74, $P=0.602$) (*Figures 13a, 13b* and *13c*). Among the treatments, the circular gaps had the highest soil moisture content in general, which was also found to be true when the treatments were compared based on data from only one specific zone. The high soil moisture characteristic of the circular gaps was found both in the center and in the edge zones in these treatments, although the difference between the control and the small circular gap in the case of the edge zone wasn't significant (*Figure 13b*). The effect of gap opening has not caused a raise in soil moisture in the under-canopy zone in any of the treatments (*Figure 13c*). The distribution of quadrats with high soil moisture values can be further explored on the map shown on *Figure 14.*

There was a significant treatment effect in the case of the canopy openness in all of the zones, with the smallest effect observed on the under-canopy zone (*Table 4*). In the center and edge zones, all treatments were significantly more open than the control, but in the under-canopy zone only the large gaps (LC and LE) had significantly higher openness values than the controls (*Figures 13d, 13e* and *13f*).

The total site factor and direct site factor were both significantly increased in the center and edge zones due to the treatments (total site factor center: Chi^2=27.35, *P<0.001;* edge: Chi^2=29.91, *P<0.001*; direct site factor center: Chi^2=21.54, *P<0.001;* edge: Chi^2=24.81, *P<0.001*), but there was no significant treatment effect in the under-canopy zone (Chi^2=5.53, *P*=0.237 for total site factor and Chi^2=4.97, *P=0.287* for direct site factor) (*Table 4, Figures 13g, 13h, 13i, 13j, 13k and 13l*). The indirect site factor had a significant treatment effect in all of the zones (center: Chi^2=102.61, *P<0.001*; edge: Chi^2=81.63, *P<0.001*), including the under-canopy zone (Chi^2=9.75, *P=0.045, Table 4*). In the under-canopy zone, the variance explained by the fixed factor was quite low (R^2m=0.11), and the *P* value was very close to α (0.05). From the pairwise multiple comparisons none has revealed a significant pairwise difference, but the result of the comparison between the large circular gap and the control was marginally significant (*P*=0.065). Even though there was a significant treatment effect in this case, it is not strong enough to drive any significant differences between the treatments in their pairwise comparisons.

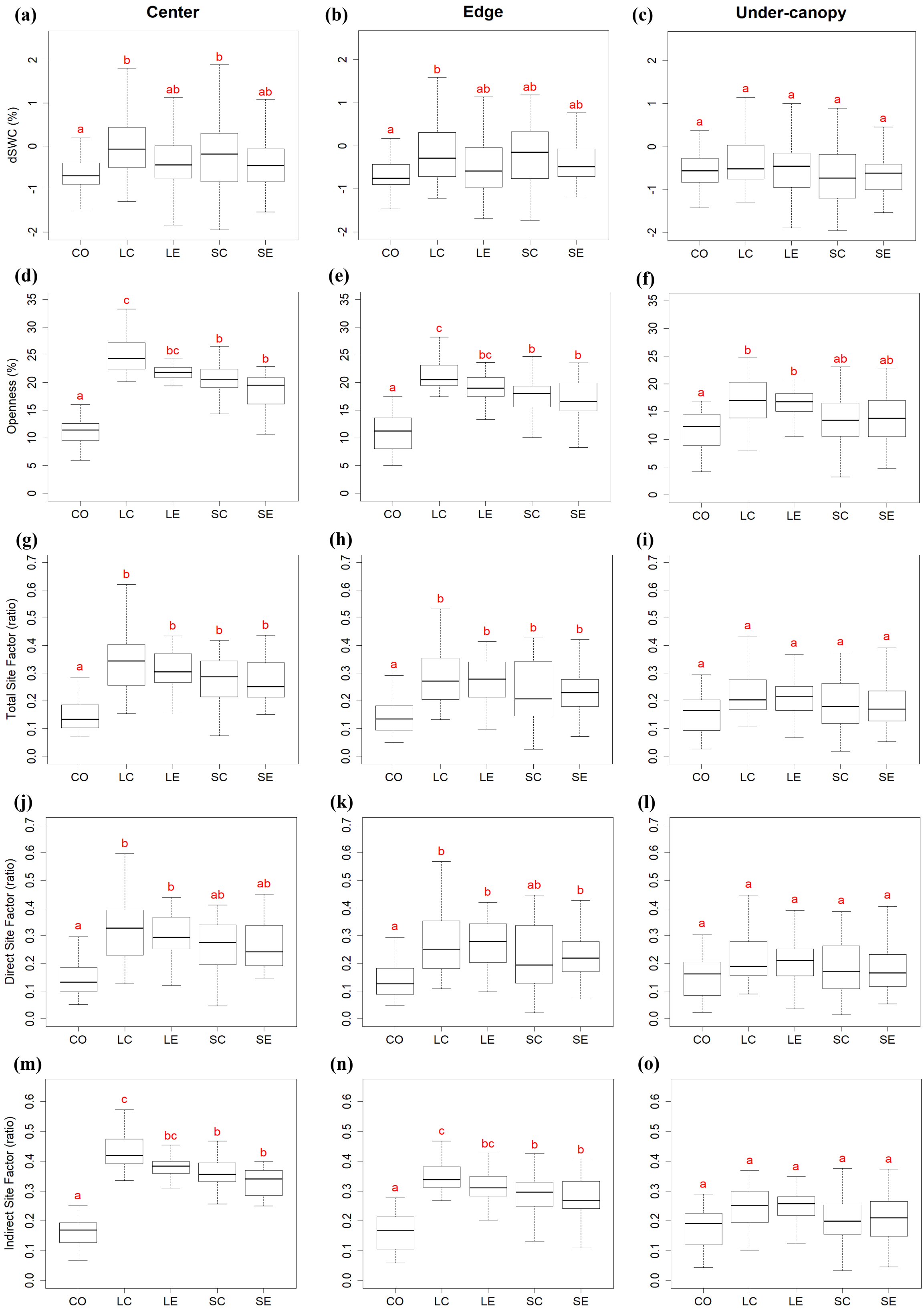

Figure 13: Boxplot about the effect of treatments on the environmental variables in the different gap zones, separately. (a, b, c) relative soil water content (%); (d, e, f) canopy openness (%); (g, h, i) total site factor (j, k, l); direct site factor; (m, n, o) indirect site factor. Letters designate the significant pairwise differences among the treatments (Tukey-test, alpha=0.05). Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

The patterns appearing in the soil moisture values of the quadrats along the south-north transects (*Figure 15*) indicate that soil moisture was the highest in the quadrats located slightly south from the centers of the gaps. This is especially pronounced in case of the large elongated and both circular gaps, where the more northern the quadrats were positioned within the gap, the lower their soil moisture values were – substantially lower than their corresponding southern pairs, which is also visible in *Figure 14*. The west-east transect shows less obvious trends, but it is apparent that the middle regions of the circular gaps were characterized with higher soil moisture values than the outer quadrats, which is the most typical in the case of the small circular gaps.

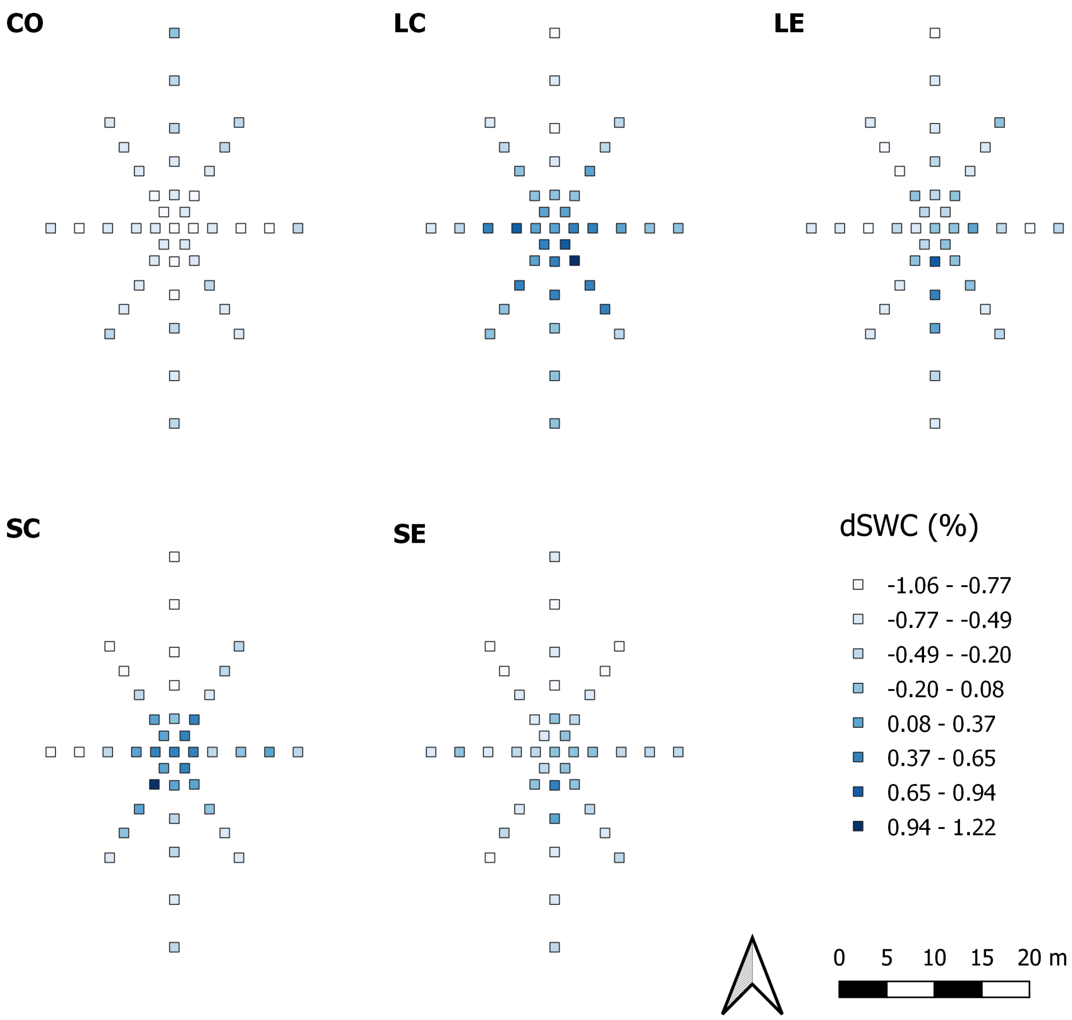

Figure 14: The average relative soil water content (dSWC) of the quadrats within the gaps. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

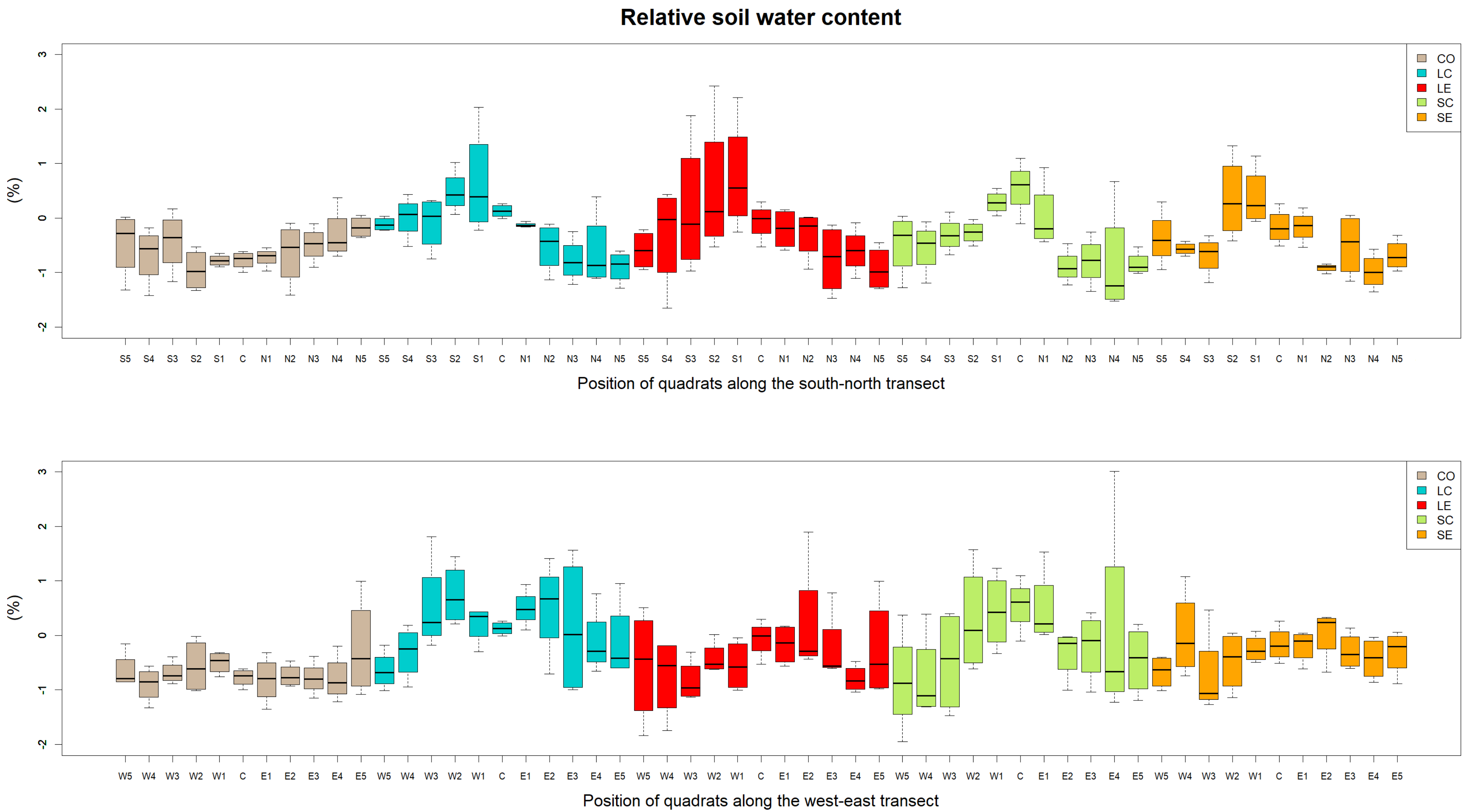

Figure 15: Relative soil water content in the quadrats along the south-north (top) and west-east (bottom) transects. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

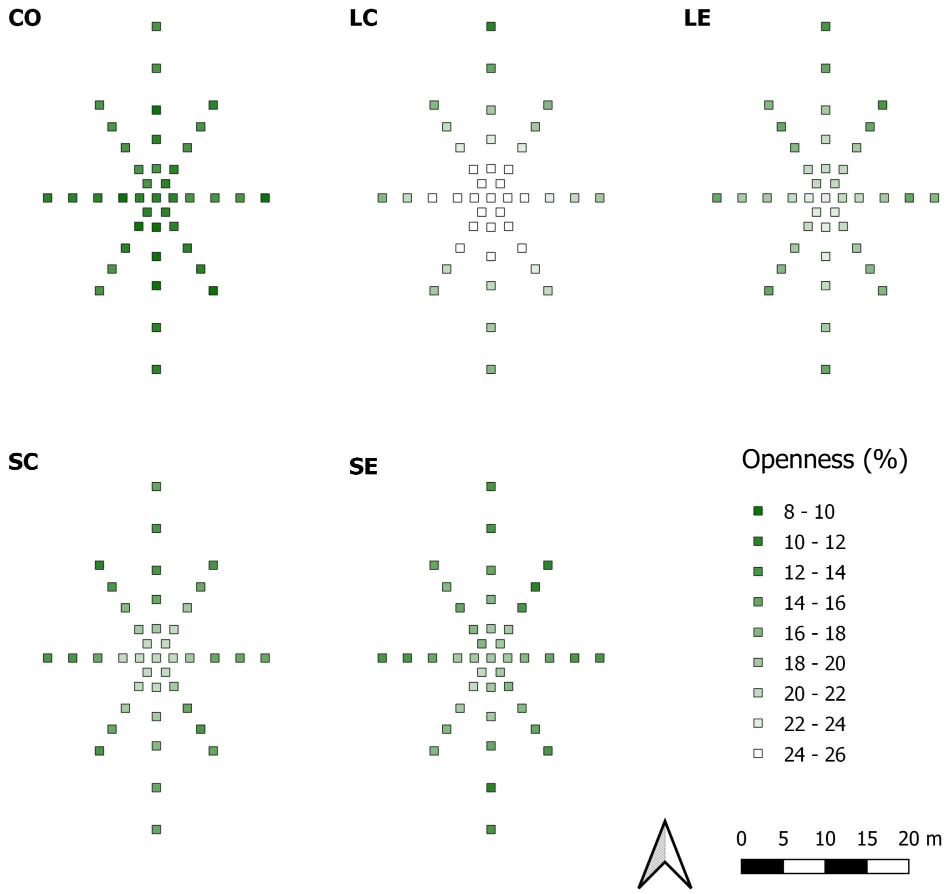

Figure 16: The average canopy openness of the quadrats within the gaps. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

In case of the canopy openness, only the pattern of the average values is shown, imposed on the map of the sampling design (*Figure 16*). The large circular gap was the treatment with the most open quadrats, with under-canopy quadrats also presenting very high canopy openness. The small gaps are very similar to each other, regarding their patterns of openness. This result is coherent with what we were expecting from the treatments.

For the total site factor (*Figure 17*), the quadrats receiving the highest amount of total incident light were the northern ones, however the total site factor decreased as the quadrats ranged further under the canopy. This disposition of the total incident light is also evident in the south-north transect (*Figure 20*). This trend was the most marked in the large circular gaps.

The direct site factor had higher values in the northern parts of the gaps, which is visible both on the map showing its pattern in the quadrats (*Figure 18*) and on the figure showing the direct site factor values in quadrats along the south-north and west-east gradients (*Figure 21*). The excess direct irradiation in the northern part of the gaps is especially pronounced in the case of the large circular and of the large elongated gaps. In both cases, the under-canopy quadrats located in the north direction receive more direct light than the control. Along the west-east transect, all gaps showed a rather symmetrical distribution of direct irradiation.

In other hand, the cardinal directions are not influencing the indirect site factor (*Figures 19* and *22*). Both transects have a symmetrical distribution of indirect light values, with the maxima in the middle region of the gaps. The large circular gap also was the treatment with the greatest indirect site factor values, followed by the large elongated gap. The small gaps have a very similar pattern of indirect light incidence.

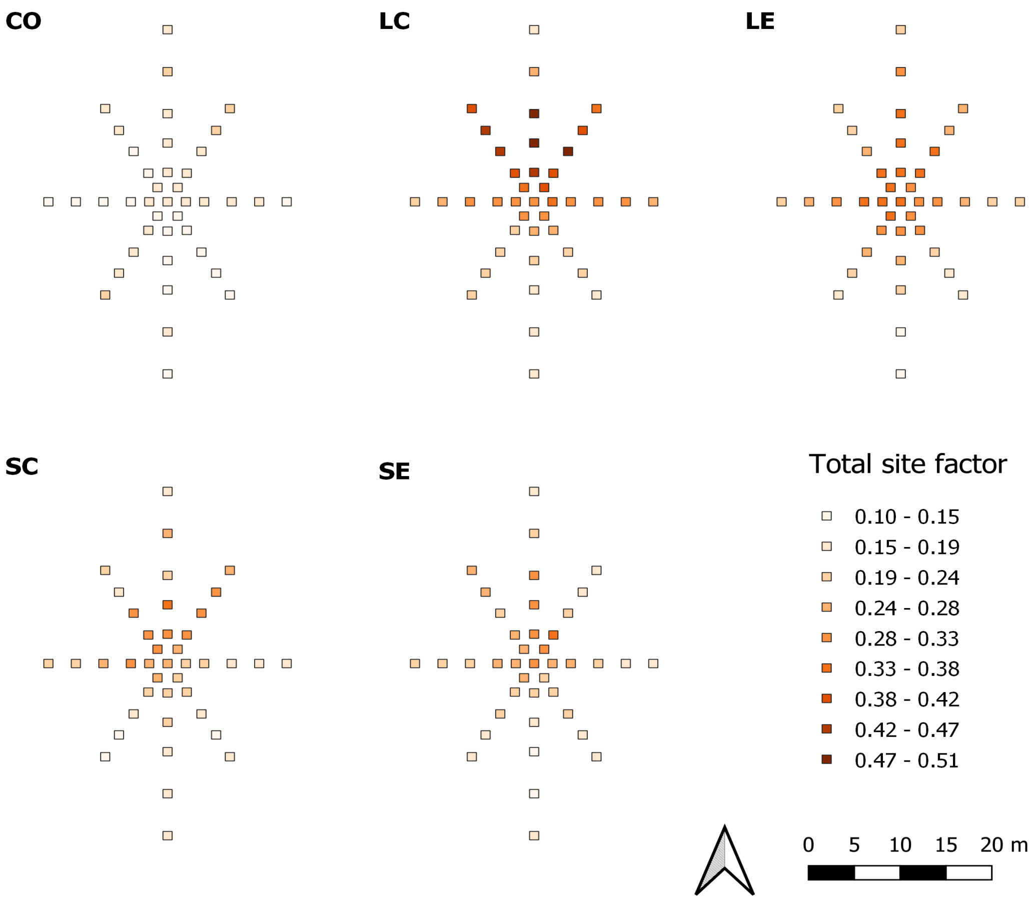

Figure 17: The average total site factor values of the quadrats within the gaps. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

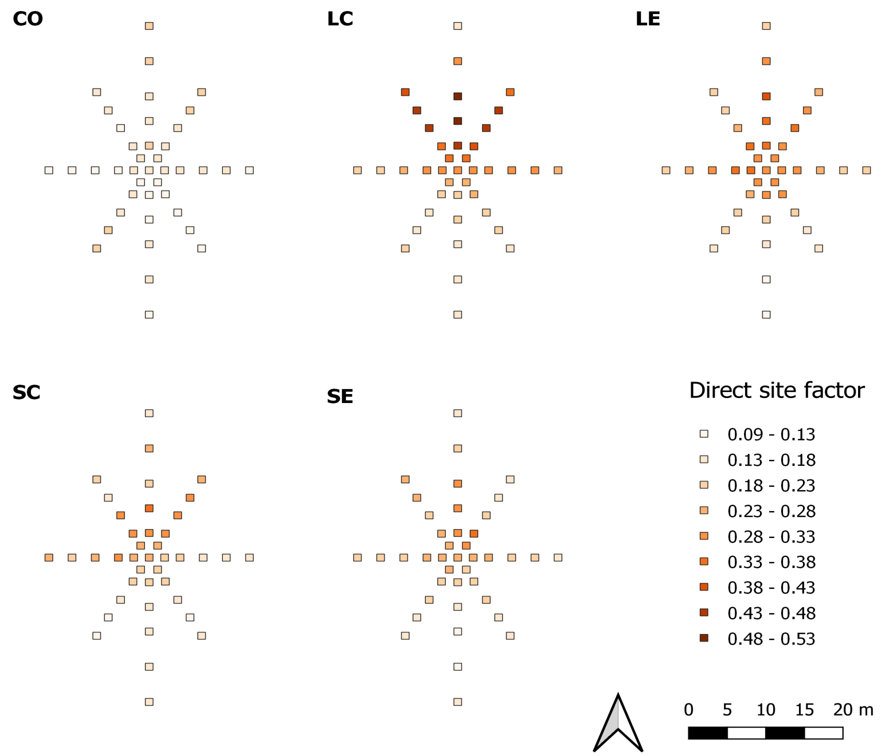

Figure 18: The average direct site factor of the quadrats within the gaps. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

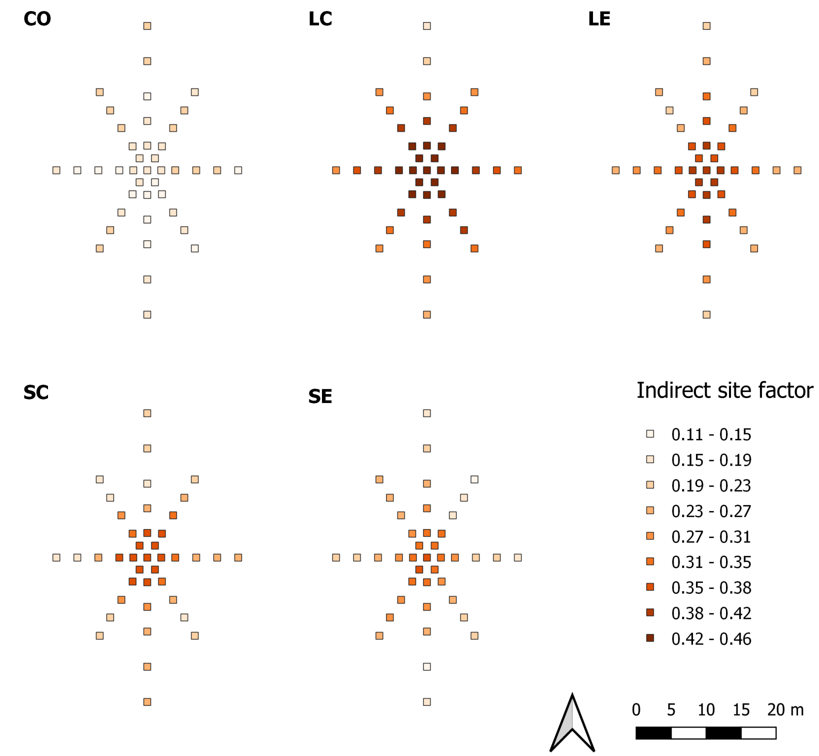

Figure 19: The average indirect site factor values of the quadrats within the gaps. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

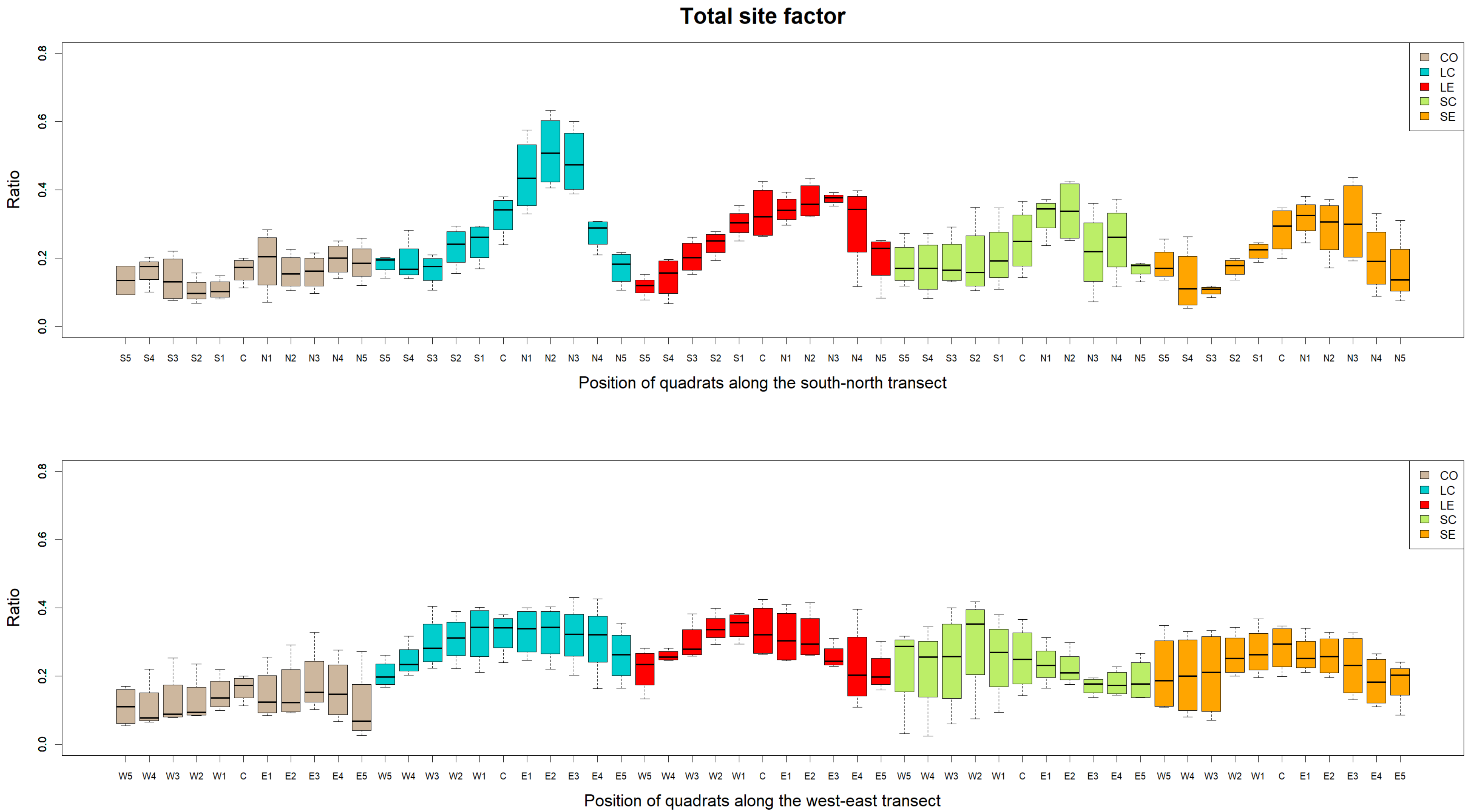

Figure 20: Total site factor in the quadrats along the south-north (top) and west-east (bottom) transects. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

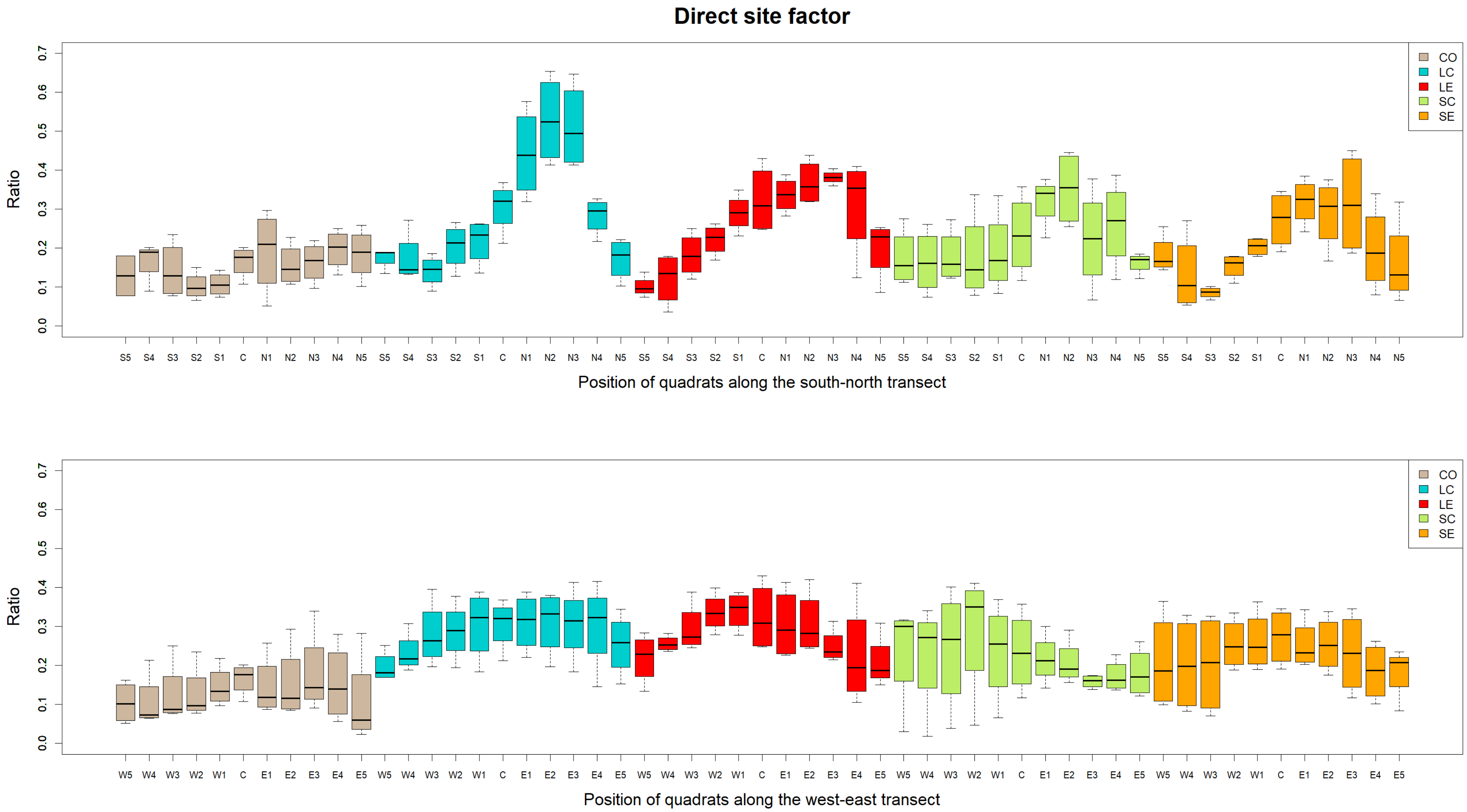

Figure 21: Direct site factor in the quadrats along the south-north (top) and west-east (bottom) transects. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated.

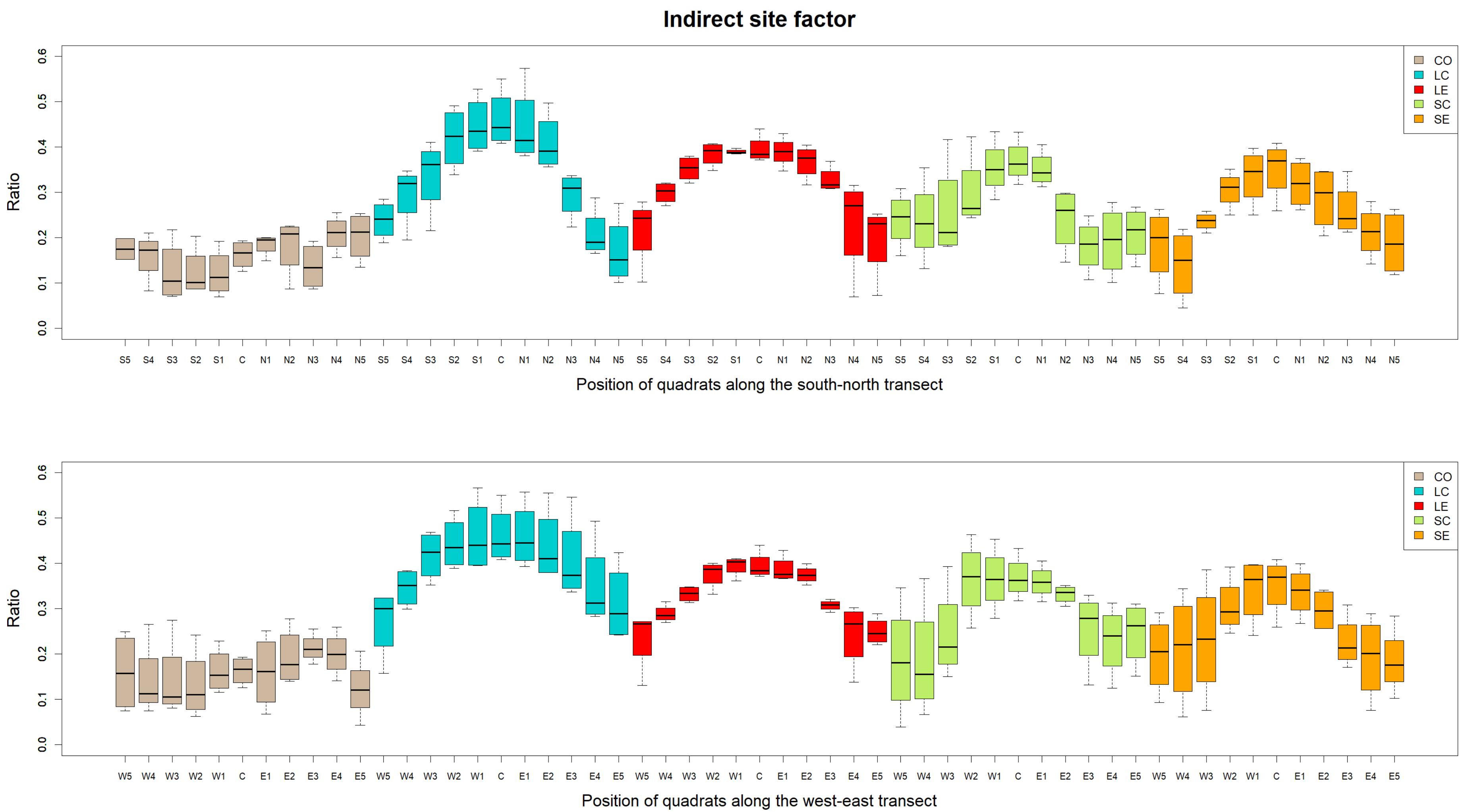

Figure 22: Indirect site factor in the quadrats along the south-north (top) and west-east (bottom) transects. Treatment types are coded as follows: CO - Control; LC - Large circular; LE - Large elongated; SC - Small circular; SE - Small elongated

5. Discussion

In this study we investigated the first growing season after the creation of gaps with different designs in a sessile oak-hornbeam stand and how these disturbances affected the vegetation and some environmental variables (light and soil moisture). As expected, we found that the understory vegetation was not strongly affected by the opening of the canopy, what we believe is mainly because of the small time frame of this study. For the environmental variables investigated, the effects of the gaps were already apparent and it was possible to determine the spatial differences among the gap locations.

5.1. The effect of gap treatments on the vegetation

As the resource availability increases right after the disturbance, the diversity of the understory plants spikes and, after some time, decreases due to the closure of the canopy (Duguid & Ashton, 2013). In a similar oak-hornbeam stand as the one in this experiment, two years after the implementation of treatments a significant increase in species richness was reported in gaps (Tinya et al., 2019). However, in our work there was no significant treatment effect on the species richness. We believe that the reason for that is the short time since the disturbance, being that the most important effects in species richness will probably occur in the upcoming years. Despite that no significant changes were observed, there is already an increasing tendency in the mean number of species in some quadrats of the gaps (*Figure 9*). A positive correlation between the gap size and the number of species were reported in deciduous forests (Schumann et al., 2003; Kelemen et al., 2012). When the canopy opening is too large it favors the growth of weeds of arable lands and plant species typical of meadows and clear-cutting areas, in other words, non-forest plant species (Márialigeti et al., 2016). Therefore, to promote natural regeneration of the forest and maintain its important species richness typical of this herb layer of this ecosystem, unproportionally large disturbances are not desirable.

In terms of vegetation cover, the large elongated gaps had a slightly, but significantly higher vegetation cover than control plots. In another study, Ritter et al. (2005) also verified a higher vegetation cover in a natural gap at the first year after its opening, but this increase was more pronounced two years later. A study by Kelemen et al. (2012) on the transition of shelterwood system to continuous cover forestry in beech forests also reported an increase in the vegetation cover after the gap creation, especially in the center zone of the gaps. Other works have shown similar results as well (Mihók et al., 2005; Kollár, 2017).

Curiously, the large circular gap presented smaller vegetation cover than the small circular gap and similar vegetation cover as seen in the small elongated gap. Gálhidy et al. (2006) similarly described greater cover in the small gaps in the first year after its creation, but this changed in the second year, with higher values in the larger gaps.

The understory vegetation cover was higher in the northern area of the gaps close to the center. This same pattern was reported by Ritter et al. (2005) in a semi-natural beech dominated forest. It is proposed that light plays a crucial role and is the most important factor affecting the course and pace of the forest dynamics (Kelemen et al., 2012). Corroborating with that, case studies in closed mixed forests verified that the most important environmental variable for the herb layer is the light incidence, which is determined by the canopy structure, and so by the forest management strategy used (Tinya et al., 2009; Márialigeti et al., 2016). Our results indicate that there must be a correlation between the larger development of the vegetation and the intensity of direct incidence of light, which is higher in the northern area of the quadrats, especially in large canopy openings. Furthermore, the soil moisture seems to influence the vegetation cover in the gaps. Diaci et al. (2007) compared gaps with different soil moisture conditions and verified a significantly higher herbaceous cover in the wetter gaps.

The species composition was not affected by the treatments, and a similar result was presented by Schumann et al. (2003). In the case study by Tinya et al. (2019), the species composition of gaps was considerably different from the control plots after two years of different silvicultural treatment implementations.

5.2. The effect of gap treatments on the environmental variables

5.2.1. Soil moisture

The absolute soil water content (SWC) observed in our studied area was very low compared with other studies (e.g. Ritter et al., 2005; Gálhidy et al., 2006; Latif and Blackburn, 2010; Kollár, 2017). Despite this, the results exhibited changes in this site parameter which are consistent with earlier studies.

Soil moisture (dSWC) was affected by the treatment in the case of the large circular gap design. Besides that, circular gaps in general had higher soil moisture than the elongated ones. This emphasizes the importance of the shape of the gap in the soil water content and can be attributed to the root system of surrounding trees not reaching the central portion of the gap in circular gaps. Some other case studies have also verified that larger gaps have higher soil moisture than the small ones (Gray et al., 2002; Latif and Blackburn, 2010). A contrary study show no significant differences between the soil moisture of large and small gaps in a beech forest, but both gap sizes had higher soil moisture than the closed stand in this case as well (Gálhidy et al., 2006).

According to the zone's separation, the center was the wettest area of the gaps in all gap designs. This corroborates with other works, as the soil moisture decreases from the center to the closed forest (Gray et al., 2002; Ritter et al., 2005; Kollár, 2017). The lower levels of plant transpiration and the absence of interception of precipitation in the gaps are reported as the causes of this spatial pattern (Ritter et al., 2005).

Considering the south-north transect (*Figure 15*) the soil in the southern part of the gaps tends to be moister than in the northern, which was also reported by Gray et al. (2002). This is explained by the extra direct solar radiation in the northern part of the gaps in the Northern Hemisphere and a consequently higher transpiration and evaporation of the soil water content (Gray et al., 2002).

In another experiment in a nearby oak-hornbeam forest stand, the soil moisture was greater in the gaps than in the clear-cutting (Kovács et al., 2020). They argue that in large clear-cuts the high temperature and low air humidity during the growing season increases the water evaporation from the soil, which results in a lower soil moisture than in gaps, which are surrounded by forest and characterized by mitigated microclimate.

In the under-canopy zone, located just 1.5 m from the canopy edge, the roots and canopies already cause the soil moisture to be as low as it is in closed forest in all gap types.

5.2.2. Openness

Canopy openness is directly altered by silviculture systems, as a consequence of the removal of canopy trees. Despite the relatively homogenous stand characteristics before the intervention, the created gaps have an irregular canopy projection, but we can see differences between the different gap designs, what it is visible in our LiDAR image (*Figure 4*) as well as the hemispherical photographs (*Annex 4*).

According to Promis et al. (2009) the canopy openness is the most important factor affecting the variation of the total solar irradiance in the ground level in forest gaps. For foresters, the canopy openness is a useful measurement to lead canopy manipulation and control the incidence of light in the understory and the natural regeneration of the forest (Angelini et al., 2015).

In our work, the canopy openness was the highest in the large circular gaps, but the small gaps have shown significant treatment effects too. In the analysis of the gap zones, the openness was significantly higher in the center and edge of all gap designs, and only the under-canopy quadrats of the small gaps have shown no treatment effect. This corroborates with the findings of Kollár (2017), with the greatest canopy openness values being registered in the center of the gaps, decreasing to the sides and towards the closed canopy.

5.2.3. Light incidence

Many studies proved a positive correlation between gap size and solar irradiance (Gray et al., 2002; Mihók et al., 2005; Gálhidy et al., 2006; Latif and Blackburn, 2010). In our measurements, the larger gaps also showed higher solar radiation compared to small ones. Considering gap shapes for the whole sampling area (*Figure 12d*), we found very similar results for different shapes in case of the direct site factor, which contradicts the results of Schliemann and Bockheim (2011) suggested that narrow gaps receive less photosynthetically active radiation than circular gaps. This can be explained by the orientation of the elongated gaps in our study, north-south, which as we could see, keeps the shade provided by surrounding trees very similar to the circular gaps and does not affect the direct sun radiation. Even though, there is a difference in the pattern distribution along with the gaps of the same size and different shapes. In elongated gaps there is slightly higher direct incident light compared to circular ones in the edge zone (*Figure 13k*), and in the extreme north quadrats (quadrats N4 and N5, *Figure 21*) in the large elongated gap.

Other studies in the Northern Hemisphere reported a higher direct light in the northern part of the gaps (Gray et al., 2002; Ritter et al., 2005; Gálhidy et al., 2006), while in the Southern Hemisphere the southern region of gaps received higher direct solar radiation (Promis et al., 2009). This is due to the sun's path, and according to Gálhidy et al. (2006) the aspect and topography of neighboring slopes also influence the direct sun radiation that reaches the ground level.

The indirect site factor was the highest in the larger circular gaps, but in small gaps it was also higher than in the control. The positive effect of gap size on indirect radiation was observed in other studies as well (Gray et al., 2002; Ritter et al., 2005; Diaci et al., 2007). In the case study reported by Gray et al. (2002) the diffuse light was the highest in the center of the gap, as it is not related with the sun's position on the sky, which was also observed in our study. According to Promis et al. (2009), the most influential factors regarding diffuse solar irradiance are the quantity, size and spatial distribution of canopy gaps.

The total site factor, as a combination of direct and indirect site factor, is determined mainly by the direct site factor, while indirect site factor had very similar response than canopy openness.

Concluding anything regarding the regeneration success of woody species, and of oak in particular, is beyond the scope of the work presented in this thesis. The uncertainty of oak regeneration is a major concern about the implementation of continuous cover forestry in oak-hornbeam stands, especially because of the specific conditions necessary to promote oak regeneration. We can conclude that the different gaps designs have changed the environmental conditions, and this emphasizes the importance of further exploration of these, as they directly affect the understory vegetation, and so the regeneration of the woody species.

6. Conclusion

The presented study is preliminary, providing a first assessment of the effects of different gap designs on the understory vegetation and on-site conditions influencing it, in an even-aged sessile oak-hornbeam forest. The results from the first growing season demonstrated that the environmental variables were substantially affected by the gap openings. The size of the gaps influenced more the canopy openness and light, while the soil moisture was most affected by the gap shape. For the following years we would expect (1) an increasing vegetation response to the gap openings; (2) a decrease in the soil moisture content as the understory vegetation develops; (3) a change in openness and light patterns caused by the growth of branches of neighboring trees and by the development of tree sprouts and saplings. We expect that the continuation of this study will enable us to grasp how the site conditions interfere with the understory vegetation, especially with the survival and growth of the woody species.

Although it is still impossible to prescribe which gap designs are the most favorable for this forest type, the first-year measurements and analyses are nonetheless relevant because they reveal the patterns of the changes in the gaps, which will subsequently affect and frame the forest ecosystem. The most intricate aspect in the search for an optimal gap design for this forest type is to promote enough light availability to allow the oak regeneration, while also preventing the understory vegetation to outcompete this species.

The management of sessile oak with continuous cover forestry is challenging, and it is essential to understand how to implement these small-scale treatments, by exploring which gap designs can ensure the environmental conditions crucial for the maintenance of oak dominance concomitant to old-growth forest attributes and the conservation of forest biodiversity.

SUMMARY

Oak forests are important both for the economic value of their wood and for nature conservation. To promote more biodiverse and uneven-aged stands, the implementation of continuous cover forestry methods is considered as an alternative to rotation forestry systems, including shelterwood forestry. This work is a preliminary study on the effects of the implementation of continuous cover forestry in an even-aged deciduous forest dominated by sessile oak (*Quercus petraea*) and hornbeam (*Carpinus betulus*) in the Pilis Mountains, Hungary. This study aims to investigate the changes and spatial differences driven by different gap designs (large circular, large elongated, small circular and small elongated) on the vegetation (number of species, vegetation cover and species composition) and abiotic environmental variables (soil water content, canopy openness and incident light). The sessile oak regeneration is the main challenge to be faced for the implementation of continuous cover forestry in this forest type. In this way, the study of changes in environmental conditions is essential to verify which gap design allows a better result in the upkeep of the oak as dominant species.

In our results so far, the number of species and the composition of the understory vegetation didn't show any significant treatment effect, only the vegetation cover has moderately risen as a weak effect of the large elongated gap. The soil water content was greater mostly in the circular gaps, with the highest values in the large circular gap. The quadrats slightly south from the center had the highest soil moisture. The openness was directly correlated with the gap size and all of the gaps had significant treatment effect for this variable. The direct site factor had higher incidence on the larger gaps, and the northern area of the gaps received more direct solar radiation. Considering the indirect site factor, no difference was observed regarding the cardinal directions and all gaps had greater indirect site factor when compared to the controls, with higher values in larger gaps. As an initial study, we could not yet prescribe which gap design is more suitable for this forest type, however in the continuation of the study it will be possible to analyze further the response of the vegetation, the environmental conditions and especially the oak regeneration.

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ANNEXES

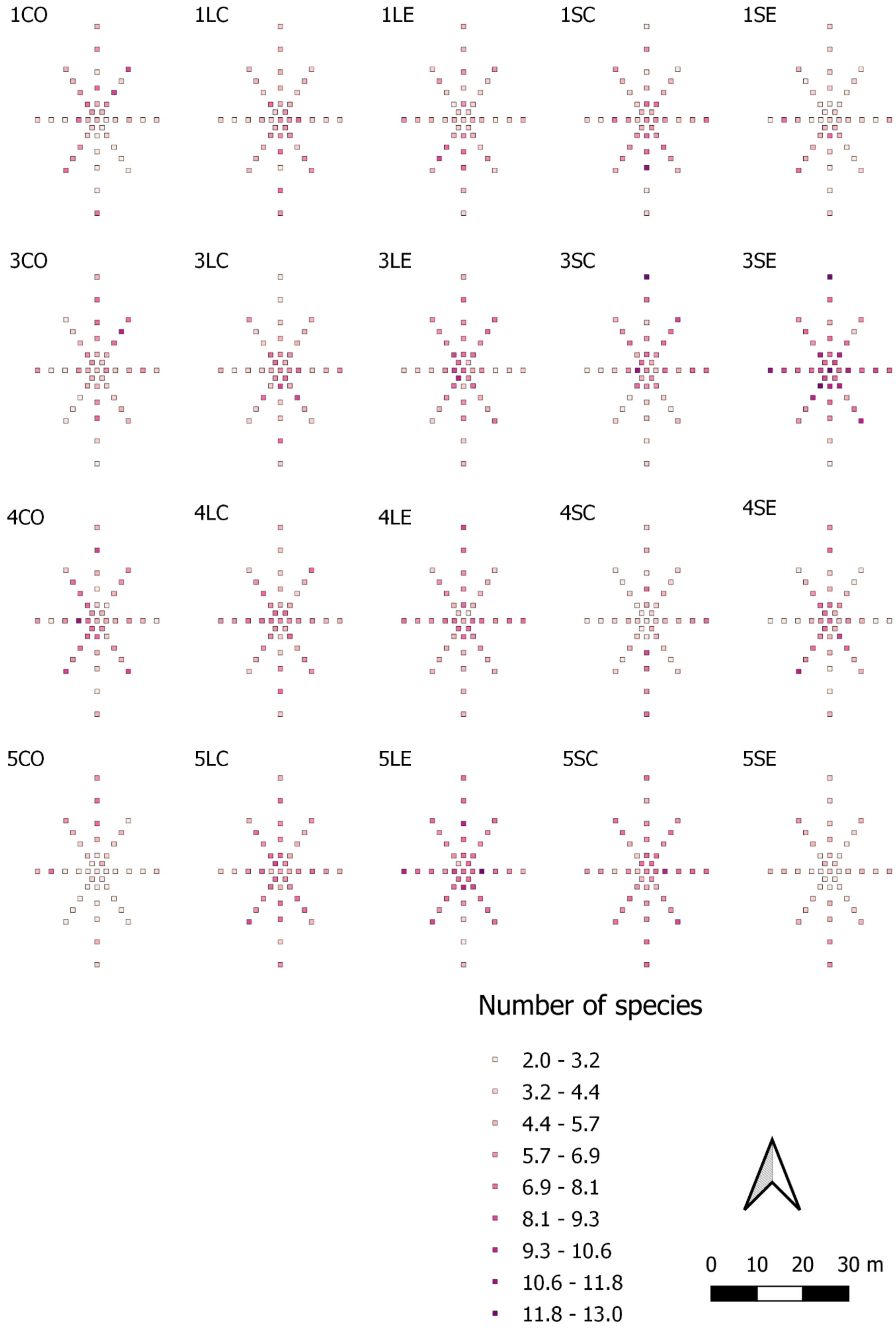
Annex 1: Understory species

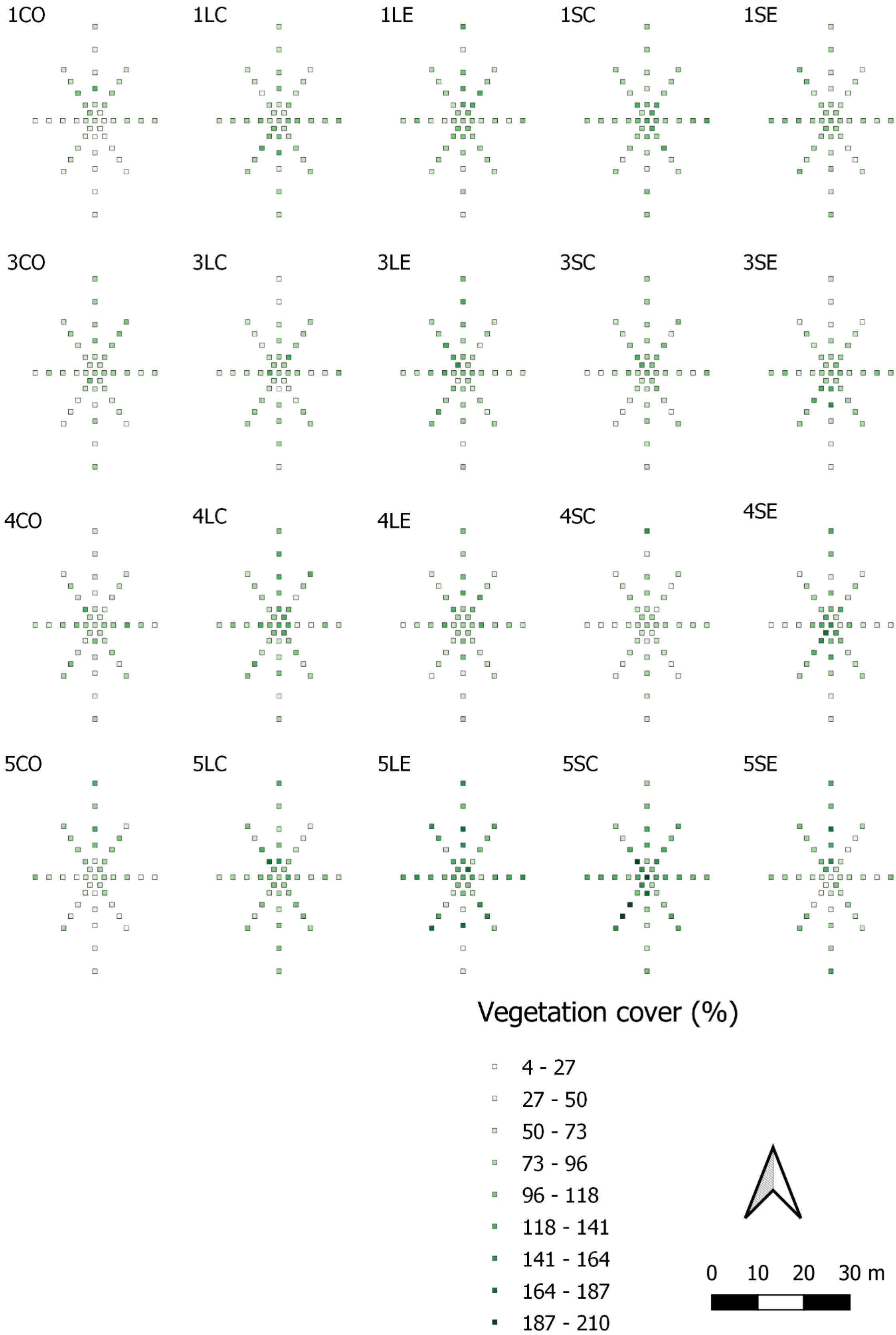
Functional groups: woody (W), perennial graminoid (PG), perennial herb (PH), annual herb (A).

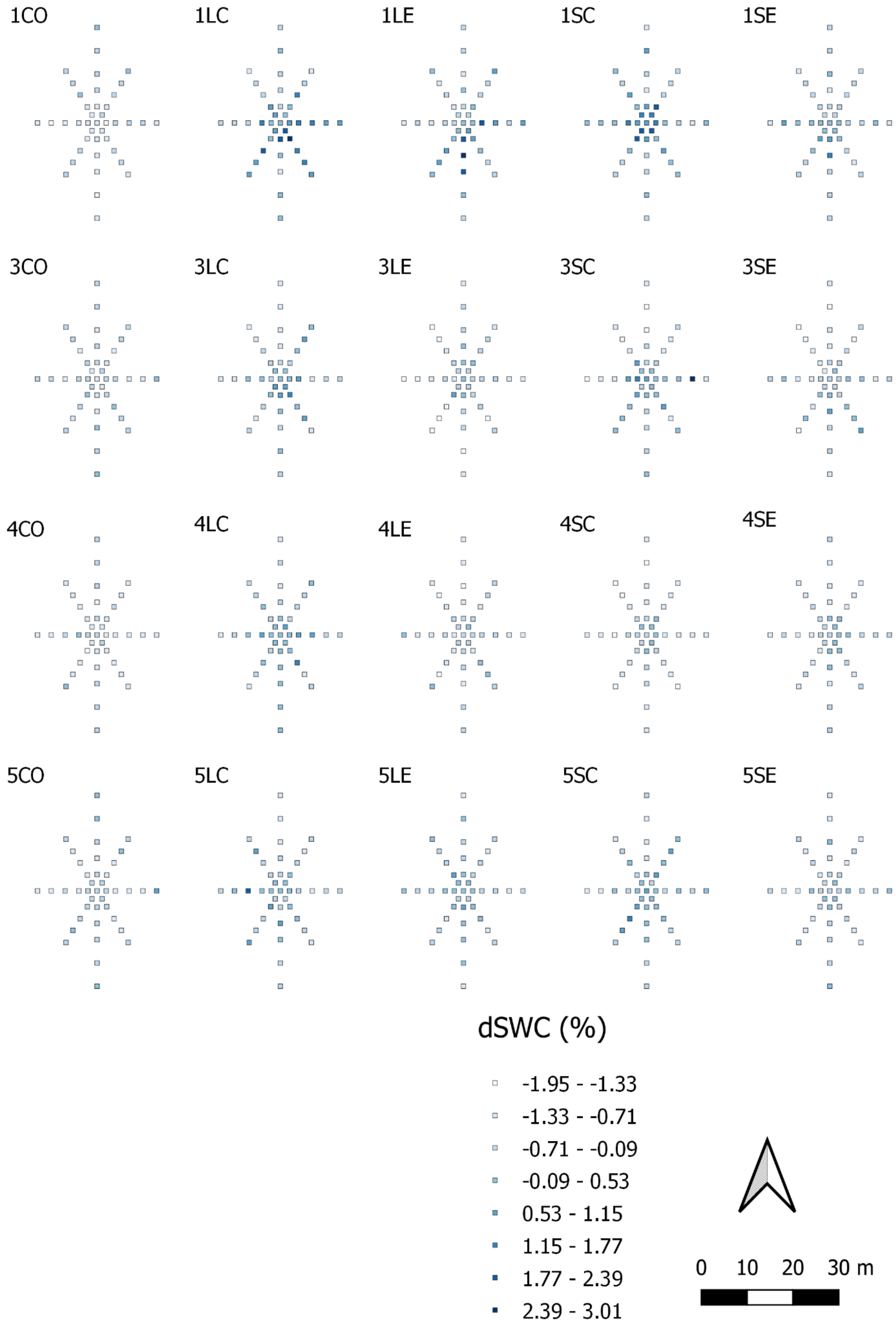
Species	Functional group	Mean cover (%)	Frequency (%)
Acer campestre	W	0.01	0.12
Ajuga reptans	PH	0.15	3.17
Brachypodium pinnatum	PG	0.36	1.95
Brachypodium sylvaticum	PG	0.05	0.49
Bromus benekenii	PG	0.01	0.24
Buglossoides purpurocaerulea	PH	0.17	1.10
Campanula rapunculoides	PH	0.00	0.12
Campanula trachelium	PH	0.00	0.12
Carex pilosa	PG	25.81	84.39
Carpinus betulus	W	0.96	27.07
Cephalanthera longifolia	PH	0.02	0.85
Cirsium arvense	PH	0.00	0.12
Clematis vitalba	W	0.36	1.10
Clinopodium vulgare	PH	0.03	0.85
Convallaria majalis	PH	0.15	4.63
Cornus sanguinea	W	0.22	1.46
Crataegus monogyna	W	0.01	0.24
Dactylis polygama	PG	0.09	2.20
Dryopteris filix-mas	PH	0.00	0.12
Epipactis helleborine	PH	0.00	0.12
Erigeron annuus	A	0.00	0.12
Euphorbia amygdaloides	PH	0.04	3.54
Fagus sylvatica	W	0.00	0.12
Fallopia dumetorum	A	0.01	0.24
Festuca gigantea	PG	0.03	0.49
Festuca heterophylla	PG	0.02	0.61
Fragaria vesca	PH	0.52	9.39
Fraxinus ornus	W	0.10	2.07
Galeobdolon montanum	PH	0.06	0.61
Galium aparine	A	0.02	0.85
Galium odoratum	PH	0.74	9.63
Galium schultesii	PH	6.20	55.98
Geranium robertianum	A	0.00	0.37
Geum urbanum	PH	0.01	0.12
Hedera helix	W	0.00	0.12
Heracleum sphondylium	PH	0.01	0.24
Hieracium murorum	PH	0.01	0.12
Hieracium sabaudum	PH	0.04	1.34
Hypericum hirsutum	PH	0.00	0.12
Hypericum perforatum	PH	0.01	0.73

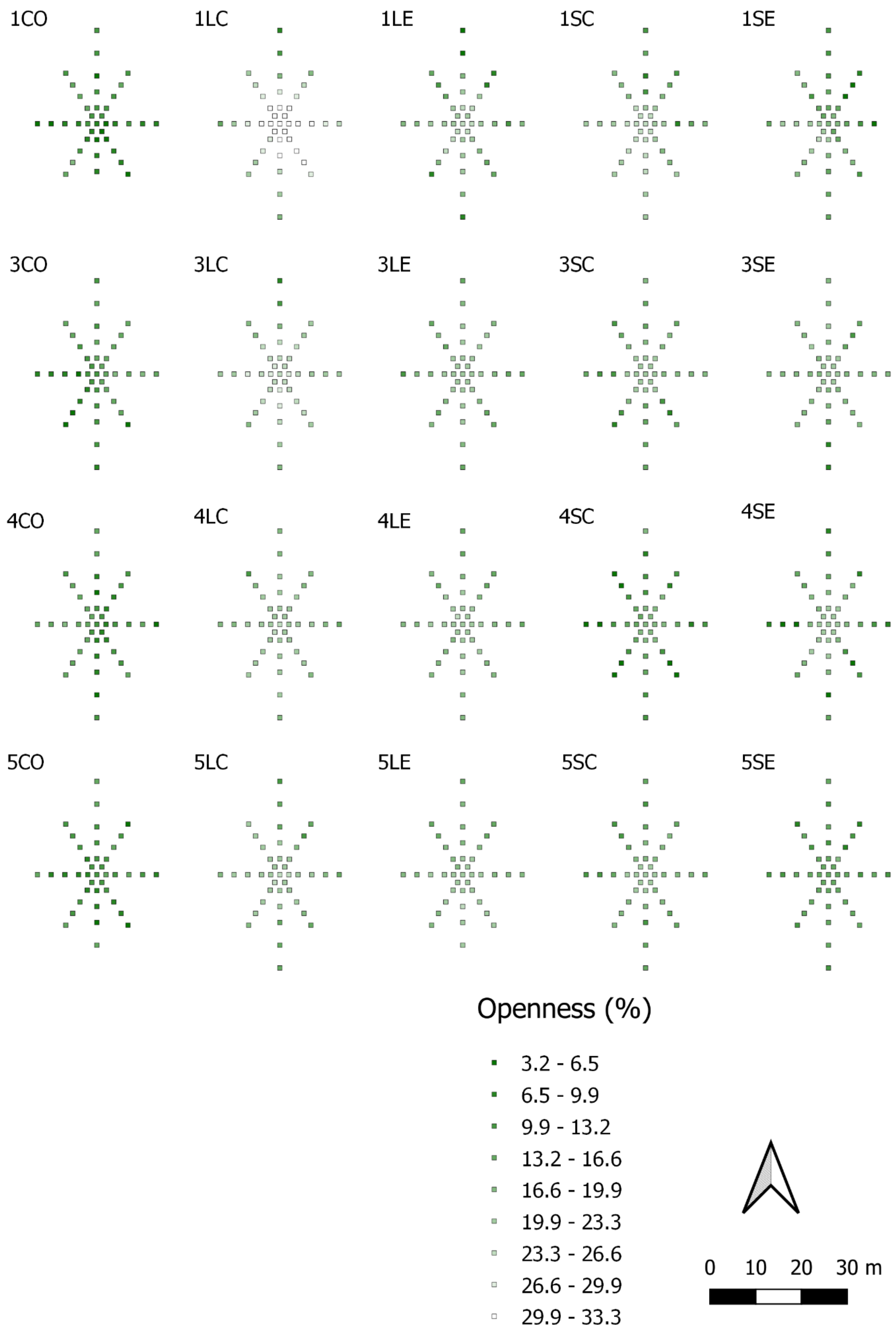
Species	Functional group	Mean cover (%)	Frequency (%)
Impatiens parviflora	A	0.14	1.22
Lathyrus niger	PH	0.00	0.12
Lathyrus vernus	PH	0.18	4.15
Ligustrum vulgare	W	0.01	0.12
Luzula luzuloides	PG	0.03	0.73
Lysimachia punctata	PH	0.01	0.12
Melampyrum nemorosum	A	0.36	5.00
Melampyrum pratense	A	0.02	0.98
Melica uniflora	PG	21.85	98.17
Melittis melissophyllum	PH	0.60	15.61
Moehringia trinervia	A	0.07	4.39
Molinia arundinacea	PG	0.02	0.12
Mycelis muralis	PH	0.05	2.68
Poa nemoralis	PG	0.49	14.27
Polypodium vulgare	PH	0.01	0.12
Polygonatum multiflorum	PH	0.24	5.49
Prunus avium	W	0.03	0.73
Pulmonaria mollissima	PH	0.00	0.12
Quercus cerris	W	0.04	0.98
Quercus petraea	W	13.81	97.93
Ranunculus auricomus agg.	PH	0.00	0.49
Rosa canina	W	0.02	0.49
Rubus fruticosus agg.	PH	3.59	21.83
Rumex sanguineus	PH	0.01	0.61
Sanicula europaea	PH	0.01	0.24
Scrophularia nodosa	PH	0.02	1.46
Sorbus domestica	W	0.00	0.12
Stellaria holostea	PH	1.34	29.51
Stellaria media	A	0.00	1.10
Symphytum officinale	PH	0.01	0.12
Symphytum tuberosum	PH	0.01	0.37
Tanacetum corymbosum	PH	0.03	0.98
Taraxacum officinale	PH	0.00	0.12
Trifolium pratense	PH	0.00	0.12
Valeriana officinalis	PH	0.03	0.12
Veratrum nigrum	PH	0.09	0.49
Veronica chamaedrys	PH	0.03	0.85
Veronica officinalis	PH	0.02	0.61
Vicia cassubica	PH	0.00	0.12
Vicia hirsuta	A	0.00	0.61
Vicia sepium	PH	0.05	1.71
Viola alba	PH	0.03	1.10
Viola reichenbachiana	PH	0.20	8.54

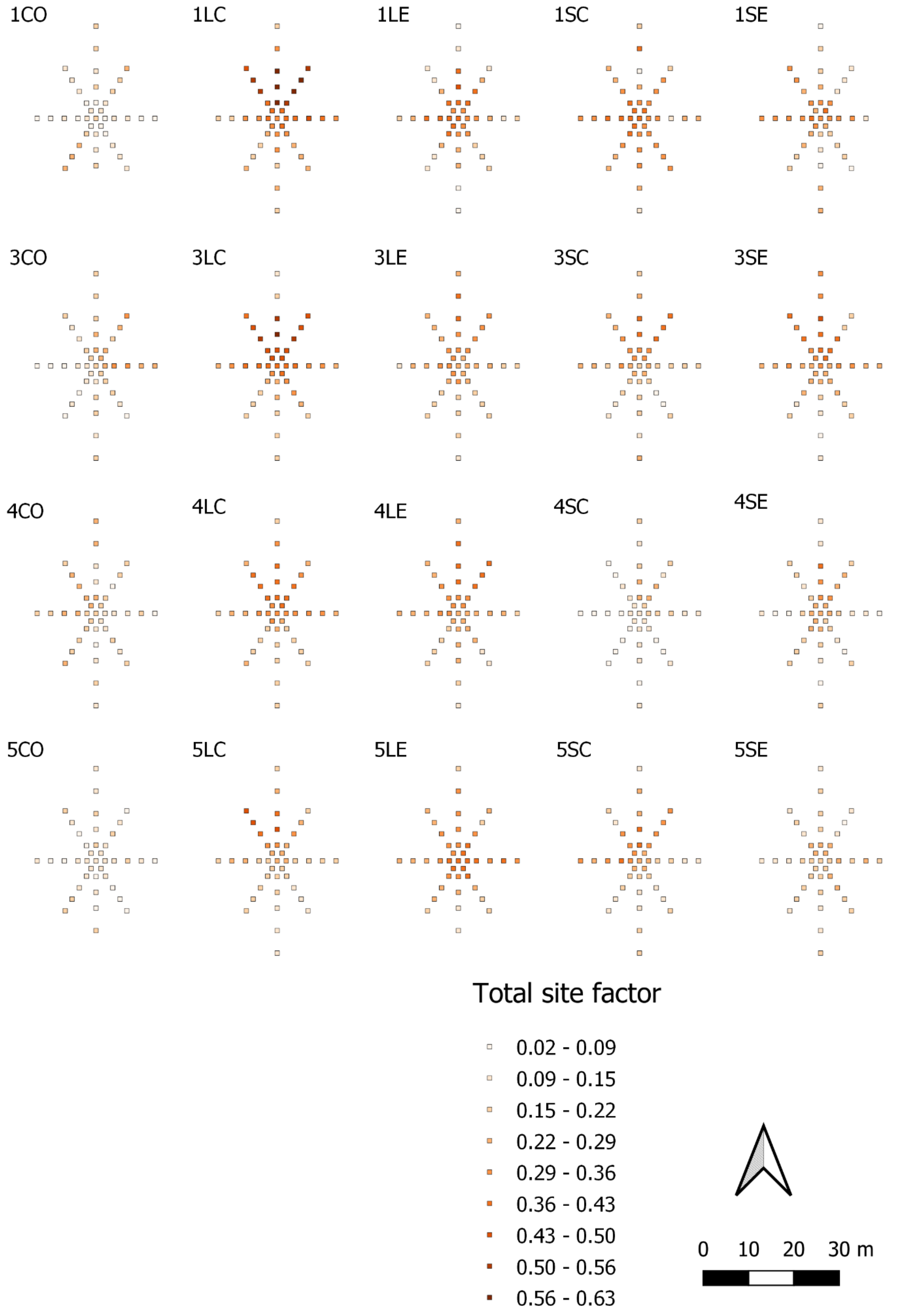
Annex 2: Pattern of the quadrats within the plots

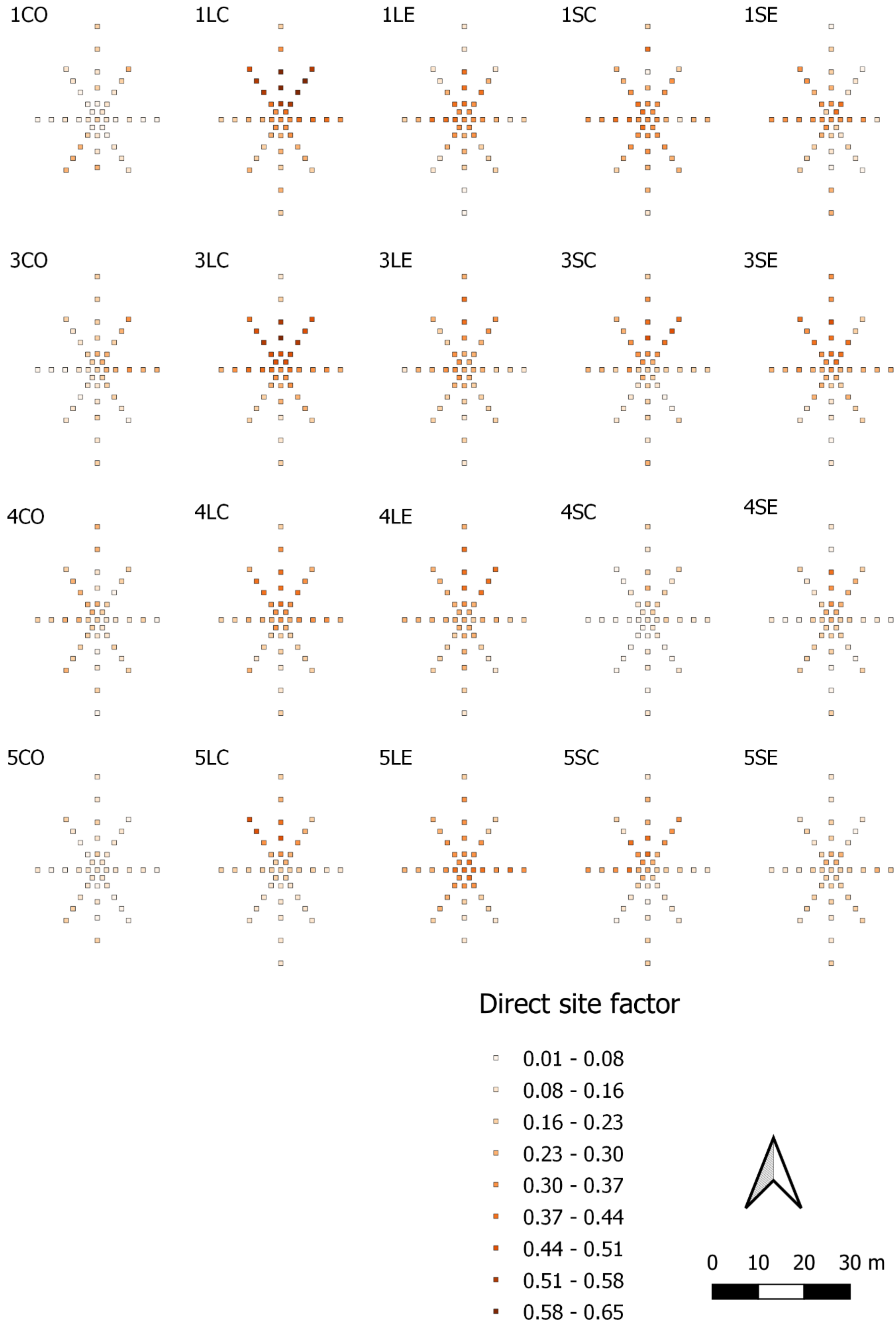



1CO
1LC
1LE
1SC
1SE
3CO
3LC
3LE
3SC
3SE
4CO
4LC
4LE
4SC
4SE
5CO
5LC
5LE
5SC
5SE
Vegetation cover (%)
4 - 27
27 - 50
50 - 73
73 - 96
96 - 118
118 - 141
141 - 164
164 - 187
187 - 210
0 10 20 30 m

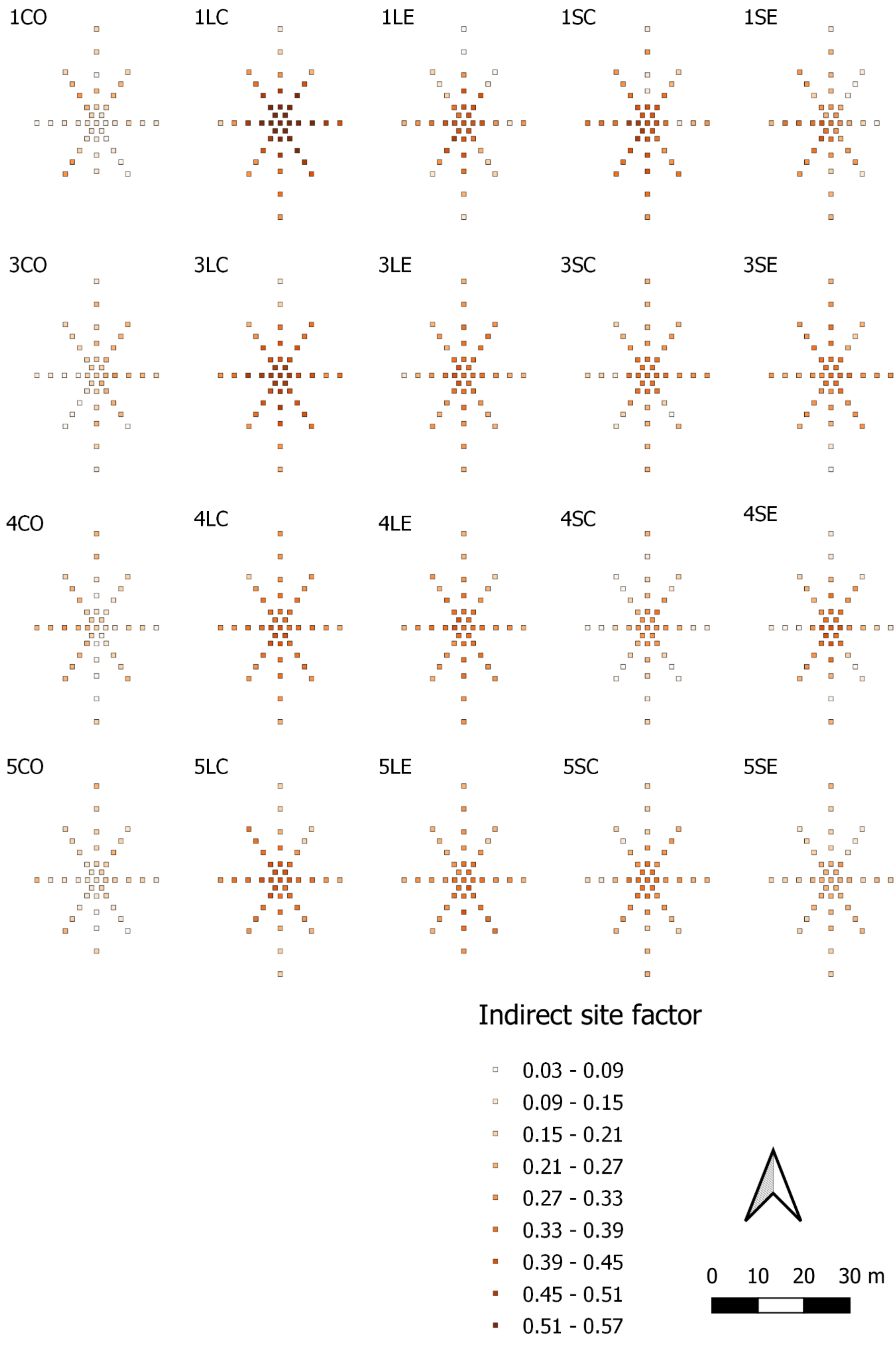

1CO
1LC
1LE
1SC
1SE
3CO
3LC
3LE
3SC
3SE
4CO
4LC
4LE
4SC
4SE
5CO
5LC
5LE
5SC
5SE
dSWC (%)
-1.95 - -1.33
-1.33 - -0.71
-0.71 - -0.09
-0.09 - 0.53
0.53 - 1.15
1.15 - 1.77
1.77 - 2.39
2.39 - 3.01
0 10 20 30 m


1CO
1LC
1LE
1SC
1SE
3CO
3LC
3LE
3SC
3SE
4CO
4LC
4LE
4SC
4SE
5CO
5LC
5LE
5SC
5SE
Openness (%)
3.2 - 6.5
6.5 - 9.9
9.9 - 13.2
13.2 - 16.6
16.6 - 19.9
19.9 - 23.3
23.3 - 26.6
26.6 - 29.9
29.9 - 33.3
0 10 20 30 m

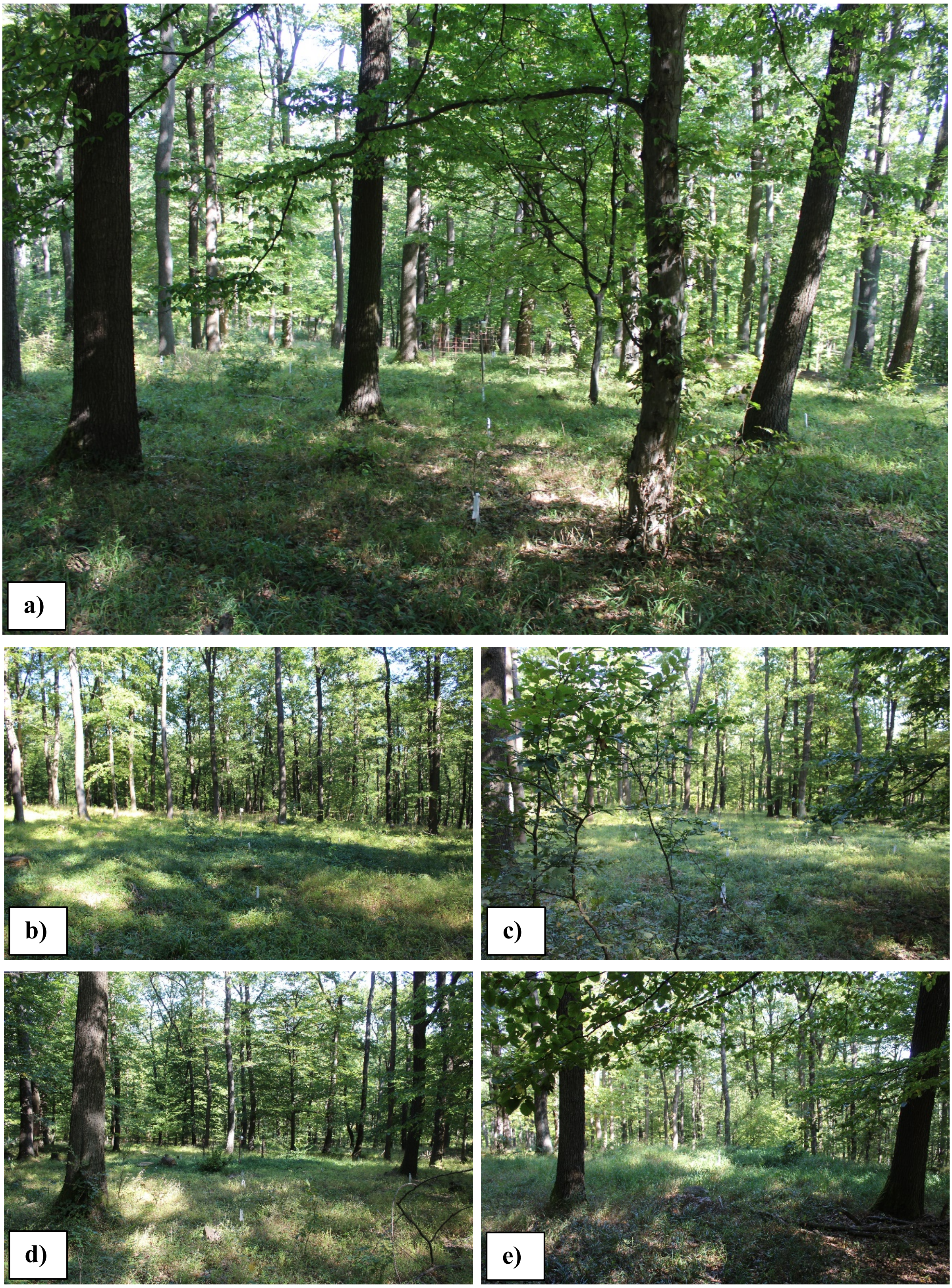

1CO
1LC
1LE
1SC
1SE
3CO
3LC
3LE
3SC
3SE
4CO
4LC
4LE
4SC
4SE
5CO
5LC
5LE
5SC
5SE
Total site factor
0.02 - 0.09
0.09 - 0.15
0.15 - 0.22
0.22 - 0.29
0.29 - 0.36
0.36 - 0.43
0.43 - 0.50
0.50 - 0.56
0.56 - 0.63
0 10 20 30 m



1CO
1LC
1LE
1SC
1SE
3CO
3LC
3LE
3SC
3SE
4CO
4LC
4LE
4SC
4SE
5CO
5LC
5LE
5SC
5SE
Direct site factor
0.01 - 0.08
0.08 - 0.16
0.16 - 0.23
0.23 - 0.30
0.30 - 0.37
0.37 - 0.44
0.44 - 0.51
0.51 - 0.58
0.58 - 0.65
0 10 20 30 m


1CO
1LC
1LE
1SC
1SE
3CO
3LC
3LE
3SC
3SE
4CO
4LC
4LE
4SC
4SE
5CO
5LC
5LE
5SC
5SE
Indirect site factor
0.03 - 0.09
0.09 - 0.15
0.15 - 0.21
0.21 - 0.27
0.27 - 0.33
0.33 - 0.39
0.39 - 0.45
0.45 - 0.51
0.51 - 0.57
0 10 20 30 m

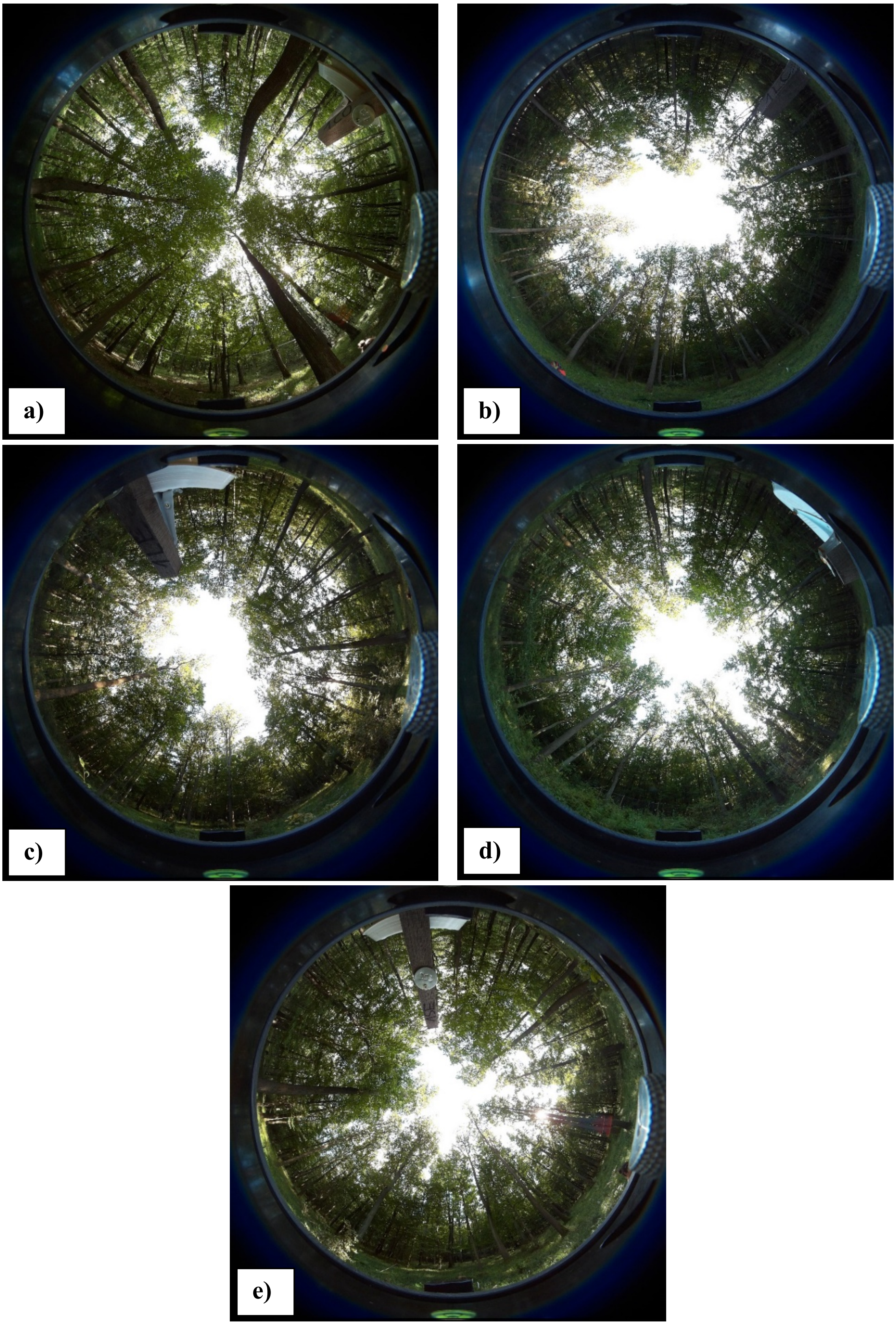
Annex 3: Photos of the first growing season after the treatment implementation



The treatments are as follow:

a) Control, b) Large Circular, c) Large elongated, d) Small circular, e) Small elongated. (Photos taken by Csenge Veronika Horváth)

Annex 4: Hemispherical photographs of the treatments from the center quadrat



The treatments are as follow:

a) Control, b) Large Circular, c) Large elongated, d) Small circular, e) Small elongated. (Photos taken by Flóra Tinya)

AUTHOR CONTRIBUTION

This thesis work is part of the Pilis Gap Experiment implemented by the Centre for Ecological Research, Institute of Ecology and Botany, Forest Ecological Research Group.

The field work for the vegetation survey and soil water content measurement was carried out by Csenge Veronika Horváth and myself, with additional help of Lorenzo Crecco, Flóra Tinya and Bence Kovács.

The composition and environmental data analysis and writing were done by me with the assistance of my supervisor, Péter Ódor, and Csenge Veronika Horváth.

The LiDAR data was collected by Gábor Illés, while Bence Kovács and Lorenzo Crecco accomplished the spatial analysis (GIS and gap projections). Bence Kovács made the maps presented in this thesis.

Flóra Tinya performed the hemispherical photographs and software analysis of the light data.

ACKNOWLEDGEMENTS

My deepest gratitude to my supervisor, Péter Ódor, for all the guidance, comprehension and support, and Csenge Veronika Horváth, for becoming much more than a fieldwork colleague and always giving me encouragement and great support for the thesis work.

In addition, my thanks to Flóra Tinya, Bence Kovács, Lorenzo Crecco and Gábor Illés for their participation in this thesis, by their data collection, help in the field work, and analysis performed.

I am thankful to professor Tamás Weiszburg and professor Tibor Kalapos, both dedicated to the Environmental Science master's and the Applied Ecology specialization. Besides, all the teachers and professionals who are part of the Environmental Science Master's, friends and colleagues who I was very glad to have met, learn with and share experiences.

Finally, I am grateful for my caring husband Tomaz, who was always supportive and giving me help in reviewing the text. To my son, for being always cheerful with the forest stories. For my parents, João and Jussara, and my brother, João Felipe, who were always encouraging my studies and decisions.

STATEMENT

Name: Julia Schadeck Locatelli
Neptun ID: BZVGKN
ELTE Faculty of Science: Environmental Science MSc
Specialization: Applied Ecology
Title of diploma work: Effects of gap size and shape on the understory vegetation in an oak-hornbeam forest

As the author of the diploma work I declare, with disciplinary responsibility that my thesis is my own intellectual product and the result of my own work. Furthermore I declare that I have consistently applied the standard rules of references and citations.

I acknowledge that the following cases are considered plagiarism:
– using a literal quotation without quotation mark and adding citation;
– referencing content without citing the source;
– representing another person's published thoughts as my own thoughts.

Furthermore, I declare that the printed and electronical versions of the submitted diploma work are textually and contextually identical.

Budapest, 20th May 2020

Julia S. Locatelli

Signature of Student