

Spatial Variability of Microclimate Characteristics in Transition Zone of the Forest: A Case Study of Slătioara Secular Forest

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Abstract

Although the importance of forest margins in ecology is recognized, no study has been carried out in the Slătioara Secular Forest Reserve with reference to the variability of abiotic parameters along forest margins. With this study, we investigate to what extent microclimatic variables (air temperature—T_{air}, air humidity—H_{air}, soil temperature—T_{soil}, soil humidity—H_{soil} wind intensity (WIND) and photosynthetically active radiation intensity (PAR)) are correlated with the distance from the edge to the forest interior and the habitat type (forest interior, inner and outer edge and meadow) in the Slătioara Secular Forest Reserve. In order to measure these microenvironment variables we used the strip transect method, positioned perpendicular to the forest edge. Differences in the microenvironment variables considered in the analysis between the four habitat types were assessed using one-way ANOVA followed by Tukey-test post-hoc. To assess differences along transects, each of the six measurements went through a one-way ANOVA against distance to edge, followed by a Levene's test for variances and finally a Tukey-test post-hoc. The results indicate that the values of microclimatic variables were significantly different in relation to the gradient of distance from the edge and to the habitat type (interior-exterior forest) and that edge habitats are significantly more susceptible to lower humidity, high winds, lower light and higher air temperatures than forest interior habitats. The ecological study of the edge areas in this reserve provides the basis for future research on forest dynamics and can guide conservation efforts to maintain the diversity and endemism of species in the Slătioara Secular Forest.

Keywords

Component, Forest Microclimate, Edge Effects, Edge-Interior Relationships,

1. Introduction

The effects of margins differ in the intensity and magnitude of change in microclimatic parameters (Harper, 2005), and most of these effects penetrate less than 300 m into forests (Laurance et al., 2002).

In coniferous forests, the canopy reduces the intensity of solar radiation (both incoming and outgoing), decreases air circulation and influences evapotranspiration, thus creating a different microclimate in which soil and air temperature variation inside the forest is attenuated relative to those outside (Barry & Blanken, 2016; De Frenne et al., 2021).

In contrast, the microclimatic variability of air and soil temperature outside the forest can be influenced by exposure to high solar radiation intensities and high wind speed fluctuations (Aalto et al., 2013; Kemppinen et al., 2021).

As for the temperature variation in the soil depth, it is determined by the temperature fluctuations at the soil surface, the snow cover that insulates the soil from changes in the temperature of the air outside the soil and the specific heat capacity of the soil (e.g. soil moisture, as water has a high specific heat capacity) (Grundstein et al., 2005; Aalto et al., 2018; Fernández-Pascual & Correia-Álvarez, 2021).

Transition zones become highly relevant because they have a large above-ground carbon storage capacity (Paula et al., 2011; Pütz et al., 2014), alter matter cycling (Laurance et al., 2007, 2011; Nascimento & Laurance, 2004) and have altered decomposition rates and primary production (Chen et al., 1992), thus, Ewers and Banks-Leite (2013) hypothesize that as global climate change occurs, transition zones will gain increasing importance.

In addition, these interface areas between forest and grassland can serve as 'early warning' indicators or detectors of global climate change by analysing changes in this habitat type over time. (Buras et al., 2023)

At the same time, the magnitude of the multitude of effects of microclimatic (abiotic) parameters that correlate strongly with distance to the forest edge (showing a linear or exponential relationship) can be clearly seen in microclimatic changes and the response of phytoindividuals and their populations (Broadbent, 2008).

In Codrul Secular Slătioara Reserve only a few studies have been carried out to the forest edge microclimate, and interest in the abiotic characteristics of this microclimate is driven by the possibility of understanding, monitoring and predicting the response of phytoindividuals and plant communities to this changing environment.

This paper describes the variation of the main microclimatic parameters in four habitat types (meadow, forest interior edge, forest exterior edge and interior

forest) as well as along the forest outer-inner distance gradient in the Slătioara Secular Forest Reserve.

Specifically, we investigated gradients in air temperature and humidity, soil temperature and humidity, wind speed and photosynthetically active radiation intensity at six locations.

The objectives of this study are 1) to determine how microclimate variables change with the transition from meadow habitat to edge (inner-outer) and forest interior, 2) to quantify the change in microclimate variables as a function of distance gradient from forest edge to forest interior and exterior, 3) to analyze microclimate as a complex interaction of variables using multivariate techniques.

2. Materials and Methods

2.1. Study Site

This study was carried out in the Slătioara Secular Forest Reserve located in the northern part of the Eastern Carpathians, south-eastern limit of the Rarău Mountains between the valley of the Slătioara stream (790 m) and the Todirescu peak (1353 m), its limits having the following coordinates (West: 47°26'49"N, 25°36'06"E; North: 47°27'18"N, 25°37'29"E; East: 47°26'37"N, 25°38'59"E; South: 47°26'03"N, 25°37'00"E) (see **Figure 1**).

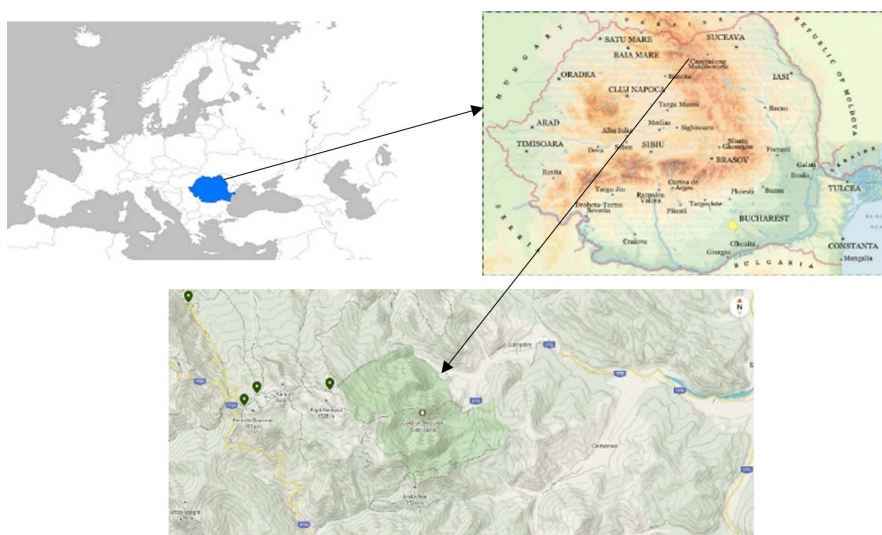


Figure 1. Location of the study site.

The forest ecosystem under study is complex both functionally and structurally, consisting of forests with a high degree of naturalness, also called “virgin forests”, in which the composition of tree species consists of beech (*Fagus sylvatica* L.), fir (*Abies alba* Mill.) and spruce (*Picea abies* (L.) H. Karst.), which have different ages (plurien) and a dynamic balance, which gives these forests an optimal stability and a maximum polyfunctional efficiency (Cenuşă et al., 2002).

The area analysed is characterised by a mountainous topoclimate of coniferous forests, in which ridge, valley and depressional corridor areas can be charac-

terised, being situated in the zone of interference between the relatively warmer and less humid coniferous-beech mixture climate (800 - 1100 m) and the cold and humid spruce-spruce climate (1200 - 1600 m).

According to Köppen's classification (Dfk), the territory is generally characterised as a boreal climate (D), with cold winters, year-round precipitation (f) and temperatures above 10°C in the warmest month (c).

Thus, the area has a moderate regime of air temperature oscillations, with high relative humidity in summer and abundant rainfall distributed differently on opposite slopes of the mountain massif.

In terms of the wind regime, the reserve's territory is characterised by very intense activity in terms of wind speed and direction, which vary greatly. Wind direction and frequency is predominantly from the west (31.7%), but also from the east (9.4%) and south-east (8.4%), with a constant moderate intensity (3.2 m/s) and periods of strong intensity are also evident, especially in the narrow valleys.

2.2. Methods

In order to quantify the spatial variation of microclimatic parameters as a function of distance gradient from the forest edge and in relation to habitat type, six study areas were established (see **Figure 2(a)**), in which 21 belt transects were located, each consisting of 39 squares (sample areas) of 4 m², progressively numbered from the forest edge towards the forest interior and the meadow (see **Figure 2(b)**).

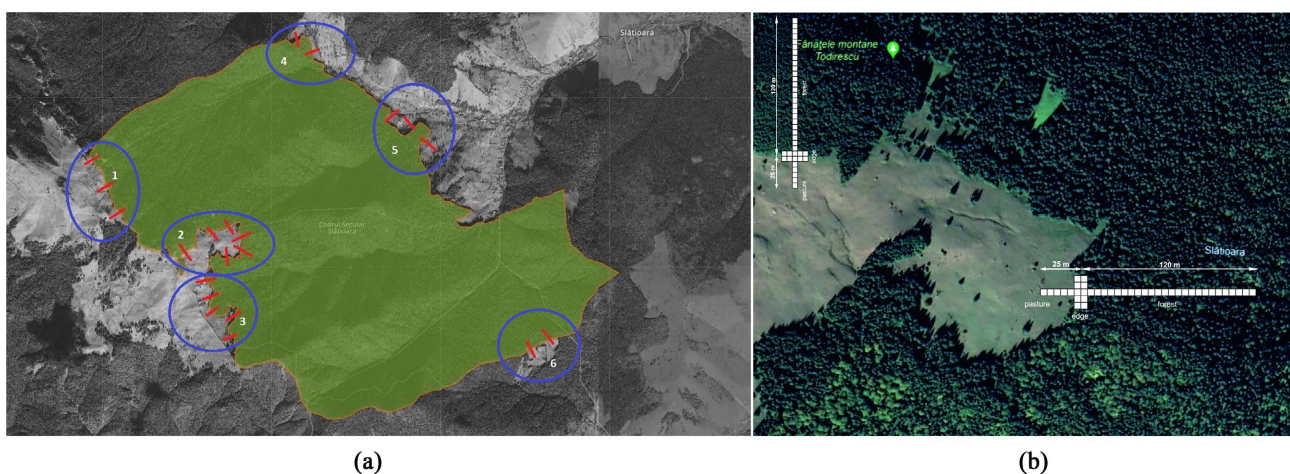


Figure 2. Location of the six study areas (a); The structure and positioning of the transect (b).

The middle part of the transect is placed along the edge of the forest (the boundary between forest and meadow) for 10 m on the interior edge and 10 m on the exterior edge, and the longer arm of the cross is positioned at right angles to the forest edge, 120 m inside the forest, and 25 m in the meadow.

Each transect is cross-shaped and was positioned perpendicular to the forest-pasture boundary to determine changes in climate variables along each forest

edge zone. (Łuczaj & Sadowska, 1997) (See **Figure 2(b)**)

The total length of each transect is 150 m, which can be considered sufficient for edge effect detection (Matlack, 1993; Young & Mitchell, 1994; Murcia, 1995), and the distance between transects was at least 200 m.

The identification of the edges was referred to the description commonly used in forest management for homogeneous stationary and stand units (management units, UP VIII Slătioara Management, 2016), which allowed clear identification of the phytocenoses in these areas.

We selected four habitat types (forest interior = P; land adjacent to the forest = PA; forest edge, in which we delimited two edge types: interior edge = LI and exterior edge = LE).

At the level of each 4 m² sample area (819) topographic data were measured: aspect, slope inclination (digital clinometer), altitude (altimeter) and geographical coordinates, using a Garmin Montana 680t GPS as well as microclimatic variables: air temperature (T_{air}), air humidity (H_{air}), soil temperature (T_{soil}), soil humidity (H_{soil}), photosynthetic active radiation (PAR) and wind intensity (WIND) (see **Table 1**).

Table 1. Method and tools for measuring microclimatic variables.

Microclimate variable	Measuring method and instruments
Photosynthetically active radiation intensity (PAR)	Measured at 2 m above ground with a handheld digital light meter (Voltcraft MS-1300 Digital Light Meter)
Air temperature (T _{air})	Measured at 1.30 m above ground with Thermo Hygroanemometer with propeller—Testo 410-2
Soil temperature (T _{soil})	Measured at 10 cm below ground level with Digital Soil Tester 4 in 1 PM-MG-4W1T Powermat PM1038
Soil moisture (H _{soil})	Measured at 5 cm depth, taken at 5 different locations with the PM-MG-4W1T Powermat PM1038 4-in-1 Digital Soil Tester
Air humidity (H _{air})	Measured at 1.30 m above ground with Thermo Hygroanemometer with propeller—Testo 410-2.
Wind intensity (WIND)	Measured at a height of about 2 metres above the ground, at two points one for each direction N-S and V-E with Thermo hygroanemometer with propeller—Testo 410-2

All measurements of microclimate variables were recorded from the meadow to the forest interior during clear days between 11:00 and 15:00 to obtain uniform and comparable data (Geiger, 1965; Hutchinson & Matt, 1977; Aude & Lawesson, 1998). We walked the transect from the meadow to the forest edge and then into the forest, measuring abiotic variables in each sample area of the transect.

In view of the measurement method mentioned above and because of the length of the transects, the number of variables and occasional equipment fail-

ure, the recording is not simultaneous but is done with a delta depending on the travel time on the transect (minimum distance between transects is 200 m).

Edge influence depth (EID) is estimated subjectively, following the model of [Chen et al. \(1995\)](#) and is defined as the distance from the forest interior to the edge at which the values of the microclimatic variables increase or decrease and the maximum distance is when these values become constant.

3. Statistical Analysis

Prior to statistical analyses, each variable was tested for deviations from normal distribution and for homoscedasticity using the Levene's test for equality of variances. All variables, including distance from forest edge, were log transformed in all analyses to normalize their distributions to meet this assumption of parametric statistics.

To quantify the differences between the values of the microclimate variables considered in the study in relation to the four habitat types, the six variables were evaluated by one-way ANOVA followed by Tukey's post-hoc test to investigate differences between means ([Zar, 1984](#)).

To assess differences along transects, each of the measurements of the six microclimate variables was tested by a one-way ANOVA with the independent variable distance from the forest edge, followed by the Fisher Least Significant Difference (LSD) linear transformation test and to find out at which distances from the edge differ significantly from each other ([Zar, 1984](#)).

In order to analyze microclimate as a complex interaction of variables, multivariate analysis was performed in two steps, as suggested by [Hatcher and Stepanski \(1994\)](#). Thus, in the first step MANOVA (Multivariate Analysis of Variance) analysis was carried out which provides a regression analysis and an analysis of variance for dependent variables (microclimate variables) with two covariates (distance to forest edge and habitat type). To verify the MANOVA test, the LDA test was performed to project the original data matrix into a lower dimensional space.

To achieve this goal, three steps had to be taken. The first step is to calculate the separability between different classes (i.e. the distance between the means of different classes), which is called the between-class variance or between-class matrix. The second step is to calculate the distance between the mean and the samples of each class, which is called the within-class variance or within-class matrix. The third step is to construct the lower dimensional space that maximizes the between-class variance and minimizes the within-class variance.

PCA (Principal Component Analysis) analysis was used to reduce the dimensionality of the variables, grouping the variables according to their similarities and therefore analysing the most important variables for each group involved, in the case of this study, habitat type.

Principal component analysis (PCA) is a method of dimensionality reduction and was used in this study to reduce the large size of the data set by transforming

the large set of variables into a smaller one that contains, however, most of the information from the large set.

This organization of the information into principal components eliminates the components with low information and is considered relevant and the remaining components are considered as new variables.

All environmental variables recorded in this study were transformed to zero skewness in line with Økland et al. (2001). For all gradient and multivariate analyses, were used the *vegan* (Oksanen et al., 2007) and *MASS* packages in R software.

4. Results

4.1. Effect of Habitat Type on Microclimatic Variables

All six microclimate variables analyzed indicate a certain degree of change once the transition from one habitat to another (see **Figure 3**).

Figure 3 shows that air and soil temperature, soil moisture and wind intensity have a high variation of data between groups (individual group mean differs from the overall mean of the data). As for the dependent variable PAR, a high variation of measurements is observed within and between groups, while for air humidity a low variation within and between groups is identified.

The means of the measured values, which express air humidity, also differ between meadow and forest, but do not differ between meadow -outer and outer edge and between forest and outer edge, but also do not differ between inner edge and forest.

Photosynthetically active radiation (PAR) intensity values do not differ between inner and outer edge, but are clearly different between meadow and forest interior as well as between forest interior and the two edge types (inner and outer).

The mean values of the variables: soil moisture, wind intensity and air temperature are different in all four habitat types.

The F-test statistic tells us how closely the observed data match the expected distribution under the null hypothesis of the ANOVA statistical test, so the higher the F-value, the more likely it is that the variation caused by the independent variable is real and not due to chance.

The F-test statistic shows that $p < 0.001$, which explains that the difference between the means is highly significant (HS, in the 99.9% confidence interval), thus the means of the values of the microclimate variables are not equal.

Therefore, it is suggested, that at least one group mean within the microclimate variables is different from the others in relation to habitat type, so there is a tendency that habitat type has a real impact on these microclimate variables.

The ANOVA test reveals that the results obtained are significant overall, but it is not known exactly where those differences lie, so we run Tukey's HSD (**Figure 4**) to identify pairs of means in a set of groups that are significantly different from each other.

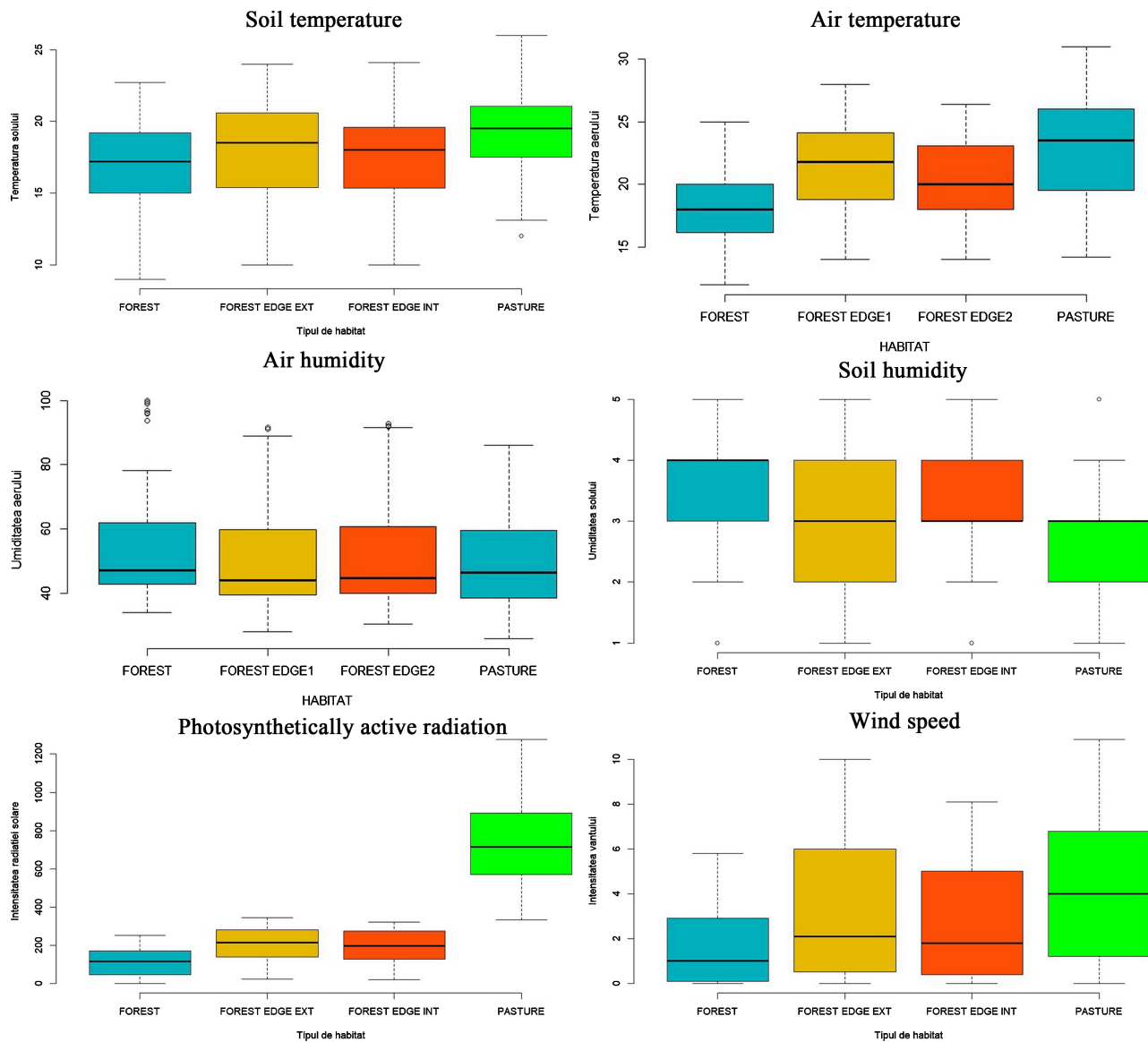
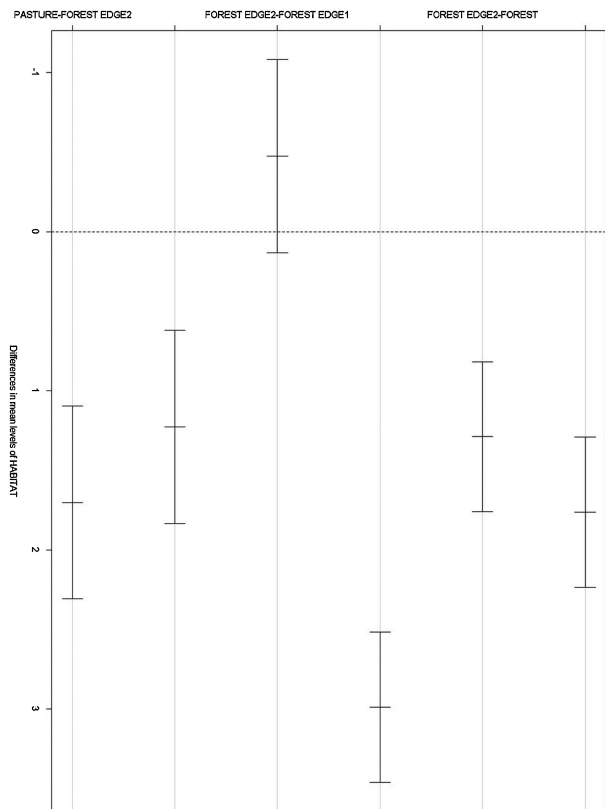


Figure 3. Mean values (± 1 SE) for microclimate variables according to type of habitat.

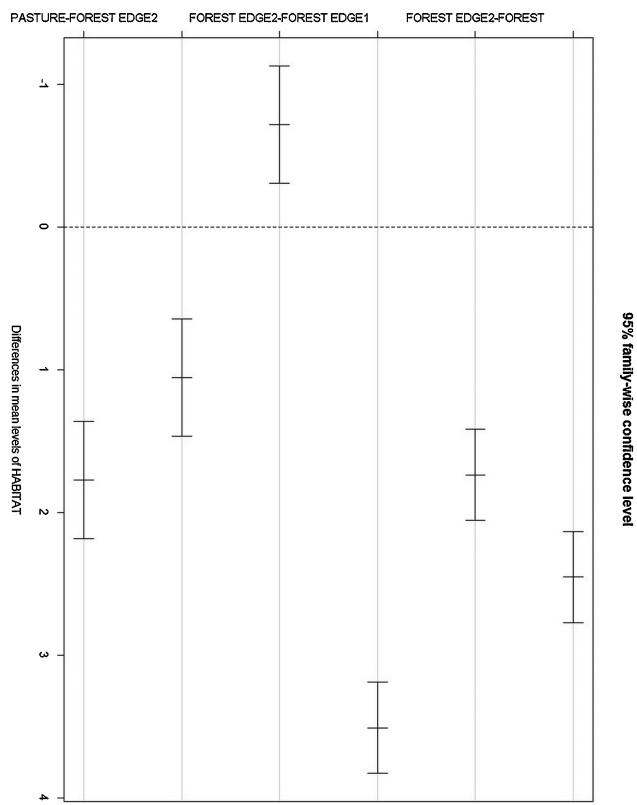
The result of the Tuckey HSD post hoc test suggests that soil temperature, air humidity and photosynthetically active radiation confidence intervals for the mean value between groups contain zero value, thus the following is highlighted: soil moisture values are not different between inner and outer edge, but are different in the other habitat type combinations (meadow-inner edge; meadow-outer edge; meadow-forest inner edge; outer edge-forest inner edge; inner edge-forest inner edge). Air humidity has distinct values only between meadow and forest interior and between outer edge and forest interior. Photosynthetically active radiation has the same values between outer and inner edge, and different values for the other habitat combinations.

4.2. Effect of Distance to Forest Edge on Microclimatic Variables

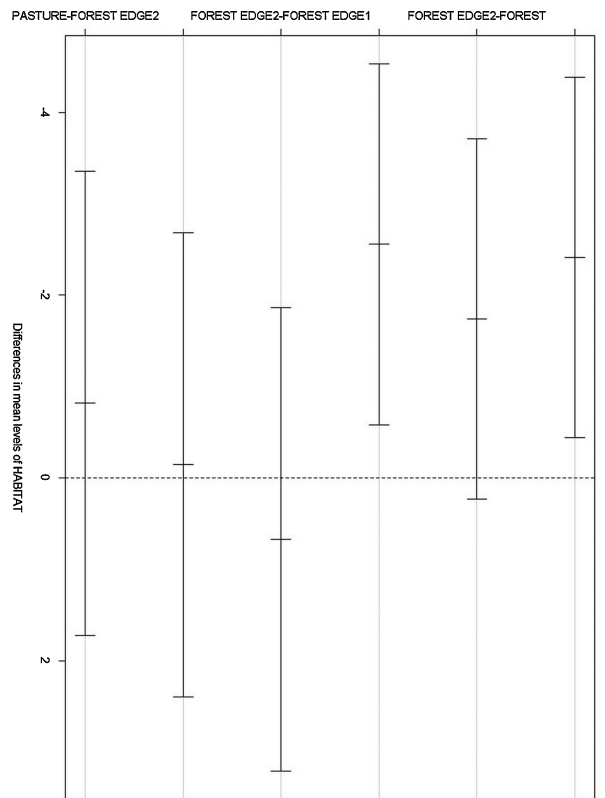
The one-way ANOVA test in which the independent variable is considered,



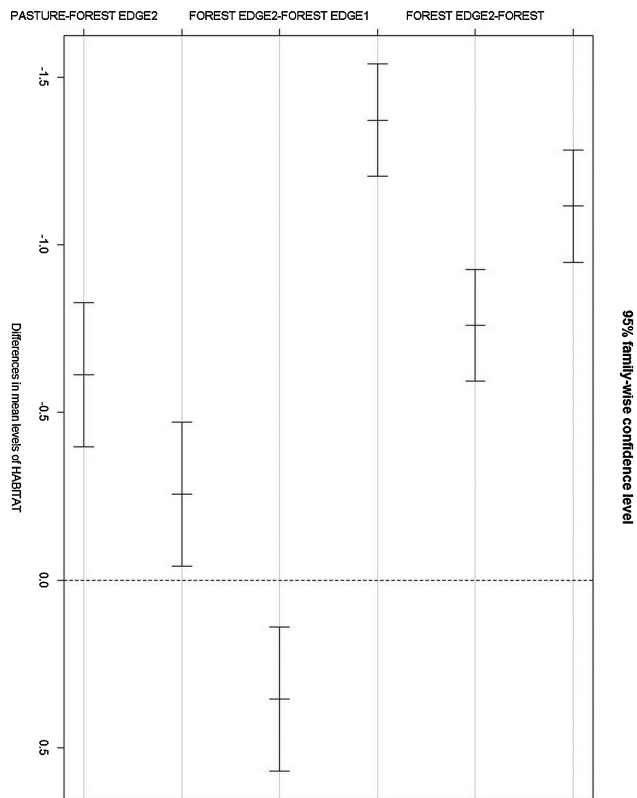
Soil temperature



Air temperature



Air humidity



Soil humidity

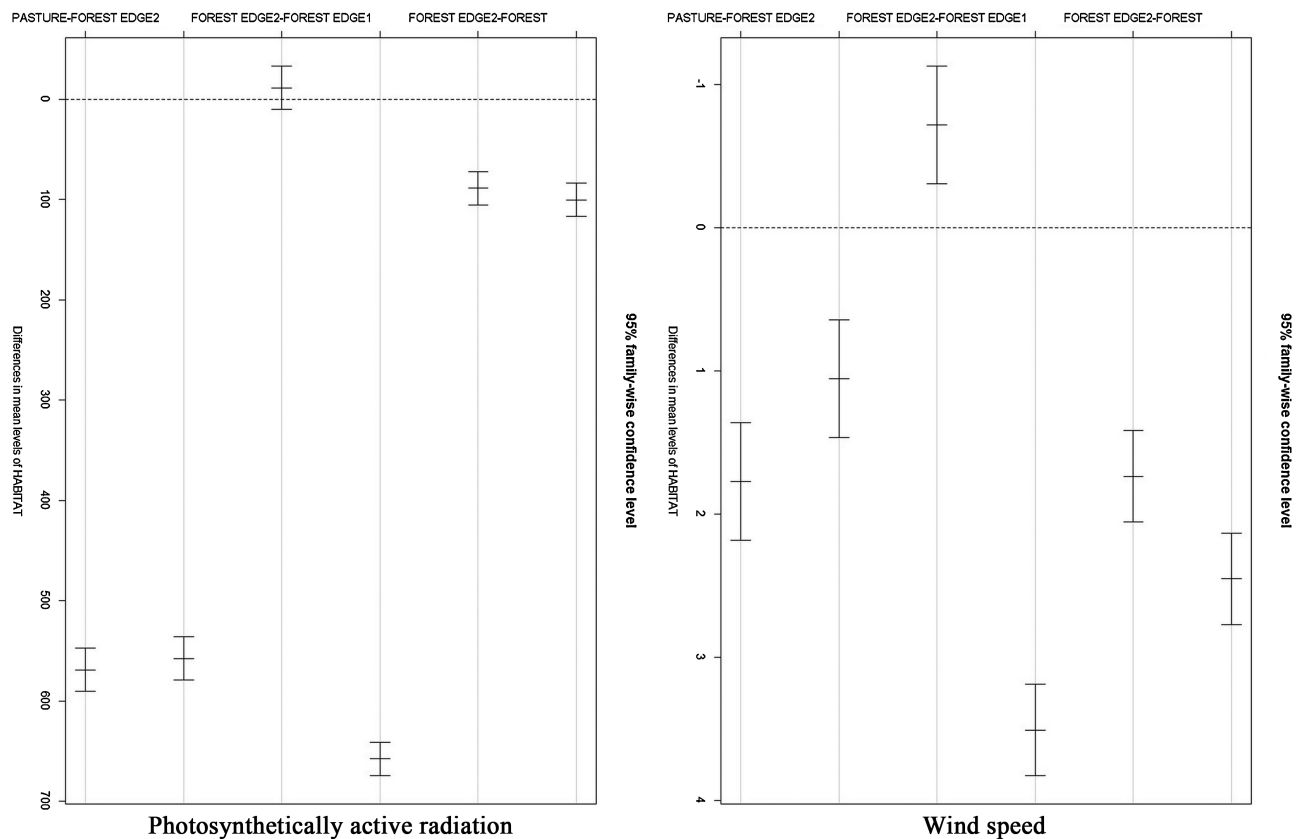


Figure 4. Tuckey HSD post hoc test result for habitat type.

distance from the edge, shows that almost all the values of the measured micro-environment variables (except soil moisture) have a high variation in the between-groups data set (the individual group mean differs from the overall mean of the data), and in the group of dependent variables PAR and wind speed, there is a high within-group variation, but also between-group variation. (Figure 5)

As for soil moisture, there is a small within-group and between-group variation suggesting that soil moisture is not influenced by distance from the edge.

Figure 5 suggests that mean air temperature values vary up to a distance of 70 m within the forest, and after this distance tend to equalize up to a distance of 120 m. Soil humidity tends not to be greatly influenced by distance from the edge, the means of the values within this variable do not differ along the transects. Soil temperature is higher in the first 15 m inside the forest, after which it has a gradually decreasing trend.

Since the p -value < 0.05 for wind intensity, air temperature, photosynthetically active radiation intensity, this suggests that at least one group average within these microclimate variables is different from the others, relative to the distance from the forest edge, thus it has a real impact on these microclimate variables.

Regarding the variables air humidity, soil temperature and soil moisture, they have $p > 0.05$, which indicates that the values of these variables are not changed in relation to the distance from the forest edge.

Therefore, the Fisher Least Significant Difference (LSD) test is applied (Figure 6)

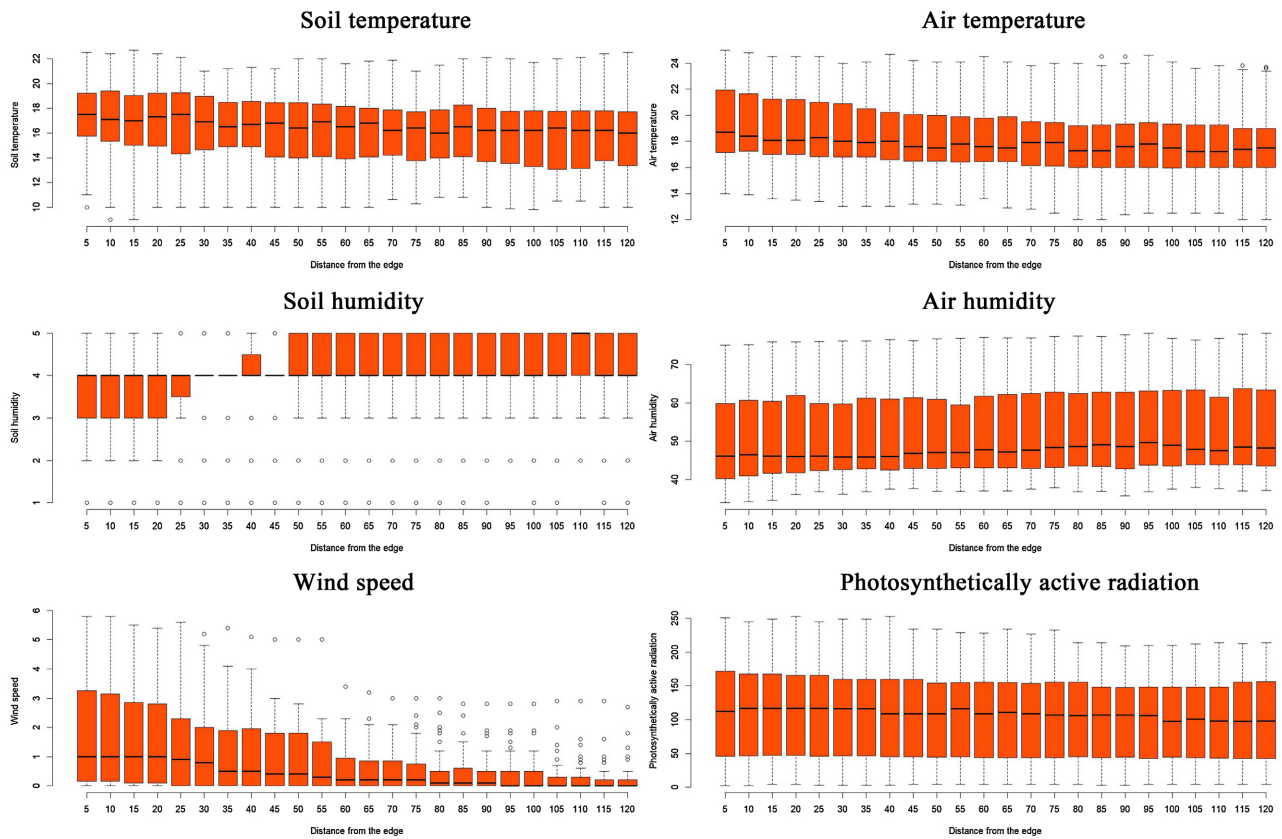


Figure 5. Mean values (± 1 SE) for microclimate variables according to distance to forest edge.

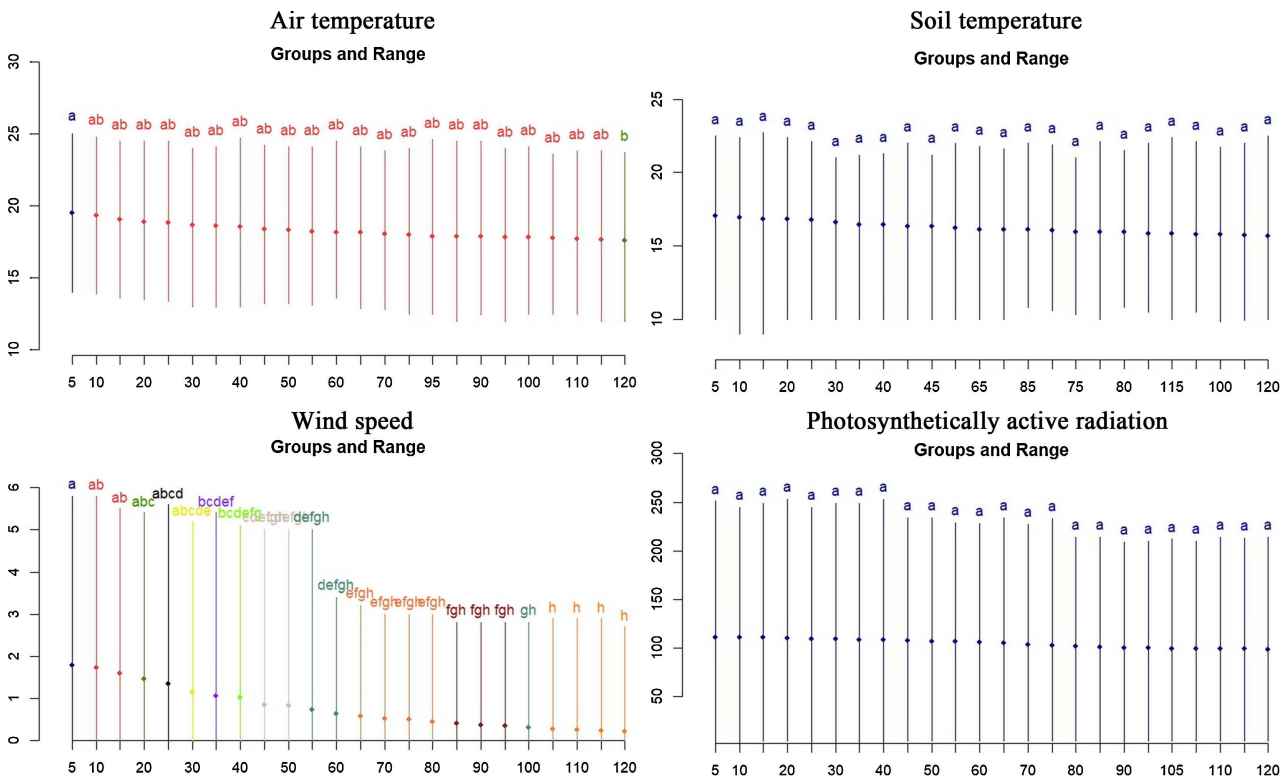


Figure 6. Fisher Least Significant Difference (LSD) test result.

only for the variables: soil and air temperature, photosynthetically active radiation intensity and wind intensity to identify the distance from the forest edge at which these variables change their values in the recorded data set.

The Fisher Least Significant Difference (LSD) test results for the variables analysed suggest that the soil temperature has consistently high values (18°C - 19°C) throughout the meadow area, then from the outer edge, the values decrease slightly (16°C) until 100 m inside the forest and from this distance, the values remain constant. Due to the different degrees of canopy closure, the presence of lower layers (shrubs, sub-shrubs) and the different degrees of litter cover, with increasing distance from the forest edge, the soil temperature becomes constant with very small differences (0.5°C - 1°C).

As for the air temperature, its values show a similar dynamic to the air temperature, thus similar values (23°C - 24°C) are recorded at all points in the meadow, and between the outer and inner edges the average values have a tendency to decrease sharply (by 5°C - 6°C) and after the distance of 10 m inside the forest, the air temperature remains relatively constant (~18°C) up to 120 m, the maximum distance up to which measurements were recorded in this study.

The minimum variation in photosynthetically active radiation intensity values over the entire distance within the forest is largely determined by the vertical structure of the stands, which is characterized as multistorey, with an undulating profile and an almost continuous degree of canopy closure, thus showing constancy of values in the meadow (700 - 750 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and inside the forest (110 - 120 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), and no difference between the outer and inner edge.

The wind speed is constant in the meadow (4 - 4.2 m/s) and decreases sharply as you approach the outer edge of the forest, down to 2.5 m/s. Between the outer and the inner edge, wind intensity values decrease by about 1 m/s per metre, and from 10 m inside the forest, it decreases steadily by ca. 0.1 m/s up to 100 m, and from this distance to 120 m, the intensity is reduced to 0.

4.3. Analyze Microclimate as a Complex Interaction of Variables Using Multivariate Techniques

To highlight the complex interaction of microclimate variables with habitat type and distance from the forest edge, multivariate MANOVA analysis was used, applying the `manova()` function from the R statistics package.

The Pillai Trace test was used for the calculations, which were then converted to an F statistic and thus tested the significance of the mean differences of the group of independent variables taken in this study.

The result of Pillai's Trace test for the independent variable distance to forest edge is statistically significant [Pillai's Trace = 0.40; $F(6, 2450) = 278.29$; $p < 0.001$], showing a significant association with the 6 dependent variables. (see **Table 2**).

Also, the result of the Pillai's Trace test for the independent variable habitat type is statistically significant [Pillai's Trace = 1.00; $F(18, 7350) = 204.7$; $p < 0.001$], indicating a strong association with the 6 dependent variables (see **Table 2**).

Table 2. Pillai's Trace test statistics and effect size measure (partial eta squared η^2).

Independent variable	Pillai	Pr (>F)	Eta ² (partial)	95% CI
Habitat type	1.00	<0.001	0.33	[0.32, 1.00]
Distance to forest edge	0.40	<0.001	0.18	[0.15, 1.00]

The effect size measure (Partial eta squared; η^2) is 0.18, suggesting that the effect size of distance from edge on the 6 dependent variables combined is large (see **Table 2**).

The effect size measure (Partial eta squared; η^2) is 0.33, suggesting that the effect size of habitat type on the 6 dependent variables combined is large (see **Table 2**). This size indicates that the group mean vectors of the entire group differ.

In conclusion, the results of the Pillai's Trace test and the Measure of Effect Size (Eta) suggest that there are statistically significant differences ($p < 0.001$) between the 6 dependent variables, relative to each of two independent variables, but it has not yet been identified which groups are significantly different, therefore a post-hoc test is required.

Thus, in order to identify linear combinations of the original variables (the 6 microclimate variables) that provide the best possible separation between groups (habitat types/distance from edge) in the dataset, linear discriminant analysis (LDA) was performed, which is a dimensionality reduction technique that finds a linear combination of characteristics that best separates two or more groups.

In LDA, the independent variables are the predictors and the dependent variables are the groups, thus allowing the use of several microclimatic variables in combination to explain groupings of habitat types and edge distances.

A scatter plot was generated for the six dependent variables (microclimate variables), showing the variability within each microclimate variable (within group) as well as the variability between all six microclimate variables (between groups).

We use the `lda()` function in the MASS package in the R program to view the scatter plots of the data and identify whether they are separable (see **Figure 7**).

Pairwise correlations of all microclimate variables for which the correlation with at least one other variable is of magnitude at least 0.5. The top-right panels show the numerical values of the correlations (rounded to two decimal places) and the top-left panels show the scatter plots.

All variables are scaled to have a mean of zero and a variance of 1. Next, the coefficients of the linear discriminants were calculated, which display the linear combination of the predictor variables, and this is used to form the decision rule of the LDA model for both independent variables (see **Table 3**).

The `plot()` function was used to generate plots of the linear discriminants obtained by calculating LD1 and LD2 for each of the independent variables.

The LDA scatterplot discriminates several habitat types based on the values of the 6 dependent variables and colour-codes them to match the independent variables.

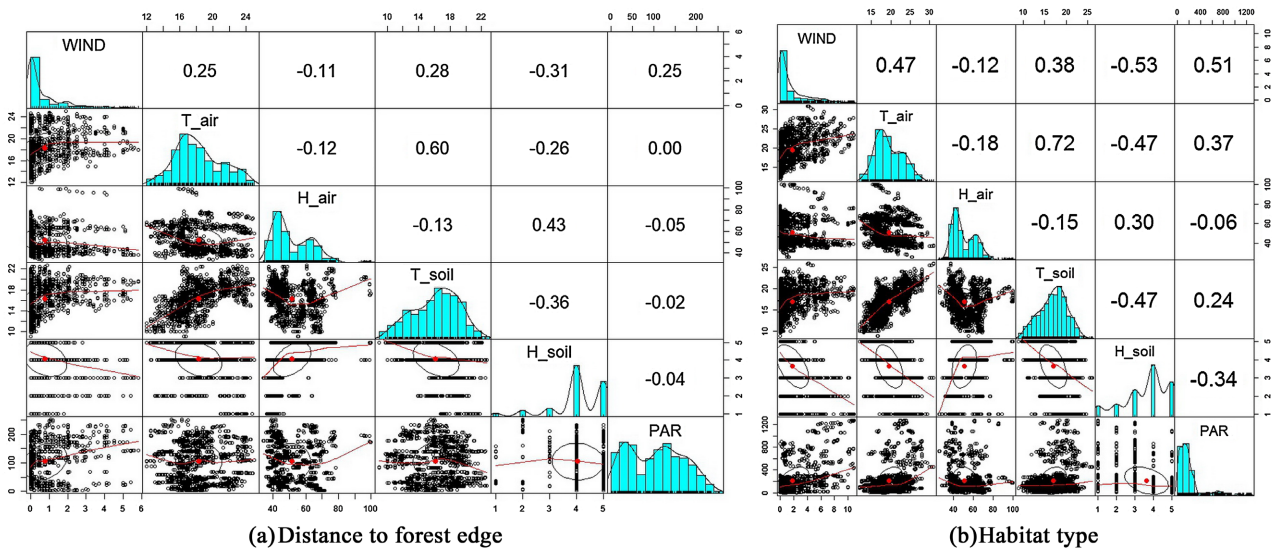


Figure 7. Scatter plot, histogram and correlation values for microclimate variables. (a) distance to forest edge; (b) habitat type.

Table 3. Linear discriminant coefficients for both independent variables.

Independent variables	Habitat type		Distance to forest edge	
	LD1	LD2	LD1	LD2
Dependent variables	LD1	LD2	LD1	LD2
Soil temperature (T _{soil})	0.01	0.14	-0.06	0.19
Air temperature (T _{air})	0.08	-0.20	0.29	1.15
Soil humidity (H _{soil})	-0.12	0.40	-0.09	0.07
Air humidity (H _{air})	0.003	-0.007	-0.06	-0.02
Photosynthetically active radiation (PAR)	0.009	0.003	-0.83	0.40
Wind speed (WIND)	-0.06	-0.29	0.001	-0.004

Thus, in Figure 8, it can be seen that the values of the dependent variables are significantly different in grassland compared to outer edge, inner edge and forest.

Also, by the percentage separation performed by each discriminant function, the “Trace Proportion” is obtained. For the studied habitat types, the percentage separation achieved by each linear discriminant coefficient (LD1 = 0.9590, LD2 = 0.04) is 95.9% and 4.0%.

The density plots and corresponding load vectors (i.e. weight vectors for the different microclimate variables) for the two linear discriminators resulting from the application of LDA for combinations of habitat types are shown in Figure 8.

The first linear discriminator LD1, shown in Figure 8, highlights the separation of grassland habitat by high values of the PAR variable in contrast to the other habitat types, and LD2 discriminates forest interior habitat by the wind intensity and air temperature variables.

Next, the LDA scatterplot discriminates based on the distance from the edge of the 6 dependent variables and color-codes them to match the independent

variable.

For the distance-to-edge gradient, the percentage of separation achieved by each linear discriminant function (LD1 = 0.851; LD2 = 0.0485) is 85.1% and 4.85% (see **Figure 9**).

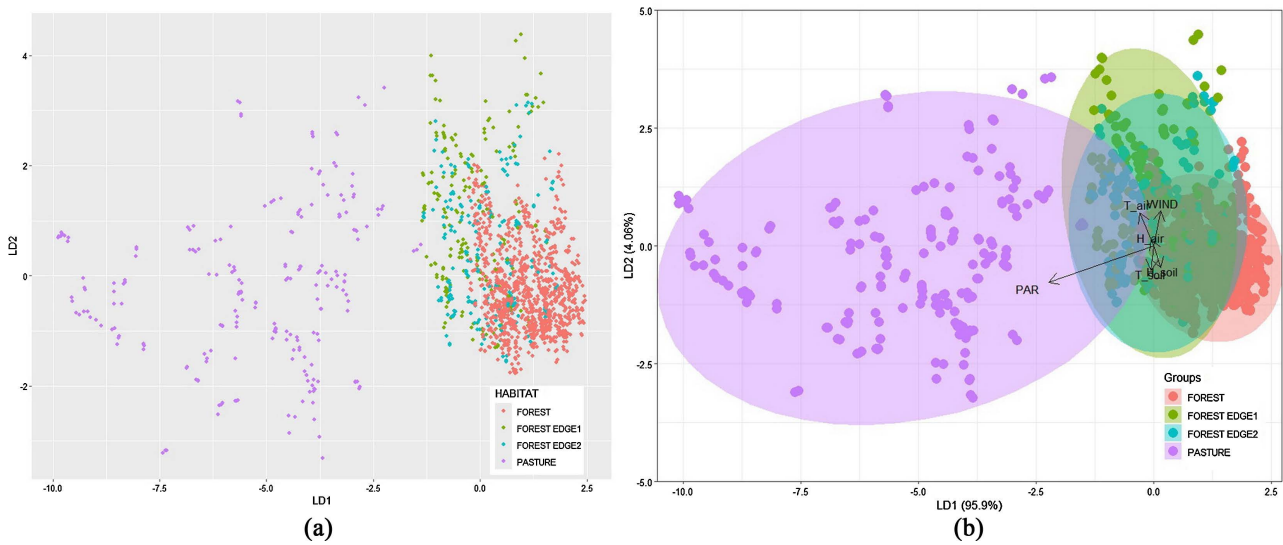


Figure 8. Data set and LDA scatter plot for habitat type.

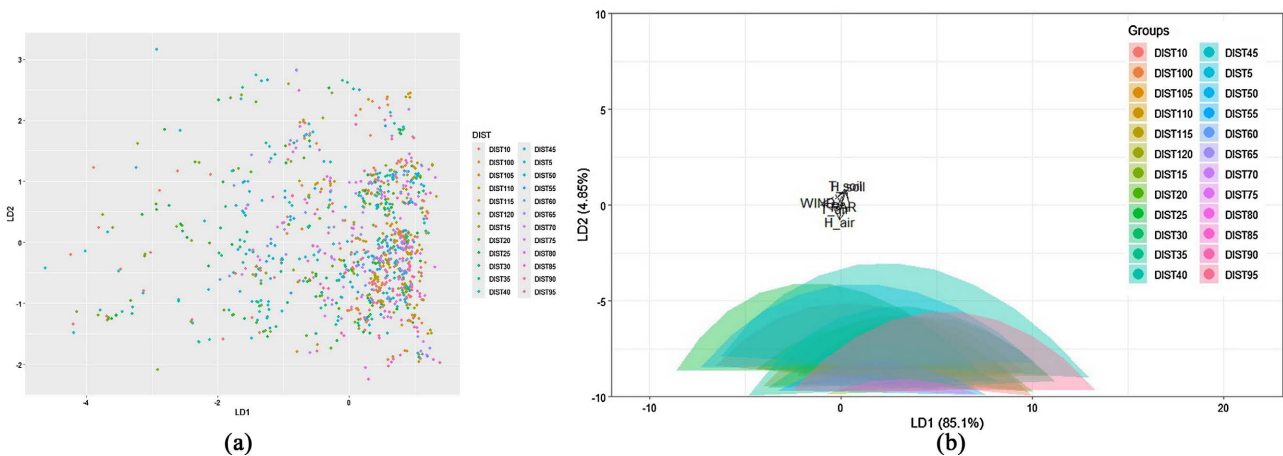


Figure 9. Data set and LDA scatter plot for distance to forest.

The LDA scatterplot separates by colour several distances from the edge based on six dependent variables. Thus, in **Figure 9**, the coefficients of the standardized canonical discriminant function indicate that the discriminant variables of distance to edge are wind intensity, temperature and air humidity.

The choice of principal components (PCs) was made by creating a covariance matrix between all pairwise combinations of microclimate variables, which measures the correlation between these variables. To determine the number of principal components to be considered, the amount of variation (eigenvalues) held by each principal component (PC) was measured.

To simplify the descriptions for further analysis, principal component analysis

(PCA) was implemented to reduce the dimensionality of the data. The variables with the highest contribution are highlighted in the bar graph (see **Figure 10**). The broken line shown in the graph corresponds to the expected mean percentage of variance explained, for each habitat type.

Figure 10 shows all five main components and the weights of each study variable for these components. In the forest interior habitat, soil temperature (T_soil), air temperature (T_air) and soil moisture (H_soil) were highlighted for PC1. For PC2, the greatest contribution was made by wind intensity (WIND) and photosynthetically active radiation intensity (PAR), and for PC3, air humidity (H_air). For the meadow, the variables that stood out in PC1 were air temperature (T_air), soil temperature (T_soil) and soil humidity (H_soil), in PC2 were photosynthetically active radiation intensity (PAR) and wind intensity (WIND), and in PC3 only air humidity (H_air).

In the outer forest edge habitat in PC1 air temperature (T_air), soil temperature (T_soil) and soil moisture (H_soil) variables are evident, in PC2 wind intensity (WIND), photosynthetically active radiation intensity (PAR) and air humidity (H_air) variables are evident and in PC3 air humidity (H_air), wind intensity (WIND) and soil moisture (H_soil).

By tracking the colour gradient, the grouping of variables, the positioning of vectors relative to the origin of the diagram, and their distance from the origin, the PCA analysis identifies the relationships between all variables evaluated in this study (see **Figure 10**).

The PCA loadings of the forest interior habitat are plotted in **Figure 10**, and the two main components, PC1 and PC2, account for 36.36% and 19.16% of the total variance.

The PCA plot shows, along the PC1 and PC2 axes, a strong association between soil and air temperature ($r = 0.76$), air and soil humidity ($r = 0.71$) for which high positive significant correlations were obtained ($p < 0.05$).

The PCA loads of the grassland habitat are plotted in **Figure 9 b**. and the two main components, PC1 and PC2, account for 39% and 23% of the total variance. A strong association between soil and air temperature ($r = 0.87$) is observed in the PCA plot along the PC1 and PC2 axes. High positive significant correlations ($p < 0.05$) were obtained for these variables. For the outer edge habitat, the two main components, PC1 and PC2, account for 41.4% and 19.8% of the total variance. The PCA plot shows, along the PC1 and PC2 axes, a strong association between soil and air temperature ($r = 0.85$), for which high positive significant correlations were obtained ($p < 0.05$).

Also, if we refer to the inner edge habitat the two main components, PC1 and PC2 account for 39.1% and 19.9% of the total variance. The PCA plot shows, along the PC1 and PC2 axes, a strong association between soil and air temperature ($r = 0.85$) and between air and soil humidity ($r = 0.49$), respectively, for which high positive significant correlations were obtained ($p < 0.05$).

Regarding the forest inner edge habitat, in PC1 the variables with a clear contribution are soil temperature (T_soil), air temperature (T_air) and air humidity

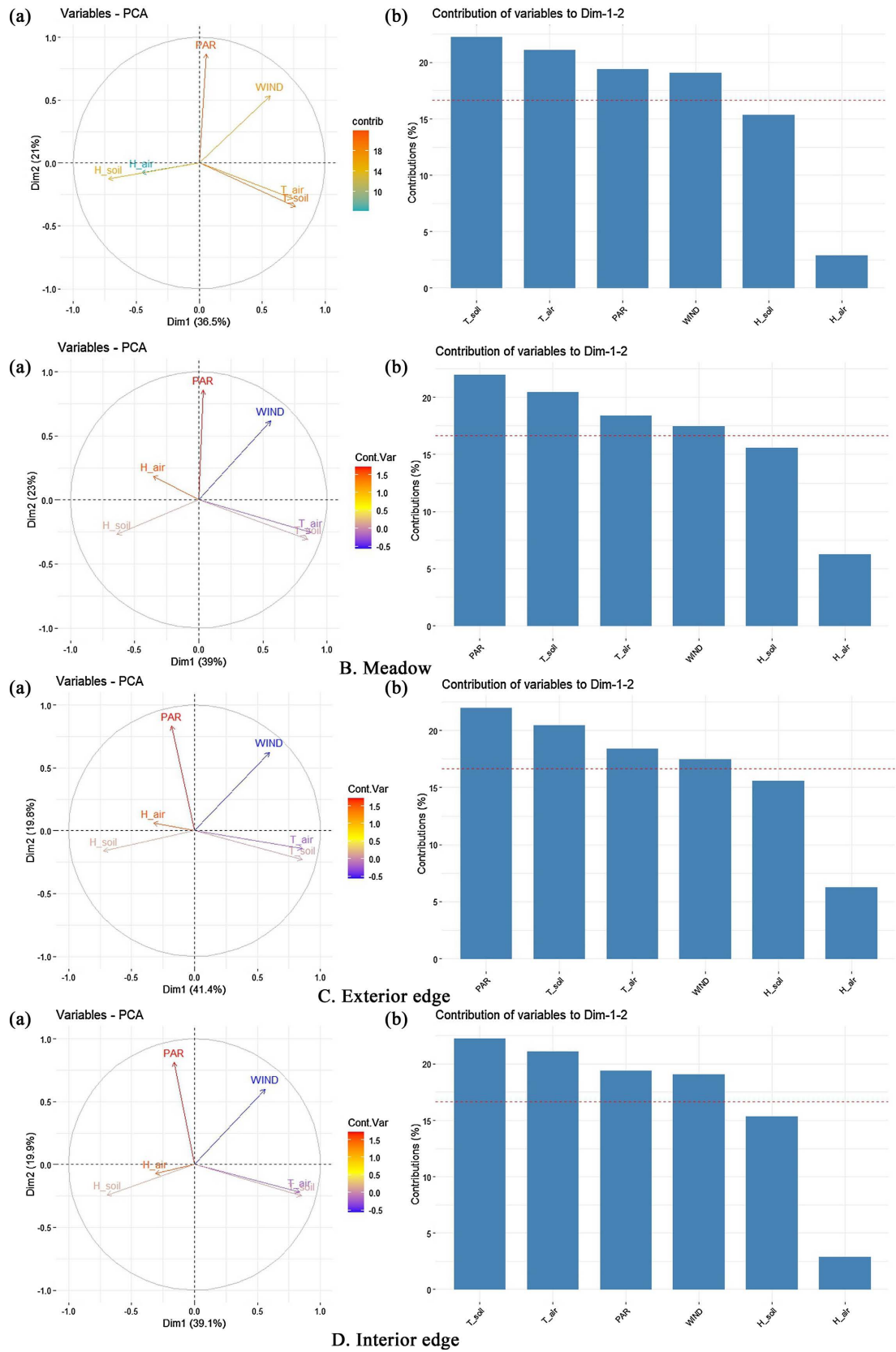


Figure 10. (a) Largest variance contribution to correlation circle PC1 and PC2 and (b) bar chart of PC contribution in 6 variables for the four habitat types.

(H_{air}), and in PC2 the variables are wind intensity (WIND) and photosynthetically active radiation intensity (PAR). In the third component PC3, air humidity (H_{air}) is the variable with the highest contribution.

In choosing the principal components, the Kaiser criterion was used, which selects components with eigenvalues > 1 or components that explain 50% of the total variance of the data set.

The first two components satisfy both criteria simultaneously, as shown in **Figure 10**, which makes it easier to visualize the point where the explained variance tends to stabilize, i.e. the first two PCs in the forest interior habitat explain 57.55% of the variance, therefore they effectively summarize the total sample variance and can be used to study the dataset.

In the meadow, the first two principal components capturing most of the information in the data explain 61.97% of the variance, and in the outer edge habitat, the first two components explain 61.16% of the variability of the entire dataset recorded in this habitat.

For the interior forest edge habitat, the first two principal components explain 59% of the possible variance of the dataset.

As for the covariance matrix between all pairwise combinations of microclimate variables, it measures the correlation between variables, i.e. how each variable varies in relation to the others.

Figure 11 shows that within the forest there are positive correlations between air temperature and soil temperature (0.60), wind intensity and air temperature (0.28), air humidity and soil moisture (0.43) and negative correlations between wind intensity and soil moisture (-0.31) and air temperature and soil moisture (-0.26).

In the meadow habitat, there are positive correlations between wind intensity and air temperature (0.30), air temperature and soil temperature (0.82), wind intensity and soil temperature (0.24), wind intensity and photosynthetically active radiation intensity (0.35), and soil moisture is strongly negatively correlated with air temperature (-0.37), wind speed (-0.36) and soil temperature (-0.35).

At the outer edge of the forest, positive correlations are found between wind intensity with air temperature (0.33) and soil temperature (0.29) and air temperature with soil temperature (0.80), while soil moisture is negatively correlated with wind intensity (-0.50), air temperature (-0.41) and soil temperature (-0.43).

For the inner edge, wind intensity is positively correlated with air temperature (0.26) and soil temperature (0.28) and air temperature with soil temperature (0.78) and soil moisture is negatively correlated with wind intensity (-0.43), air temperature (-0.34) and soil temperature (-0.40).

5. Discussion

This section presents the main topics involved in the study of the microclimate of each habitat type studied. From the results obtained, through computer simulation and multivariate analysis, it was possible to determine the existence of

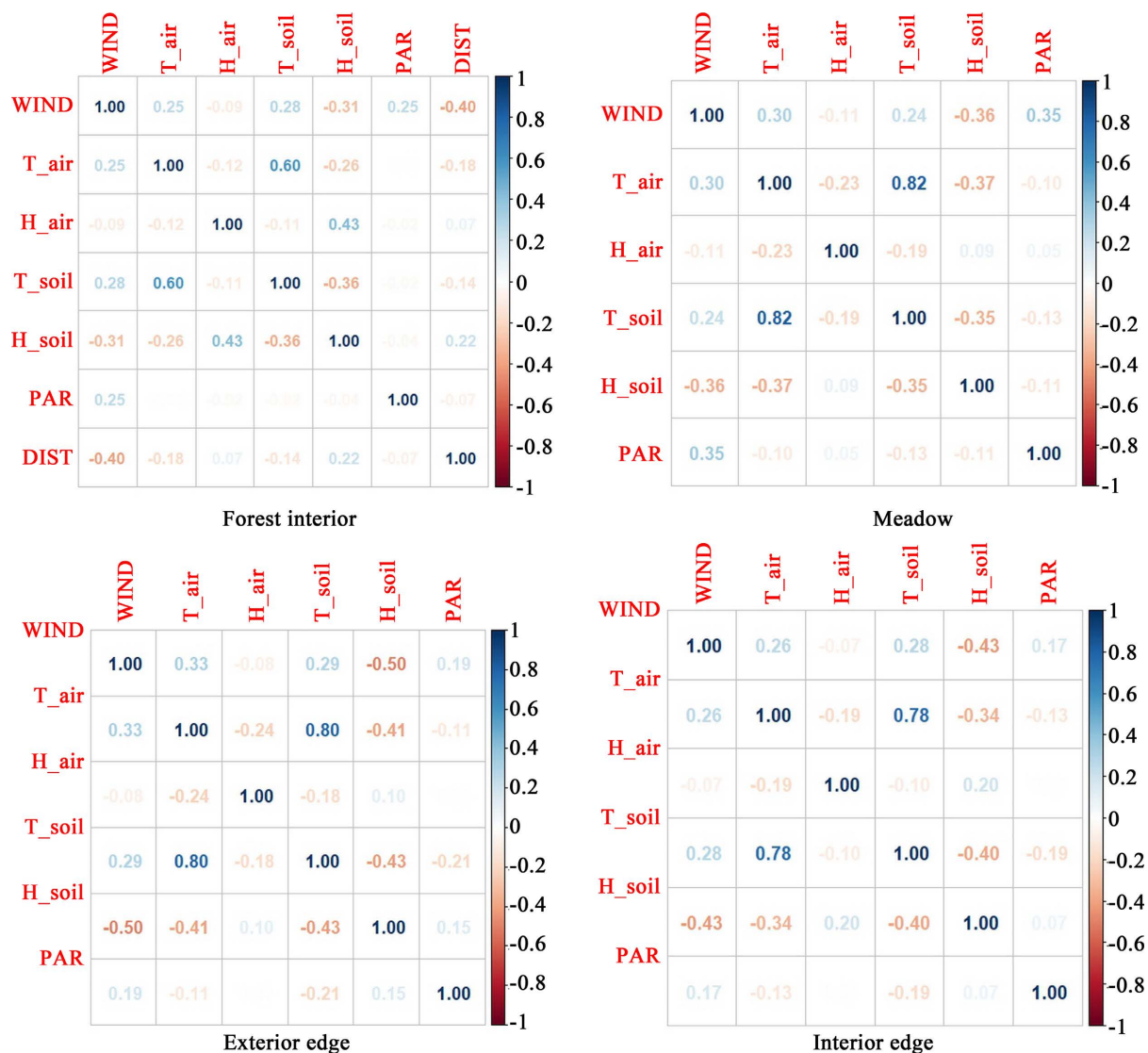


Figure 11. Covariance matrix between microclimate variables in different habitats ((a) woodland; (b) grassland; (c) outside margin; (d) inside margin).

heterogeneous groups according to the four habitat types (forest interior = P; land adjacent to the forest = PA; forest inner edge = LI and forest outer edge = LE) and in relation to distance from the forest edge.

This study allowed us to analyze which of the microenvironment variables, air temperature (T_{air}), air humidity (H_{air}), soil temperature (T_{soil}), soil humidity (H_{soil}), photosynthetically active radiation (PAR) and wind speed (WIND) showed a clear change in values in relation to the four habitat types analyzed and in relation to the distance from the edge to the interior of the forest in the Slătioara Secular Forest Reserve.

5.1. Effect of Habitat Type (Meadow, Inner Edge, Outer Edge, Forest Interior) on Microclimatic Variables

The results obtained from the univariate ANOVA analysis suggest that in the

microclimate of the habitats under study, the values of the microclimatic variables are highly spatially fluctuating, thus differences between the meadow versus forest habitat and between the outer edge of the forest versus the inner edge of the forest are very evident, each of which presents a particular microclimate configuration.

The air temperature in the meadow is much higher (max. 31°C) than inside the forest (max. 25°C), which is quite characteristic for this habitat type as the forest behaves as a significant buffer, i.e. it attenuates microclimatic temperature variations (De Frenne et al., 2021), thus inside the forest there are fewer temperature extremes and lower temperature variability especially in summer (De Frenne et al., 2019; Zellweger et al., 2019a).

Thus the specific composition of the trees, which is mainly coniferous (spruce and fir), and the degree of canopy closure ($K > 0.7$ consistency) of the mature natural forest are structural elements that screen the penetration of sunlight into the forest habitat and absorb about 35-70%, reflect between 20-25% and allow only 5% - 40% of the light radiation to reach the ground (Negulescu & Stănescu 1964), thus, inside the forest the intensity of active photosynthetic radiation has an average of $104.62 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ compared to the adjacent meadow, where it has an average of $762.33 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Another finding of this study is that air temperature values are lower at the inner edge of the forest than at the outer edge, due to the higher solar radiation input at the outer edge, but also to the natural heterogeneity of the vegetation structure which is characteristic of a closed edge, with a richer stratification of vegetation layers through the presence of undergrowth, shrubs, saplings and trees, and similar results have been obtained by (Dierschke, 1974; Stoutjesdijk & Barkman, 1992; Matlack, 1993).

As for the soil temperature, the results show a variation from the meadow (max. 26°C) to the forest interior (max. 22.7°C) and between the outer and the inner edge where the temperature difference is very small 0.1°C, similar results were also obtained by Chen et al. (1995).

Higher levels of moisture are maintained inside forests, which influences soil temperature by reducing evaporation, so wet soils generally have more stable temperatures than dry soils because water has a higher heat capacity than air or dry soil particles, which means it can absorb more heat without a significant increase in temperature.

Another important factor in regulating soil temperature in the forest is the dense vegetation and tree canopy that reduce wind speed in the forest, which limits the cooling effects of the air and helps to keep the soil temperature stable.

All of these factors contribute to more stable soil temperatures within the forest and generally cooler soil temperatures compared to open areas, which helps support the diverse plant communities in the forest ecosystem.

These variations are explained by a plausible argument, i.e. the pattern of soil temperature distribution reflects to a large extent the degree and period of its exposure to solar radiation, since it is this that causes the soil to warm up. In

open, grassland, the soil surface receives most of the sun's energy, warming the air above it, whereas in the forest, the tree canopy intercepts most of the sun's radiation, so the soil heats very little of the energy received from direct light.

Another important aspect in determining soil temperature is vegetation, so soils covered with grassy vegetation have a higher capacity for heating and heat retention compared to those covered with woody vegetation, because the former has a lower capacity for reflecting the heat emitted by solar radiation and absorb a greater air humidity, inside the forest (mean 51.90%) is higher than the other habitats, meadow (mean 29.34%), inner edge (mean 40.16%) and outer edge (35.18%), these differences can be attributed to decreased direct solar radiation and changes in wind conditions (Matlack, 1993; Davies-Colley & Quinn, 1998; Schmidt et al., 2019a), but also intense plant evapotranspiration and lower temperatures above the forest, which cause an increase in the amount of water vapour in the air inside the forest. amount of solar energy, which causes the soil to heat up.

The results of the soil moisture study reveal that the soil inside the forest is wetter than the other habitats because the soil surface inside the forest is covered with a layer of litter that allows water retention from precipitation, which slowly infiltrates into the lower soil layers keeping the soil moist for a longer time.

High soil moisture in the forest is also driven by plant evapotranspiration and dew deposition as a result of the thermal amplitude of the air between night and day. Indeed, air and soil temperature and moisture are strongly correlated and can be associated with the light gradient, which changes gradually from the meadow to the forest edge and becomes steep from the outer edge to the forest interior (Matlack, 1993; Chen et al., 1995; Davies-Colley et al., 2000; Kovács et al., 2017; Li et al., 2018).

The wind intensity is consistently lower in the forest interior (average 0.78 m/s) than in the meadow (4.26 m/s), because the trees act as a "shield" against the air masses, modifying the direction (vertical) and the values of the speed of movement, this difference is also observed between the outer edge which has an average of 2.51 m/s and the inner edge (1.76 m/s). The forest habitats studied have a majority composition of coniferous species (spruce, fir), as well as a high density of trees (consistency of 0.7), which causes mitigation of wind intensity inside the forest.

5.2. Effect of Distance from Edge on Microclimatic Variables

Through the results of this study, it was found that microclimate interacted with edge distance, with some parameters being negatively and others positively affected.

Thus, the air temperature in the first 5 m from the edge is higher and is due to the penetration of warm air from the outer matrix of the forest, and from 10 m to 110 m, the temperature shows small fluctuations of max. 1°C - 2°C, and from this distance, the temperature stabilizes up to the distance of 120 m (the maxi-

mum distance taken in the study).

The air temperature exhibits a 3.3°C amplitude along the distance gradient from the forest edge (from 0 m to 120 m), which is largely driven by reduced air circulation from the edge inwards, as wind can continue to influence this variable beyond the point where light intensity has reached a constant low level in the forest.

Fluctuations in air temperature within the forest are driven by wind directed outward from the forest, specifically by air movement caused by air penetrating through the canopy into the light mesh area created by natural tree fall (Lee, 1978; Raynor, 1971).

The data recorded at the measuring points indicate that wind penetration and air temperature inside the forest was achieved over a short distance from the edge approx. 10 m, although in some studies by Li et al. (2007) and Raynor (1971) the penetration distance is at least 60 m from the edge.

A plausible explanation for this result is the peculiarity of the edge zones in the study area, which are characterized as closed or embedded edges characterized by the horizontal intertwining of trees, saplings and shrubs in the edge and by the richer vertical structure through the presence of layers of sub-shrubs, shrubs, saplings and trees.

These edge structural features generate a particular effect on microclimate variables, which respond differently to the structural connectivity of small-scale landscape elements, leading to the formation of the “Slătioara edge effect”.

The results of the univariate analysis also suggest that soil temperature was less sensitive at distance from the edge (significant differences up to only 15 m) and stabilized at 65 m distance, because the soil is protected against temperature fluctuations by not transferring warm air from adjacent forest land into the soil (Chen et al., 1995; Davies-Colley et al., 2000; Li et al., 2018).

It is possible that this climatic parameter is affected at a greater distance from the edge than in this study (i.e., over 120 m), especially since this study examined south-facing forest edges in the northern hemisphere, which are known to have a deeper edge effect than north-facing edges (Matlack, 1993; Chen et al., 1995; Heithecker & Halpern, 2007; Orczewska & Glista, 2005).

The results of this study emphasize the importance of the degree of canopy closure and tree species composition, which are known to be markedly influential factors for air and soil temperature within the forest, reducing maximum and minimum values (Matlack, 1993; Aussenac, 2000; De Frenne et al., 2013; Frey et al., 2016; Zellweger et al., 2019b).

As for, photosynthetically active radiation intensity, this parameter was not influenced by the gradient of distance from the edge, because the study was conducted in a mature, multi-canopy forest with high diversity in size and species (predominantly coniferous) and with a stable dynamic equilibrium, consequently, the degree of canopy closure being uniform blocked the penetration of direct radiation into the forest interior.

The wind intensity is constant up to a distance of 20 m inside the forest, mainly due to the strength of the meadow wind, which has penetrated up to this distance. After 30 m, the wind intensity has a steady steep decrease, reaching 0 m/s after the distance of 75 m from the edge. Thus, the results of this study are in agreement with other results of studies by (Matlack, 1993; Chen et al., 1999; Gehlhausen et al., 2000), in which the microclimate of the outer forest edges is characterized by increased wind speeds and high solar radiation intensity, resulting in drier soil compared to the forest interiors.

5.3. Multivariate Analyses Synthesize the Interactions between Microclimate Variables and Their Effects in Different Microclimate Types

Linear discriminant analysis (LDA) is used in combination with a subset selection package in R (<https://www.r-project.org/>) to identify a subset of microclimate variables that best discriminates between the four habitat types as well as between distances from the forest edge.

The results of the PCA analysis suggest that all the values of the microclimate variables considered in the study exhibit spatial variability within the four habitat types, but wind intensity and photosynthetically active radiation intensity were the variables that most strongly influence and to some extent define the microclimate of the habitats. These data give us a much more complete picture of the microclimate pattern in the different habitat types and allow us to identify which microclimate variables are most influential and their mutual influence.

From the analysis performed, in the forest interior habitat the values of the variables wind intensity and photosynthetically active radiation intensity do not influence the microclimate (low \cos^2), but have a negative correlation with soil moisture and air temperature, which favours the creation of a colder and wetter climate and thus the air mass circulation is reduced in this habitat. At the same time, air temperature with soil temperature and air humidity with soil moisture are positively correlated (vectors are clustered), giving a uniform and directly proportional variation in their values.

In the meadow habitat, the values of the variables: photosynthetically active radiation intensity, air temperature and soil temperature have a major contribution in explaining the whole dataset, they are the variables that define this habitat type.

PCA results indicated that edge microclimates differ considerably from interior microclimates and therefore these spatial fluctuations especially in soil temperature affect ecosystem functioning and certain edge zone processes such as litter decomposition or carbon removal (Riutta et al., 2012; Fekete et al., 2016; Schmidt et al., 2019b; Meeussen et al., 2021).

The microclimate is influenced by a number of local factors that determine climatic variations over small distances. These factors can have a significant impact on environmental conditions and hence on plant, animal and human life in a given area. The results of this study suggest that forest interior habitats have

cooler and wetter conditions by providing shade and reducing wind speed.

The dense vegetation in the forest through the richness of the vegetation layers retains heat and moisture, moderating temperature fluctuations and maintaining higher levels of soil and air humidity.

The amount and intensity of sunlight reaching an area can significantly affect temperatures, so the interior of the forest and the inner edge of the forest are cooler, while exposed areas, the grassland adjacent to the forest, will be warmer.

The results of the study are in agreement with other studies, which have found that lower air temperatures and high humidity are found towards the forest interior, which may be attributed to decreased direct solar radiation and changes in wind conditions (Matlack, 1993; Davies-Colley et al., 2000; Heithecker & Halpern, 2007; Schmidt et al., 2019a).

6. Conclusion

Microclimate variables refer to the local atmospheric conditions that can vary significantly over short distances and these variables influence the local climate and the conditions experienced by plants, animals, and humans.

Understanding the importance of biodiversity and the variables that influence microclimates is essential for effective environmental management and conservation. Biodiversity ensures ecosystem stability, resilience, and the provision of essential services, while microclimate variables determine the local conditions that affect the health and productivity of ecosystems. Protecting biodiversity and managing microclimate factors are critical for sustaining healthy ecosystems and human well-being.

Using the information from this study, it can be seen how microclimate affects abiotic factors differently in this forest reserve.

The microclimate within a forest interior is influenced by various factors that create a distinct environment compared to the surrounding areas such as forest edges or open fields (pasture).

However, more studies are needed that sample microclimate and vegetation beyond 120 m and that examine species interactions as a determinant of changes in community composition at the edge and within the forest.

We believe that this study is important because understanding the extent, drivers and implications of forest microclimate on biodiversity is necessary to better manage forest ecosystems, support their sustainable use and ensure viable ecosystem services for future generations, and even the microclimate of these forest habitats can be considered an ecosystem service in itself.

For future studies, it is suggested to carry out a phytosociological study in the light gaps in the tree canopy, study the physical and chemical characteristics of the soil and retrospective analysis of satellite images of the area, for a deeper understanding of the characteristics of the forest and the history of its marginal areas, i.e., to favour the conservation of the marginal areas of this forest reserve.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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