Hungarian University of Agriculture and Life Sciences

Functional organization of sandy forest-steppe transition zones based on the microclimate patterns and topography

Thesis of PhD dissertation

DOI: 10.54598/001920

Süle Gabriella Erzsébet

Gödöllő

2022

The doctoral school

Name: Doctoral School of Biological Sciences

Discipline: Biological sciences

Head of school: Prof. Dr. Zoltán Nagy
Head of department, DSc
Hungarian University of Agriculture and Life Sciences,
Institute of Agronomy,
Department of Plant Physiology and Plant Ecology

Supervisor 1: Dr. László Körmöczi
Associate professor, PhD, Habil.
University of Szeged,
Faculty of Science and Informatics,
Department of Ecology

Supervisor 2: Dr. János Balogh
Associate professor, PhD, Habil.
Hungarian University of Agriculture and Life Sciences,
Institute of Agronomy,
Department of Plant Physiology and Plant Ecology

....
Approval of the head of school Approval of the supervisor

BACKGROUND AND OBJECTIVES

One of the most significant problems of our time is global climate change. Global climate change involves a variety of changes on both large and fine scales, including increasing frequency of extreme weather events, in addition to the rise in global average temperature.

There are signs in Hungary that can be linked to global climate change. Summer periods are getting warmer, while winter cooling is decreasing year by year. This aridification suggests that there will be significant changes in the structure and function of habitats in the Carpathian Basin region, with major impacts on the natural flora and fauna.

Since the Hungarian Great Plain is considered climatically sensitive, its plant communities can undergo rapid and spectacular community-level changes even at a small rate of climate change. These changes could be most easily observed in vegetation-mosaic transition zones, because these areas can be sensitive to the changes of environmental parameters. Global changes affect the macroclimate, which together with other parameters (soil conditions, topography, etc.), influence the microclimate that plays an important role in shaping the fine structure of habitats. Hence, global climate change has a major role in shaping the structure of habitats, therefore the investigation of ecosystems through instrumental measurements (particularly microclimate measurements) is of great importance. Habitats with different characteristics may respond differently to these changes depending on their sensitivity. Transition zones can be sensitive habitats, for example forest-steppes, whose importance has long been recognised.

Therefore, microclimate patterns in vegetation transition zones can be used to model the impact of global climate change. By studying microclimate dynamics, we can understand processes at population, community and ecosystem levels. In addition, the sandy forest-steppe vegetation in Hungary in which the fragmented structure is of natural origin may completely disappear in the near future due to the aridification observed in the Carpathian Basin. Hence, improving our knowledge about this ecosystem is important to understand the dynamics of abiotic and biotic factors in temperate transition zones.

Objectives

Due to the issues mentioned above, the research focused on the investigation of sandy steppe-steppe vegetation aiming to answer the following questions:

1. How does the microclimate modifying effect of a tree group change from the edge to the grassland by the cardinal directions? In this context, how does the spatial pattern of microclimate change by the phenological stages? Can we find different patches in terms of species composition and ecological requirements in the seemingly homogeneous grassland, which are related to the microclimate modifying effect of the tree group?
2. Can the duration curve analysis method be applied in plant ecology research?
3. What are the main influencing factors of soil respiration in an ecosystem with a very heterogeneous spatial vegetation structure? Is there a significant difference between the open area and the below-canopy area based on soil respiration, organic matter content and their influencing factors? Is there a difference in the functional responses by phenological stages?
4. Are there any terrain attributes that have an influencing power on forest-steppe habitats?
5. Is there covariance between the terrain attributes and the shading effect of the grove? Is the influence of topography stronger than the microclimate modifying effect of the grove?

MATERIALS AND METHODS

Study sites and measuring campaigns

The study sites were located in the Fülöpháza sand dunes area of the Kiskunság National Park, in the Danube-Tisza Interfluve. The 10-year (2010–2020) temperature and precipitation averages of this area were 11.5 °C and 622.17 mm, respectively (National Meteorological Service, Fülöpháza Meteorological Station). Two groves of poplar (*Populus alba* L.) and their surrounding grasslands were surveyed in the period of 2018-2020 (Table 1): first grove (46°53’28.18” N., 19°24’46.91” E., 107 m a.s.l) and second grove (46°53’06.11” N., 19°24’29.17” E., 106 m a.s.l).

Table 1: Measuring campaigns

Measurement	**Year**	**2018**	**2019**	**2020**
	Campaigns	Spring (2018. 05. 24-25.), Summer (2018. 07. 12-14.), Autumn (2018. 10. 08-10.)	Summer (2019. 06. 27-29.), Autumn (2019. 09. 30.-10-02.)	Spring (2020. 06. 03-05.), Summer (2020. 07. 21-24.), Autumn (2020. 09. 30.-10-02.)
	Number of positions	89	61	61
Study site	**Location**	First grove	Second grove	First grove
	Average diameter of grove	15 m	26 m	15 m
Transects	**Quantity of transects**	4	2	2
	Length of each transect	44 m	60 m	60 m
	Cardinal directions	N-S, EN-SW, E-W, SW-NW	N-S, E-W	N-S, E-W
	Max. elevation difference of positions	4,72 m	2,63 m	5,51 m

Measurements of environmental and functional variables were performed in intersecting transects with 2 m intervals between the measurement positions. The transects with different cardinal directions were formed together a star and cross-shape sampling arrangement with the group of trees in the middle.

Microclimate measurements

Air temperature and air humidity were measured in the herb layer with a sensor network along the transects at 2 m intervals for 48-h (1 min resolution) during each measurement campaign. The data loggers were placed 20 cm above the soil surface, at the average height of the herbaceous vegetation. Crossbow MICA XM2110CA mote (Crossbow Technology Inc., Milpitas, CA, USA), UNI-T UT330B Mini USB temperature humidity logger (UNI-TREND Technology CO Ltd., Guangdong, China) and Voltcraft DL-120TH USB temperature humidity logger (Voltcraft, Hirschau, Bavaria, Germany) were used. The sensors were shielded with a white plastic plate to avoid direct solar radiation. The sensors were calibrated before the measurements.

Measurements of soil parameters, functional variables and GPS

Measurements of soil parameters (ts, SWC) and functional variables (Rs, LAI, SOC) were performed along transects with 2 m intervals between the measurement positions. Manual measurements were taken between 11:00-13:00 and lasted about 1.5 h.

Soil respiration (Rs) and soil temperature (ts): measured by an EGM-4 infrared gas analyzer (PP Systems, UK).

Soil water content (SWC): measured by a FieldScout TDR 300 (FieldScout, USA) with a 3.0 in. (7.62 cm) rod.

Leaf area-index (LAI): measured by an ACCUPAR LP-80 ceptometer (METER Group, USA).

Soil organic carbon (SOC): in each measurement year, bulk soil samples were taken from the upper 10 cm at the measurement positions along the transects. SOC (%) of sieved soil was determined by sulfochromic oxidation and loss on ignition. Coordinates and altitude of measuring positions: recorded by high-precision STONEX S8 PLUS GPS (STONEX Srl., Paderno Dugnano, Italy) along the transects.

Vegetation sampling

Microcoenological relevés (percent cover) were recorded in 0.5m × 0.5m contiguous plots in each measurement campaign along the transects in parallel with the measurements. Ecological indicator values (temperature requirement (TZ) and moisture requirement (WZ) elaborated by Zólyomi) were assigned to the plant species.

Meteorological data

The National Meteorological Service's Fülöpháza Meteorological Station has provided data on daily average of air temperature, daily sum of precipitation and daily average of global radiation for the study period between May 2018 and October 2020.

Calculations

Vapour pressure deficit

Vapour pressure deficit (VPD) was computed from relative air humidity (RH) and air temperature (t) according to the formula developed by Bolton:

$$VPD = (100 - RH) \times 6.112 \times e^{(17.67 \times t/(t+234.5))} \qquad \text{(egyenlet 1)}$$

with t in °C, RH in % and VPD in Pa.

Duration curve analysis method

Our study focused primarily on the VPD duration curves, which were constructed from 24-hour period of records (1 min resolution). For all measurement positions, the period between 12:00-12:00 was considered as a 24-h period. The duration curve of one variable is created by sorting all data in descending order. Thus, the rank of the highest value is 1, while the smallest is n (n=number of measurements). The ordered data can be plotted to show the duration curve, where the relative order (e.g. percentage) on the X-axis reflects the exceedance probability of a particular value of the variable on the Y-axis (e.g. vapour pressure deficit of one measuring position) during the current period. If a threshold is given to the duration curve for the variable, we can read what percentage of the values of the variable exceeded the given threshold during the current period, this is the exceedance rate.

Digital elevation model (DEM) processing and terrain attribute calculations

Four terrain attributes were calculated from the measured altitude data for the best characterization of the surface.

Standard deviation of elevation (SD):

$$SD = \sqrt{\frac{1}{n_R - 1} \sum_{i=1} (z_i - \bar{z})^2}, \qquad (2)$$

where z_i values are the elevations of the correspondent R radius while $\bar{z}$ is the mean elevation within R. SD describes the heterogeneity and local surface roughness within the raster.

Calculation of slope- and aspect-derived easterness and northness:

- Slope (Sl): expresses the rate of change in elevation between positions; it is the tangent (vertical “rise” divided by horizontal “run”) of a surface angle to the horizontal in degrees.
- Easterness and northness (East, North): the compass direction that a slope faces. Northness and easterness with the values close to +1 mean that the slope is

northward and eastward in general, while values close to −1 mean a generally south- and west-facing slope.

Data processing

Statistical evaluation was performed in R:

PCA ordinations and duration curves were constructed from 24-hour VPD quantiles.

We used standardization on the variables for principal component analysis (PCA biplot) to reveal the complex relationships between the variables. To illustrate the simpler relationships, regression analysis was also performed, where the data were log-transformed too.

We also wanted to know the proportion of soil respiration components, so we used linear regression between LAI-Rs per measurement campaigns. After that we determined the y-axis intercept (where LAI is theoretically 0), considering it as the average Rhet rate. Therefore, we calculated Raut rate:

$$Raut = Rs - Rhet \tag{3}$$

, where $Raut$ is the autotrophic respiration component, Rs is the mean soil respiration rate, $Rhet$ is the heterotrophic respiration component.

Spatial maps were generated by spline interpolation to plot altitude and other spatial data. Terrain attributes were calculated and analysed from the GPS data as detailed in Calculations. We calculated Spearman correlation coefficients between PCA axes of the biplots, SOC and terrain attributes.

RESULTS AND DISCUSSIONS

Measuring circumstances (National Meteorological Service, Fülöpháza meteorological station)

2018 was the warmest and driest of the three years with 19.20 °C average temperature and 295.20 mm precipitation. In comparison, the average temperature was 18.46 °C and precipitation sum was 351.30 mm in 2019, while the average temperature was 18.02 °C and precipitation sum was 360.60 mm in 2020. During the autumn 2020 measurement campaign, there was 0.2 mm of rain and overcast weather, resulting in very low global radiation (35.28 W m^{-2}) compared to the other measurement campaigns. Among the measurement days, summer 2020 had the highest average air temperature (22.27 °C), while the highest average global radiation (301.32 W m^{-2}) was in summer 2018.

Connections between the variables and vegetation physiognomy

PCA biplots were used to analyze relationships among variables. The below-canopy points were generally located in the positive direction along the PCA I axis, while the grassland points were generally located in the negative direction. During the autumn 2020 measurement campaign, the orientation of the sampling positions' distribution in the PCA space changed, so the positions of the two vegetation types were located in opposite directions along the PCA I axis compared to the other measurement campaigns. The positions below the groves were notably separated from the positions in the surrounding grasslands. Rs showed a positive relationship with SWC and LAI, while it showed a negative relationship with ts and VPD. The loadings of Rs-SWC-LAI correlated positively with the distribution of the new PCA scores originating from the positions of the groves, while the distribution of the grasslands' positions followed ts-VPD loadings. Rs and LAI were higher as well as VPD and ts were lower in the below-canopy area. In contrast, the grassland had higher ts and VPD as well as lower Rs and LAI values. These parameters indicate the functional differences within the study site, especially between the grove and the surrounding grassland. However, differences in function can also be observed between grassland areas with different cardinal directions. The shading effect of the grove created differences in function between the more shaded (W-NE) and less shaded (E-SW) grassland areas around the grove.

In the regression analysis of the values of all measurement campaigns Rs showed significant positive correlation with SWC ($P<0.001$, $R^2=0.13$) and LAI ($P<0.001$, $R^2=0.28$) and showed not significant negative correlation ($P=0.059$, $R^2=0.004$) with ts. LAI showed significant negative correlation ($P<0.001$, $R^2=0.08$) with VPD. In general, Rs was the lowest (min: 0.13 μmol $m^{-2}s^{-1}$ in autumn 2018) in autumn, while the highest soil respiration values were measured in summer 2019 at the second grove (23.99 μmol $m^{-2}s^{-1}$), which was a slightly wetter habitat than the first grove. The highest SWC value (12.54%) was measured in summer 2020. In addition, most of the high SWC values (10-12%) were measured in summer 2019 and the lowest (3.53%) is measured in autumn 2018, which were consistent with the Rs intensity rate. Relatedly, the lowest ts value (13.2 °C) was also measured in autumn 2018, while the highest ts value (42.3 °C) was detected in summer 2018. In addition, the lowest LAI (0 m^2 m^{-2}) and the highest LAI (5.98 m^2 m^{-2}) were measured in the summer of 2018 in the grassland area. The lowest VPD (0.35 kPa) was measured in autumn 2020 and the highest is measured in summer 2018, due to the extremely low (autumn 2020) and the very high (summer 2018) global radiation. Characteristic groupings can be observed based on phenological stages, showing the different environmental circumstances of the measurement campaigns. Due to the high heterogeneity of the variances, log-transformation was applied to the data to remove the differences caused by the two different vegetation types (grassland vs. tree group). The observed relationships between the variables did not change notably. Rs still showed significant positive correlation with SWC ($P<0,001$, $R^2=0.13$) and LAI ($P<0,001$,

R^2=0.22), and showed not significant negative correlation (P=0,011, R^2=0,003) with ts. LAI still showed significant negative correlation (P <0,001, R^2=0.02) with VPD.

Soil respiration component rates

A seasonal difference was observed between the measurement campaigns within a year, as the spring and summer phenological stages were similar to each other, with a slightly higher autotrophic component in summer, while this value was the lowest in autumn. Differences between the study sites were also observed, as 2019 had higher Rs and LAI values than the other two years, since the second grove was a slightly wetter habitat than the first grove. The proportion of autotrophic soil respiration component followed closely the variation of LAI during all measurement campaigns. This relationship indicate the impact of vegetation structure on the ecosystem functions.

Relationships between the studied variables, soil organic carbon and terrain attributes

The PCA axes represent the variables and the vegetation structure, which are showed in the PCA plots. The relationship between these and terrain attributes is presented by Spearman correlation coefficients. The PCA I axis represents the grove, so if one of the variables showed a positive relationship with the PCA I axis, it was related to the tree group. On the other hand, if the relationship was negative, it showed a positive relationship with the grassland area. During the autumn 2020 measurement campaign, the orientation of the sampling positions' distribution changed in the PCA space.

Soil organic carbon and the conservation value of tree groups

Soil organic carbon showed a strong positive correlation with the PCA I axis for all measurement campaigns except autumn 2020, where it showed a strong negative correlation. This strong positive correlation indicates that the spatial pattern of SOC followed the spatial change of the vegetation structure, because the below-canopy area had a higher carbon content than the grassland. Thus, the transition of woody vegetation to some short vegetation type, for example forest-steppe mosaics, may be an important factor in the dynamics of carbon cycle. Even such small groups of trees have significant carbon storages in the sandy forest-steppe habitat, which may play an important role in the carbon cycle.

The influence of terrain attributes

Eastern orientation had a significant negative correlation with PCA I axes (and the opposite again in the case of autumn 2020), similarly to the findings in the biplot analysis, when "warmer" grassland positions matched with ts-VPD loadings, so the eastern grassland positions were warmer. Sl and SD showed negative correlations with PCA II axes in the 2018 spring phenological stage, which means that larger Rs and SWC were measured at smaller elevation differences with slight slopes. Since Rs and SWC were correlated with the grove, the surface heterogeneity was lower under the grove. At the study site in 2019, North showed a negative correlation with PCA I axes, while Sl and SD showed a negative correlation with PCA I axes in spring and a positive correlation with PCA II axes in autumn. These correlations again suggest larger ts-VPD values at south-facing directions and also larger Rs and LAI values in those positions with less surface heterogeneity including the below-canopy area.

Co-varying effects of the habitat's terrain features and the shading of the grove

Dominance of organic carbon and soil respiration activity under the grove can be detected. It can be linked to topography and the microclimate modifying effect of the grove's vegetation structure, thus the co-varying influence of topography and tree group can be observed. We detected the combined effect of topography and shading, as the influence of topography was masked by the shading effect associated with forest-steppe structure. However, the extent of the canopy cover's influence may vary between groups of trees with different locations and vegetation structures, as well as for slightly different sampling resolution and arrangement. Topography and shading have created spatial variability in ecosystem functional responses, but rainy weather and seasonal variability could be also strong drivers of these parameters.

Connections between vapour pressure deficit and vegetation physiognomy

In the PCA ordinations from VPD quantiles, the below-canopy areas were usually separated from the grassland areas, but not in all measurement campaigns, due to the edges formed transition zones. Cold-warm areas were generally not separated but were grouped. In the case of VPD, the separation of the areas is less clear than plotting all variables together, because the VPD quantiles were calculated from a 24-h period including night-time. Global radiation was low during the autumn 2020 measurement campaign, but no overlapping was observed between the below-canopy and open areas.

Comparison of duration curves

In terms of the stress threshold (1.2 kPa), the summer exceedance rate (52-60%) differed significantly from the spring (29-41%) and autumn (22-36%). The distribution of the values measured in the centre of the tree group did not show any seasonal differences, as there was no major difference in the maximum VPD values. In spring and summer measurements, the maximum values at the end-of-transects and at the edges were in the range of 8-11 kPa, and in the centre of the tree group in the range of 3-5 kPa. Above 2.5 kPa, the variability of the exceedance rates began to increase in all transects; therefore, we examined the exceedance rates at 3.0 kPa as well. Exceedance rates above 3.0 kPa threshold ranged from 12-22% in spring, 26-48% in summer and 7-22% in autumn. VPD values measured in the summer measurement campaign at the end-of-transects were much higher than the other measurement positions. In summer, the ends-of-transects’ exceedance rates above 3.0 kPa were over 50%, while the other positions’ were only below 32%.

VPD exceedance rates

Exceedance rates of 2018 measurement campaigns in transect-based analysis

I obtained the exceedance rates by the duration curve analysis method. In all three measurement campaigns of 2018, at least 30% of the values exceeded the 1.2 kPa threshold. VPD also showed seasonal variability at the 1.2 kPa threshold: spring and autumn did not differ significantly (30-38%), but summer (51-56%) had a much higher exceedance rate. The exceedance rate was balanced along the transects. The exceedance rate was not significantly lower in below-canopy area than in the grassland area, but the exceedance rate in the open areas did not vary notably either. When the threshold value for the exceedance rate was set at 3.0 kPa, the exceedance rate ranged from 8-22% in spring, 18-48% in summer and 0-28% in autumn. Exceedance rates above 3.0 kPa showed stronger differences between the below-canopy areas and the grassland areas, as well as between different grassland areas, especially between the opposite edges and between the opposite ends-of-transects. In the edges, values were higher on the warmer side of the grove with a more abrupt rise towards the open area. However, on the colder side of the grove, consistent with the shading effect of the trees, there was no sudden rise in VPD in the edges. A gradual increase was observed here with the distance from the grove towards the open area. Therefore, cooler-warmer grassland areas can be indentified within the study site.

Exceedance rates of edges and ends-of-transects in the measurement campaigns of 2018

Because of the observed cooler-warmer contrast between the areas, I analysed the exceedance rates of the edges and the ends-of-transect positions, which are representing the grassland areas. At 1.2 kPa threshold, the VPD exceedance rates did not differ significantly between the edges and between the grassland areas based on cardinal directions. At 1.2 kPa threshold, a slight increasing tendency was observed in the edges from west to southeast, followed by a decreasing trend from southeast to west. In the case of VPD exceedance rates above 3.0 kPa threshold, a different trend was observed at the edges. The west, northwest, north, and northeast edges had significantly lower exceedance rates at the 3.0 kPa threshold than the other edges. In autumn, the exceedance rate was close to 0% in the north edge, while it was actually 0% in the northeast edge. Therefore, cooler-warmer edge areas can be indentified. The ends-of-transects did not follow a consistent trend at either threshold.

Exceedance rates of 2018 measurement campaigns in spatial analysis

The four transects of the sampling arrangement in 2018 provided sufficient coverage to produce spatial interpolation plot for the whole sampling site. In the case of 1.2 kPa threshold, the exceedance rate was strikingly balanced over the whole sampling area in the spatial plots. In the case of 3.0 kPa threshold, the spatial pattern of the exceedance rate varied depending on weather conditions and phenological stages. The high VPD exceedance rates indicated the areas with persistently high stress conditions. Values were lower in the below-canopy area, but they varied at the edges and in the surrounding grassland. Only a small difference was observed between the grassland areas on the different sides of the grove in spring, which showed the influence of the weather, as it was slightly cloudy in spring. The measurements were made under clear skies in summer and autumn. The opposite grassland areas of the grove were in sync in summer, NE and SW had lower values, and SE and NW had higher values. The warmer (E-SW) and colder (W-NE) zones expanded in autumn and the transition between the two different microclimate zones was sharp. The warmer grassland side was E-SW, and W-NE was notably colder in autumn. The eastern and southeastern grassland areas had the highest VPD exceedance rates during both measurement campaigns. This suggests that the microclimate modifying effect of the grove did not decrease gradually with increasing distance from the edge in each cardinal direction. Considering the small size of the studied grove, this effect proved to be strong.

Relationships between the microclimate and the herb layer

Spatial distribution of plant species and the conservation value of tree groups

The influence of warmer and colder areas (according to the spatial plots) can be observed in the species composition and distribution of the herb layer. Five characteristic spatial species groupings were observed along the transects based on the coenological data of all three measurement campaigns. Group A included species that occurred both in the grassland and under the grove along the transect. *Festuca vaginata* Waldst. et Kit. ex Willd. is the dominant species of the *Festucetum vaginatae* Rapaics ex Soó association. It was always present in group A. Group B included species that were found on both sides of the tree group. Cryptogams and xeric grass species were always found in group B. Furthermore, three characteristic species groups have been identified: species occurring on one side (C) or on the other side (D) of the grove in the grassland and species occurring mainly or exclusively under the grove (E). Plant species under the grove had higher moisture and lower temperature requirements compared to species in the grassland. On the other hand, there were also differences between species group on opposite sides of the grassland. The species of group C had lower moisture requirement and higher temperature requirement than the species of group D. This spatial distribution of plant species indicated the changing environmental conditions even under such a small group of trees. In our case, the shading effect of the grove had a significant influencing power, which was also observed in the surrounding grassland. The spatial grouping of species according to their moisture and temperature requirements indicate the microclimatic differences in the study site. It makes this seemingly homogeneous grassland area very heterogeneous based on the herb layer patterns. The conservation value of small forest patches and tree groups in the sandy forest-steppe habitats is generally not fully acknowledged in conservation and restoration projects. Since the plant species have significantly different ecological requirements under and on the shaded side of even such a small woody vegetation, these small tree groups may act as refugium for more moisture-demanding and less drought-tolerant species during further aridification. Thus they may be important in mitigating the negative effects of climate change.

NEW SCIENTIFIC RESULTS

I. Based on the results, we found that in the case of sandy forest-steppe vegetation, the vapor pressure deficit was a sensitive indicator of the environmental conditions affecting the vegetation. It could also indicate the microclimatic differences between the grove and the surrounding grassland area, as well as the differences between certain grassland areas.

II. This was the first research in which the duration curve analysis method was successfully applied in the analysis of microclimatic data. It proved to be a promising tool for the analysis of air temperature, air humidity or vapour pressure deficit data measured during plant ecological studies. Based on our results, the 3.0 kPa VPD threshold can also be used as an important threshold for this vegetation type in addition to the 1.2 kPa stress threshold. VPD duration curves were informative in spatio-temporal analyses with these thresholds, as the exceedance rates are able to reveal the stress levels of the vegetation. High VPD exceedance rates are able to indicate areas with consistently high stress conditions.

III. We described the relationships between soil respiration, soil temperature, soil water content, leaf area-index, vapor pressure deficit, soil organic carbon and terrain attributes in the case of sandy forest-steppe vegetation.

IV. In this habitat, the terrain attributes (slope, aspect, elevation differences) and physiognomy of the woody vegetation had a co-varying influence on the abiotic and biotic factors of this ecosystem. The functioning of the ecosystem and the spatial distribution of soil organic carbon content were strongly influenced by topography, but the location of measurement positions, vegetation structure, weather and differences in phenological stages were also significant factors.

CONCLUSIONS AND SUGGESTIONS

Using the duration curve analysis method to analyse microclimate data in plant ecological studies can provide a more accurate picture of the state of an ecosystem. We recommend its inclusion in the standard data analysis methods. In addition to the 1.2 kPa VPD stress threshold, the 3.0 kPa VPD threshold is also very informative in spatio-temporal analyses in this vegetation type. It is worth experimenting to determine appropriate thresholds for other vegetation types.

This work highlights the importance of fine-scale sampling and analysis. The use of fine-scale sampling and analysis can reveal hidden patterns not only in transition zones, but also in apparently homogeneous vegetation.

Due to climate change, this habitat will be threatened by aridification and desertification, which will cause reduction in the amount and extent of forest patches. This process should result, for example, in a reduction in carbon stocks, which in turn should strongly affect the carbon cycle.

In a landscape with heterogeneous topography and vegetation, these factors need to be involved in biogeochemical models to obtain an accurate picture of the study area. Vegetation structure, topographic factors, location of measurement positions, weather and phenological stages can be considered as important input parameters for the models.

There is a need to develop an integrated approach during the conservation of sandy forest-steppe habitats: grassland and woodland should be treated as a single unit. Sub-types of woody vegetation with different extent and exposure should be treated with the same importance in all cases. Small tree groups of *Populus alba* should also be given a high priority in sandy habitat restoration projects.

PUBLICATIONS RELATED TO THE TOPIC OF THE THESIS

Publications in scientific journals:

1. SÜLE, GABRIELLA; FÓTI, SZILVIA; KÖRMÖCZI, LÁSZLÓ; PETRÁS, DÓRA; KARDOS, LEVENTE; BALOGH, JÁNOS (2021): Co-varying effects of vegetation structure and terrain attributes are responsible for soil respiration spatial patterns in a sandy forest–steppe transition zone. *WEB ECOLOGY*, 21:(2), 95-107. p.
2. GABRIELLA, SÜLE; JÁNOS, BALOGH; SZILVIA, FÓTI; BERNADETT, GECSE; LÁSZLÓ, KÖRMÖCZI (2020): Fine-Scale Microclimate Pattern in Forest-Steppe Habitat. *FORESTS*, 11:(10), Paper: 1078.

Proceedings (international):

3. SÜLE, GABRIELLA; BALOGH, JÁNOS; GECSE, BERNADETT; FÓTI, SZILVIA; KÖRMÖCZI, LÁSZLÓ (2019): Környezeti tényezők, mikroklíma komponensek és növényzeti mintázat térbeli kapcsolata erdőssztyepp vegetációban. In: Szigyártó, I-L; Szikszai, A (szerk.) *XV. Kárpát-medencei Környezettudományi Konferencia*, Kolozsvár, Románia: Ábel Kiadó. 50-56. p.
4. SÜLE, G; KÖRMÖCZI, L (2017): Vegetáció foltmintázat és mikroklíma mintázat kapcsolata erdőssztyepp élőhelyen. In: Szigyártó, IL; Szikszai, A (szerk.) *XIII. Kárpát-medencei Környezettudományi Konferencia*, Kolozsvár, Románia: Ábel Kiadó. 28-34. p.

Conference abstracts (international):

5. SÜLE, G; BALOGH, J; FÓTI, SZ; GECSE, B; KÖRMÖCZI, L (2019): Spatial relationships of forest-steppe vegetation pattern, environmental and functional variables. In: Rosario, G. Gavilán; Alba, Guitérrez-Girón, *28th EVS Meeting:*

Abstracts & Programme: Vegetation Diversity and Global Change, Madrid, Spanyolország: Universidad Complutense de Madrid (UCM). 104. p.

6. GABRIELLA, SÜLE; JÁNOS, BALOGH; LÁSZLÓ, KÖRMÖCZI (2018): Connections between the microclimate pattern and the vegetation structure in forest-steppe habitat. *GEOPHYSICAL RESEARCH ABSTRACTS*, 20 Paper: EGU2018-18976.

Conference abstracts (hungarian):

7. SÜLE, GABRIELLA; BALOGH, JÁNOS; FÓTI, SZILVIA; PETRÁS, DÓRA; KÖRMÖCZI, LÁSZLÓ (2021): A mikroklimatikus viszonyok és a gyepszint térbeli mintázatának kapcsolata homoki erdőssztyepp élőhelyen. In: Tinya, Flóra (szerk.) *12. Magyar Ökológus Kongresszus - Előadások és poszterek összefoglalói.* 197. p.
8. FÓTI, SZILVIA; BALOGH, JÁNOS; PINTÉR, KRISZTINA; KONCZ, PÉTER; SÜLE, GABRIELLA; GIULIA, DE LUCA; NAGY, ZOLTÁN (2021): Ökoszisztéma-funkciók stabilitásának vizsgálata térbeli mérések alapján. In: Tinya, Flóra (szerk.) *12. Magyar Ökológus Kongresszus - Előadások és poszterek összefoglalói.* 49. p.
9. PINTÉR, KRISZTINA; FÓTI, SZILVIA; BALOGH, JÁNOS; PETRÁS, DÓRA; SÜLE, GABRIELLA; NAGY, ZOLTÁN (2021): Evapotranszspiráció és bruttó primer produkció becslése távérzékeléssel. In: Tinya, Flóra (szerk.) *12. Magyar Ökológus Kongresszus - Előadások és poszterek összefoglalói*. 98. p.
10. FÓTI, SZILVIA; BALOGH, JÁNOS; PINTÉR, KRISZTINA; KONCZ, PÉTER; SÜLE, GABRIELLA; NAGY, ZOLTÁN (2021): Ökoszisztéma funkciók hosszútávú stabilitásának vizsgálata agro-ökoszisztémákban. *Első Országos Interdiszciplináris Éghajlatváltozási Tudományos Konferencia* 2021-04-12 [Budapest, Magyarország], HUPCC Magyar Éghajlatváltozási Tudományos Testület.

11. SÜLE, GABRIELLA; BALOGH, JÁNOS; KÖRMÖCZI, LÁSZLÓ (2018): A mikroklíma-mintázat és a vegetációszerkezet közötti összefüggések erdőssztyepp élőhelyen. In: Molnár, V Attila; Sonkoly, Judit; Takács, Attila (szerk.) *XII. Aktuális Flóra- és Vegetációkutatás a Kárpát-medencében. Program és összefoglalók*. Debrecen, Magyarország: Debreceni Egyetem TTK Növénytani Tanszék. 89. p.

Unpublished scientific reports:

12. SÜLE, GABRIELLA (2017): Hogyan járul hozzá egy erdőszegély mikroklíma-mintázata a lágyszárú növényzet foltdinamikájához? Diplomamunka, SZEGEDI TUDOMÁNYEGYETEM, Természettudományi és Informatikai Kar Ökológiai Tanszék, 43 p.
13. SÜLE, GABRIELLA (2017): Cönológiai szerkezet és mikroklíma mintázatok összefüggése erdőssztyepp életközösségekben. XXXIII. Országos Tudományos Diákköri konferencia: Biológia Szekció. Debrecen, 2017. április 9-12.