J. Hydrol. Hydromech., 72, 2024, 2, 223–237
https://doi.org/10.2478/johh-2024-0005
© 2024 Milan Ostrihoň et al., published by Sciendo. This work is licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International Licence.

sciendo Journal of Hydrology and Hydromechanics Institute of Hydrology SAS

Influence of meteorological factors on the moisture content of fine forest fuels: responses of fire danger class to different microclimates on the example of European beech (*Fagus sylvatica* L.) stands

Milan Ostrihoň[1,3], Michaela Korená Hillayová[2*], Katarína Korísteková[3], Adriana Leštianska[3], Martin Jančo[4], Tomáš Vida[5], Jaroslav Vido[3], Jaroslav Škvarenina[3*]

[1] Department of Fire Protection, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T.G. Masaryk 24, 960 01 Zvolen, Slovakia.
[2] Department of Forest Economics and Policy, Faculty of Forestry Technical University in Zvolen, T.G. Masaryk 24, 960 01 Zvolen, Slovakia.
[3] Department of Natural Environment, Faculty of Forestry Technical University in Zvolen, T.G. Masaryk 24, 960 01 Zvolen, Slovakia.
[4] Institute of Hydrology, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia.
[5] Faculty of Political Science and International Relations, Kuzmányho 1, 974 01 Banská Bystrica, Slovakia.
[*] Corresponding authors. E-mails: michaela.hillayova@tuzvo.sk; skvarenina@tuzvo.sk

Abstract: Due to the increased number of forest fires, a detailed examination and knowledge of the effects of the microclimatic conditions of forests is currently significant. The study carried out in Arboretum Borova hora (Slovak Republik), investigates the influence of meteorological factors (air temperature, relative humidity), the value of the Angström index, and the danger class of the Angström index on the moisture content of fine fuel at the edge of a beech forest stand, but also in its interior. We tested three working hypotheses: a) meteorological conditions differ significantly between the edge and the interior of the beech forest, b) the moisture content of fine fuel is higher in the beech forest interior than at the forest edge, c) the Angström index fire danger class is higher at the edge of the beech forest than in its interior. We created a calibration curve that was also used to measure the humidity of beech leaves with the help of the ME 2000 hygrometer. Our results show that edge beech stands are significantly more susceptible to fires, lower air humidity and fine fuel moisture content, and higher air temperatures than forest interiors. From our point of view, the microclimate is considered the main factor that explains the difference between the vegetation structure of the forest edge and the forest interior.

Keywords: Microclimate; European beech; Forest stand edge and interior; Moisture content of fine fuel; Angström index danger class.

1 INTRODUCTION

European beech (*Fagus sylvatica* L.) is considered the most economically significant tree of the temperate zone in Europe. The natural range of beech covers a large part of Western and Central Europe with an oceanic and sub-oceanic climate. It requires humid summers and mild winters and, therefore, does not occur in continental areas of eastern Europe. European beech prefers a humid climate where precipitation exceeds evaporation (Ellenberg, 1996; Gömöry et al., 2011; Mráček, 1989). In Slovakia, it occurs naturally from the hills to the mountain forest areas (120–1450 m a.s.l.), with European beech accounting for 35% of the total forest area (Lukasová et al., 2019, 2020; Škvarenina et al., 2004b). It has a shallow root system that makes it susceptible to drought (Nalevanková et al., 2018; Peterken and Mountford, 1996; Vido et al., 2015), and wind and its thin bark provide little protection from forest fires (Bradshaw et al., 2010).

Forest fires in temperate beech forests of Central Europe were often considered a negligible ecosystem disturbance (Adámek et al., 2015), as the flammability of deciduous forests was assumed to be low (Ellenberg, 1996). Nevertheless, over the last decades, scientific evidence has emerged in the literature that fires occur sporadically in Central European beech forest ecosystems during dry periods (Carter et al., 2018; Tuček and Majlingová, 2009). Based on research from this area, beech is one of the most susceptible European broadleaved species to fire (Packham et al., 2012).

Trend analyses and climate models predict more frequent and extreme heat waves and droughts across Europe (Lukasová et al., 2021; Rajczak et al., 2013; Ziernicka-Wojtaszek, 2021), which may increase the risk of wildfires and the impact on forest vegetation, even in mountain regions that have so far been little affected by fires (Camia et al., 2017; Carter et al., 2018; Korena Hillayová et al., 2023; Lindner et al., 2014).

Fires in the natural environment and forests primarily affect middle-earth areas, resulting in damage or destruction of the productive and non-productive functions of the forest and endangering human life (Cerdà et al., 2022; Fajković et al., 2022; Hološ et al., 2022). Climate, topographical conditions, and vegetation cover are among the main factors that influence the occurrence and spread of fire. Climate and topographical conditions determine the zonation of vegetation cover and microclimate on slopes with different exposition. However, the occurrence and spread of fire are primarily conditioned by the weather, i.e., the immediate state of the atmosphere (Holsten et al., 2013). Because of the growing number of forest fires, an accurate assessment of the fire danger for individual locations is necessary. The fire danger assessment can be carried out using a fire weather index which simultaneously considers the action of several meteorological elements, e.g., temperature, humidity,

rainfall, and wind. There are several weather fire indices, while the flammability potential of organic material in European conditions is most often evaluated using the so-called non-cumulative indices, e.g., Angström's index, Sharples index, Fosberg index, or cumulative indices, e.g. Nesterov's index, Baumgartner's index, Canadian fire index, etc. (Škvarenina et al., 2004a). In large areas of Europe, coniferous monocultures are being transformed into mixed forests by reintroducing deciduous trees from the potential natural vegetation. The European beech is an important species of interest in this changing forest policy (Gessler et al., 2005). Sustainable forest management increasingly focuses on restoring biodiversity in forests after fires.

Fire protection of forests is highly relevant even in the conditions of the temperate zone in Slovakia due to the changing climate (Nečas and Kollár, 2018). An understanding of variation in dead fuel moisture content (FMC) is essential for accurate forecasting of wildfire risk, especially in productive wet forests where monitoring of meteorological elements and FMC constitutes the primary control of fire activity (Brown et al., 2022; Ostrihoň et al., 2021). In forests of temperate climatic zones, the woody composition of forests, age, and structure of stands influence microclimate (Geiger et al., 1995; Matejka et al., 2004; Petrík et al., 1986); on the other hand, the forest microclimate, in turn, affects FMC (Kane, 2022).

According to Petrík et al. (1986), Geiger et al. (1995), and Aussenac (2000) more homogeneous microclimatic conditions inside the forest interior are maintained by the interception of incoming solar and outgoing longwave radiation by the canopy layer (Hofmeister et al., 2019) and by buffering related to phase changes of water in the stand (i.e. evaporation, canopy interception, evapotranspiration); (Davis et al., 2019; Střelcová et al., 2006; 2013). The forest edge represents a transition zone between the forest interior and adjacent treeless area, which serves as a buffer from external climatic variability (Geiger et al., 1995; Tuff et al., 2016). Even Rožnovský et al. (2017) found a significant microclimatic stand-edge effect in urban tree vegetation. Numerous studies on the edge-related effects of the fragmentation on microclimate and studies of the interactive effects of fragmentation, structure, and fire led to the development of positive feedback models of fragmentation and fire (Watts and Kobziar, 2015).

Rainfall interception process is an essential part of the biohydrological cycle, in which vegetation plays a vital role by regulating the amount and dynamics of rainfall reaching the ground (Klamerus-Iwan and Błońska, 2017; Kofroňová et al., 2021; Zabret et al., 2023) and thus directly influencing the moisture characteristics of the vegetation microclimate. The type of tree species, the structure and composition of forest stands, and the management method influence rain interception, microclimate, and litter moisture content (Dohnal et al., 2014; Šípek et al., 2020; Šraj et al., 2008).

The assessment of fire danger index performance, along with site- and species-specific fire danger, primarily relies on the analysis of fire occurrence records. However, in regions characterized by a moderate or small overall fire danger, these analyses may be hampered by a limited number of recorded fires per unit area or the absence of comprehensive fire data. However, as fire danger is expected to be linked to micrometeorology and dead fine fuel moisture measurements, the aim of the study is to analyse the influence of meteorological factors (air temperature, relative humidity), Angström index values, and the Angström index danger class on the moisture content of fine fuel. The study also deals with the analysis of different microclimatic conditions and moisture content of fine fuel at the edge of the forest beech stand, and the interior of the forest beech stand.

In order to find out the effects of the meteorological factors on the moisture content of forest beech fine fuel and its subsequent effect on the fire hazard (in Borová hora Arboretum - Slovakia), we logically formulated the following working hypotheses:

H1: Meteorological conditions differ significantly between the edge and the interior of the beech forest.

H2: The moisture content of fine fuel is higher in the beech forest interior than at the forest edge.

H3: The Angström index fire danger class is higher at the edge of the beech forest than in its interior.

2 MATERIALS AND METHODS

2.1 Study area

Our research was conducted in the arboretum Borová hora (latitude 48.354422°N, longitude 19.081230°E, altitude 350 m a.s.l.) situated in Zvolen valley (Central Slovakia). The Borová hora is located near the middle reach of the Hron River, about 3 km N-W from the centre of Zvolen and on the S-W foot of the Zvolen country-hill. From the phytogeography viewpoint belongs to the Zvolen Basin. (Fig. 1) (Stašiov et al., 2017). According Leštianska et al. (2020) and Lukáčik et al. (2005) the soil type is cambisol. From the climatic point of view, this area is situated in the temperate climatic zone with a temperate Central European climate. The area belongs to a warm and a slightly warm region with a cold winter. Mixed beech-oak forests represent primary forest vegetation (Škvareninová, 2009; 2010). The details concerning the investigated locality/plot are given in Table 1.

The experimental part of the research influence of meteorological factors on the moisture content of fine forest fuels was carried out during five summer periods in 2017, 2018, 2020, 2021, and 2022. The moisture content of fine fuel and forest also called the litter was measured in a forest stand of forest beech (*Fagus sylvatica*). Measurements were carried out inside the stand (Fig. 2a) and at its edge (Fig. 2b). In total, 220 manual field measurements were performed during the experiment.

2.2 Data collection

The fine fuel moisture content was measured during the experiment with a Wiltronics ME 2000 moisture meter onsite and manually. This device can accurately and quickly determine the moisture content of fine fuel in natural conditions within a few minutes. The measuring device's operation consists of measuring the fuel's electrical resistance under consideration. The advantage of this device is the measuring range from 2% to 300%. The Wiltronics ME 2000 moisture meter can measure the moisture content of dead and living organic parts of plants. According to (Chatto and Tolhurst, 1997) the measurement accuracy of this device is 1% and the sensitivity is 0.1%. The chemical composition of the fine fuel of different tree species varies, so the device needs to be calibrated for the fine fuel. A detailed calibration process under laboratory conditions is given by (Korísteková, 2018), and is further described in Section 3.1 (results) of this paper. The calibrated device is ready for measurement. The measurement using Wiltronics ME 2000 consists of several steps:

- The first step is the collection of organic material on experimental forest stands.
- The collected organic material is ground into a fine fraction using a special crusher and placed in a metal hoop in a hygrometer.
- The prepared material of the fine fraction is compressed with constant pressure.

Table 1. The ecological and climatological characteristics of experimental locality/plot.

Station	Arboretum Borová hora
Altitude (m a.s.l.)	320–350
GPS	48.354422°N; 19.081230°E
Geomorphological units	Zvolen Basin/Zvolen country-hills
Positions	intermountain basin − foothills
Geological bedroc[1)]	andesite tuff
Soil type[1)]	cambisol
Average annual air temperature (°C) [2)]	7.9
Average temperature (April–September) (°C) [2)]	14.7
Average January air temperature (°C) [2)]	–3.9
Average July air temperature (°C) [2)]	18.1
Average annual precipitation total (mm) [2)]	651
Average precipitation (April–September) (mm) [2)]	377
Climatic typ[3)]	valley climate
Climatic subtyp[3)]	warm valley climate
Altitudinal vegetation stages[4)]	1st oak stage / 2nd beech−oak stage/
forest type groups[5)]	*Fageto-Quercetum / Querceto-Fagetum*
NATURA potential vegetation[6)]	91G0 Pannonic woods with *Quercus petrea* and *Carpinus betulus*
Beech stand age (year)	45–50
Average trees thickness (cm)	18–26
Average stand height (m)	16–23
Canopy density	0.9 (closed canopy cover)
Growing phase	pole timber phase

[1)] natural conditions Borová hora arboretum according to Lukáčik et al. (2005)
[2)] climatic conditions according to Leštianska et al. (2020) excerpted from climatological normal SHMI 1961–1990
[3)] climatic regions according to Tarábek (1980)
[4)] Altitudinal vegetation stages according to Škvarenina et al. (2004b)
[5)] Forest type groups according to Škvareninová (2009), (2010)
[6)] NATURA potential vegetation according to Stanová and Valachovič (2002).

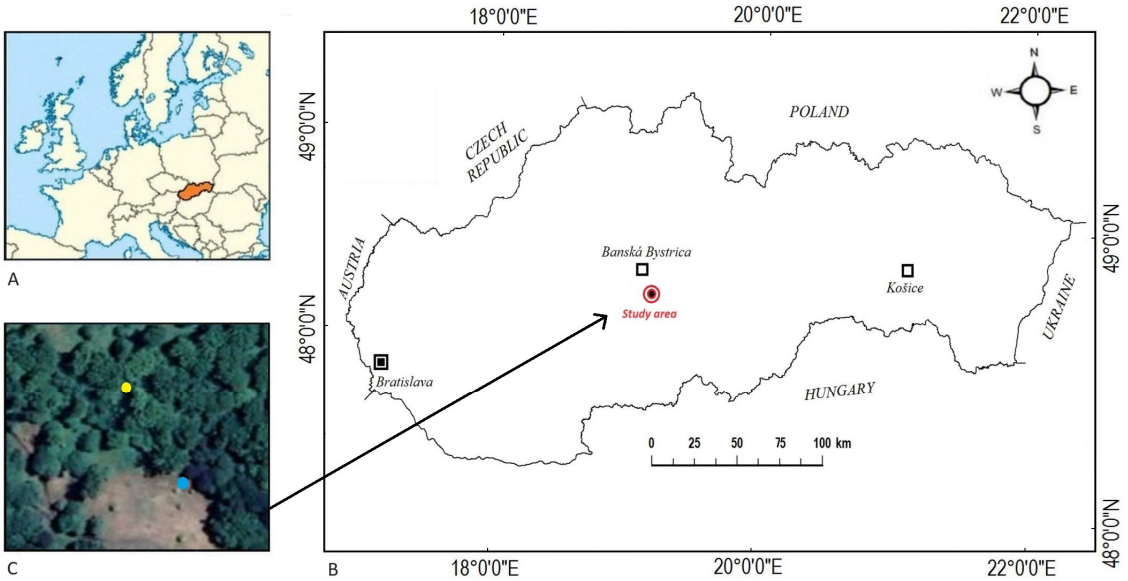


Fig. 1. a) Location of the Slovak Republic in the Central Europe. b) Location of the experimental area on the territory of the Slovak Republic. c) Locations of field measurements (forest stand edge – blue point, forest stand interior – yellow point).



Fig. 2. a) Forest stand edge (left) with his canopy cover (small picture in the top corner). b) Forest stand interior (right) with his canopy cover (small picture in the top corner).

- After pressing, the measurement process starts on the measuring device.
- After the measurement, we read off the measured values from the display.
- The measurement process is three times repeated for higher accuracy. (Chatto and Tolhurst, 1997).

All field measurements were carried out in the beech stand, specifically in two parts, the forest edge and the forest interior. The exact sampling locations were chosen randomly every day; care was taken not to sample any litter that had been excessively trampled. The measurements were carried out at selected observation dates during and at the end of the summer period in the years 2017, 2018, 2020, 2021, and 2022. Fixed Minikin i-line RTHi. measuring equipment was also installed at each experimental forest stand i.e. (forest stand interior and forest stand edge). The measuring device in the forest stand interior was installed 30 m from the southern of the forest stand edge. The measuring device in the forest stand edge was installed on the southern edge of the stand directly below the level of the ending branches of the stands. Micrometeorological measurements of temperature and relative humidity were carried out according to Geiger et al. (1995). These were taken at the edge and interior of the beech stand at a height of 5 cm above the surface and were compared with measurements in the open area also at 5 cm. These measuring devices provided continuous measurements of hourly air temperature and relative humidity. Field measurements were carried out between 1 PM and 2 PM. At this time, we assumed the most extreme values (i.e. the highest air temperature values, the lowest relative humidity values, and the lowest Angström index and fire danger level values) to be reached. Monitoring other meteorological elements for the open area was provided by the EMS Brno automatic meteorological station located at the arboretum Borová hora station, details of the measurements are provided by Střelcová et al. (2018).

2.3 Calculation of fire index and danger class

In our work, we used the proven fire index according to Angström. The Angström Index (AI) (Equation (1)) was calculated according to the following equation (Škvarenina et al., 2004a):

$$\mathrm{AI} = \left(\frac{R}{20}\right) + \left(\frac{27 - T}{10}\right) \tag{1}$$

where R represents relative humidity (%), and T represents temperature (°C), measured at local time. The index is interpreted as follows Table 2 (note that the scale of the Angström index is inverted to all others and that high values represent a low fire danger and vice versa).

2.4 Calibration procedure for measuring fine fuel moisture content of European beech (*Fagus sylvatica*) with Wiltronics ME 2000 meter

The calibration process leads to creating of a calibration curve that represents the dependence of fuel moisture on the measured electrical resistance of sampled fuel. When investigating these dependencies, a more accurate humidity prediction is observed using two linear equations (Equation (2) than expressing the relationship with a single non-linear equation (Chatto and Tolhurst, 1997).

$$\log_{10}(v) = \frac{a}{\log_{10}(R)} + b \tag{2}$$

where v represents moisture content (%), R represents measured resistance (**Ω**), a and b are regression coefficients.

Table 2. Anström index danger classes with index value and their description.

Index values	Index danger class	Interpretation
AI > 4.0	1	fire occurrence unlikely
4.0 < AI < 3.0	2	fire conditions unfavourable
3.0 < AI < 2.5	3	fire conditions favourable
2.5 < I < 2.0	4	fire conditions more favourable
I < 2.0	5	fire occurrence very likely

Table 3. Interpretation of the correlation coefficient according to Hinkle et al. (1998).

Correlation coefficient value	Interpretation	Strength
0.91 to 1.00 (–0.90 to –1.00)	very high correlation	*****
0.71 to 0.90 (–0.70 to –0.90)	high correlation	****
0.51 to 0.70 (–0.50 to –0.70)	medium correlation	***
0.31 to 0.50 (–0.30 to –0.50)	low correlation	**
0.00 to 0.30 (0.00 to 0.30)	very low or no correlation	*

Table 4. Determined values of moisture and resistance of the biological material (one-year-old beech litter).

Moisture (%)	Moisture (log10)	Resistance (l/log10)	Moisture (%)	Moisture (log10)	Resistance (l/log10)
2.47	0.4116	0.0787	27.92	1.4459	0.1835
2.69	0.4298	0.0783	33.45	1.5244	0.2222
3.00	0.4771	0.0797	35.84	1.5544	0.1993
3.74	0.5729	0.0799	37.38	1.5726	0.2083
4.32	0.6355	0.0812	56.04	1.7485	0.2564
6.52	0.8143	0.0885	58.02	1.7636	0.2762
7.37	0.8675	0.0872	63.74	1.8044	0.2985
7.85	0.8949	0.0917	64.10	1.8069	0.2737
9.09	0.9589	0.0952	88.00	1.9445	0.3175
14.32	1.1559	0.1212	122.84	2.0893	0.3571
18.32	1.2693	0.1408	181.67	2.2593	0.3676

2.5 Statistical analysis

The statistical analysis of the measured data on air temperature and relative humidity, moisture content of fallen European beech leaves, and the calculated Angström index value/danger class was carried out in several steps as follows:

- The collected data and the calculated fire index for 2017, 2018, 2020, 2021, and 2022 in the monitored area of the Zvolen basin were analysed using basic descriptive statistics (mean, median, minimum, maximum, standard deviation, and range). Statistica ver. 12 ver. was used for statistical analyses.
- We tested the normality of the collected meteorological data, and moisture content, and calculated the Angström index value/danger class. These variables were tested with the Shapiro-Wilk test for the expectation of normality for the observed period.
- Since the data have a not normal distribution, the strength of the correlation between variables was determined by Spearman's correlation coefficient. The strength of the correlation coefficient was interpreted according to Hinkle et al. (1998) (Table3).
- The strength of the relationship between moisture content (independent variable) and meteorological data and Angström index value/danger class (dependent variable) was tested by the Mann-Whitney U test.
- Finally, we created a comprehensive data table of statistical analyses to summarise the results.

3 RESULTS

3.1 Calibration curve for European beech

The calibration was carried out based on laboratory determination of the resistance of beech foliage with the ME 2000 instrument at different humidities. Based on calibration under laboratory conditions (Korísteková, 2018), we created calibration curves for one-year beech leaves. The previous year litter from mature beech trees was collected in June and therefore the measured curves refer primarily to this type of litter characterised by its specific decomposition. From the measured values (Table 4), we calculated linear dependencies (Fig. 3) according to Equation (2).

Calculated regression coefficients for one-year-old beech litter are as follows:
Moisture up to 9 %: a = 32.393 and b = –2.0634
Moisture above 9 %: a = 4.0875 and b = 0.6625
These regression coefficients were used to set the measuring device.

3.2 Influence of meteorological factors on the moisture content of fine forest fuels

We found that meteorological data (temperature and relative air humidity) and the fine fuel moisture content of fallen European beech leaves, and thus, Angström index values differ significantly at the edge and inside the beech stand (Table 5).

The daily temperature at the edge of the stand ranged from 10.67–41.05°C, and the stand interior from 10.95–35.25 °C, depending on the measurement period. The average air temperature at the edge of the stand is 3.51 °C higher than the stand interior. The minimum temperature was approximately the same (forest stand edge 10.61°C and interior 10.95°C). We recorded higher temperature differences in the average maximum air temperature, where the air temperature was, on average, 5.8 °C higher at the forest's edge.

Air humidity at the edge of the stand ranged from 17.75–100%, and the stand interior from 23.05 – 100%, depending on the measurement period. The average air humidity was 7.72%

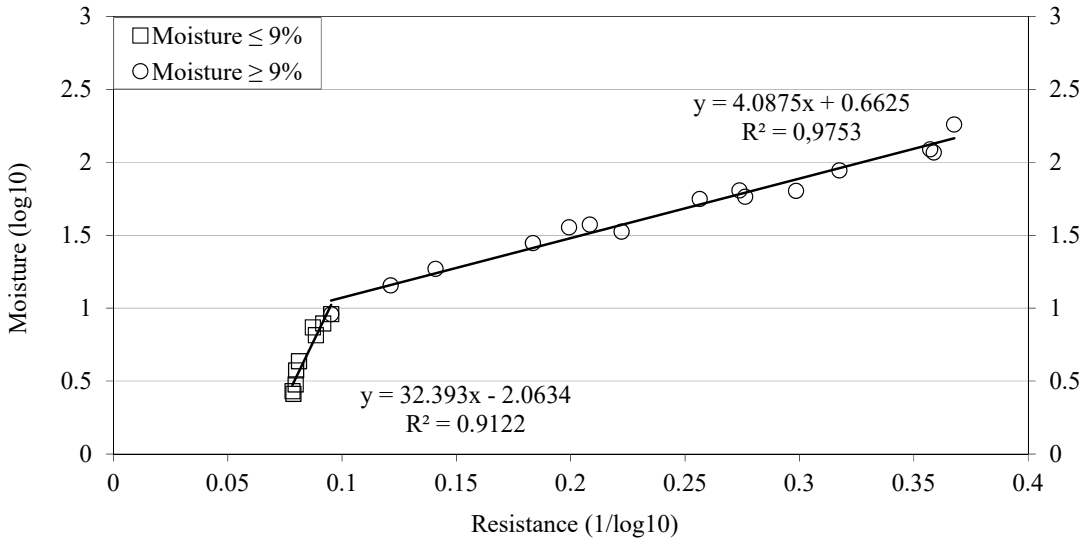


Fig. 3. Linear dependences between resistance and moisture of the biological material (one-year-old beech litter).

Table 5. Results of measures of central tendency and measures of variability (descriptive statistics), (experimental data measured in 2017–2022).

Stands position	Variable	Mean	Median	Minimum	Maximum	Standard deviation	Dispersion
Forest stand edge	Air temperature (°C)	27.32	28.50	10.67	41.05	6.58	43.34
	Relative air humidity (%)	49.49	45.09	17.75	100.00	17.84	318.21
	Fine fuel moisture content (%)	12.37	11.35	2.47	74.00	10.22	104.36
	Angström index value (–)	2.44	2.15	–0.52	6.05	1.45	2.09
	Angström index danger class (–)	3.57	4.00	1.00	5.00	1.59	2.54
Forest stand interior	Air temperature (°C)	23.81	24.39	10.95	35.25	4.95	24.51
	Relative air humidity (%)	57.21	54.44	23.05	100.00	15.80	249.63
	Fine fuel moisture content (%)	20.26	14.55	7.37	90.10	14.46	209.01
	Angström index value (–)	3.18	3.16	0.33	5.87	1.16	1.34
	Angström index danger class (–)	2.69	2.00	1.00	5.00	1.41	1.98

lower at the forest's edge. The average minimum humidity was 5.3% higher on the edge than the stand interior, and the average maximum humidity was logically the same at 100%.

The fine fuel moisture content at the edge of the stand ranged from 2.47–74.00% and in the stand's interior from 7.37–90.10%, depending on the measurement period.

The average fine fuel moisture content of fallen European beech leaves was higher at the stand interior by 7.89% than at the edge. Inside the stand, the average minimum fine fuel moisture content was higher by 4.9%, and the average maximum moisture content was higher by 16.1% compared to the stand interior. We found that the lower the air temperature and the higher the air humidity, the higher the fine fuel moisture content and the value of the Angström index also increases (Table 6). The fine fuel moisture content at the edge of the stand was positively correlated with the strength of "medium correlation". It was also negatively correlated with Angström index value and air relative humidity, with the strength of "low correlation" with air temperature and Angström index danger class. The same situation was repeated in the stand interior, but fine fuel moisture content was positively correlated with the strength of "medium correlation" with the Angström index danger class.

Mutual comparison of the dependence of air temperature and relative humidity, fine fuel moisture content, Angström index value, and Angström index danger class between the edge and the interior of the stand (Table 7). The individual variables correlate at the edge and inside the stand with the strength of "high correlation".

Table 6. Data normality and dependence between fine fuel moisture content, meteorological data, and Angström fire index values, (experimental data measured in 2017–2022).

Stands position	Variable	Statistics method						
		Shapiro-Wilk test		Spearman correlation coefficient		Mann-Whitney U test		
		W	p-value	r_s	Interpretation (Hinkle et al. 1998)	U-value	Z-Score	p-value
Forest stand edge	Air temperature (°C)	0.9719	0.01998	–0.447356	**	977	10.74543	p < 0.00001
	Air relative humidity (%)	0.941	0.00010	0.590682	***	303	12.17321	p < 0.00001
	Angström index value (–)	0.9675	0.008681	0.558463	***	391	–11.9868	p < 0.00001
	Angström index danger class (–)	0.7766	1.21e–11	0.504111	**	890	–10.92973	p < 0.00001
	Fine fuel moisture content (%)	0.6512	8.44E–15	1.000000	–	–	–	–
Forest stand interior	Air temperature (°C)	0.9868	0.3564	–0.478182	**	2795	6.89423	p < 0.00001
	Air relative humidity (%)	0.9748	0.03469	0.702829	***	611	11.52075	p < 0.00001
	Angström index value (–)	0.9916	0.7366	0.664635	***	0	–12.81508	p < 0.00001
	Angström index danger class (–)	0.8681	1.867e–8	0.682511	***	0	–12.81508	p < 0.00001
	Fine fuel moisture content (%)	0.624	2.22E–15	1.000000	–	–	–	–

Table 7. Correlation of individual variables between the edge and the interior of the stand, (experimental data measured in 2017–2022).

Position	Variable	Statistics method				
		Spearman correlation coefficient		Mann-Whitney U test		
		r_s	Interpretation (Hinkle et al., 1998)	U-value	Z-Score	p-value
Forest stand edge and forest stand interior	Air temperature (°C)	0.838480	****	3787	4.79281	p < 0.00001
	Air relative humidity (%)	0.858530	****	4182	–3.95606	0.00008
	Moisture content (%)	0.731794	****	2256.5	–8.03498	p < 0.00001
	Angström index value (–)	0.851642	****	3949	–4.44964	p < 0.00001
	Angström index danger class (–)	0.765734	****	4109	4.1107	p < 0.00001

3.3 Analysis of the diurnal course of micrometeorological elements and Angström index value

In this part, we analyse the microclimatic conditions of the days when the lowest and highest moisture values of fine beech fuel occurred on our experimental plots.

During the field measurements on **25 July 2022, the lowest moisture content of fine fuel** from all measurements was measured **at the forest stand edge, only 2.5%** (Table 8).

When comparing the forest stand edge (Fig. 4 a), the forest stand interior (Fig. 4 b), and an open area (Fig. 4 c) on 25.7.2022, we see the following facts. During this period, Slovakia was under the permanent influence of the Wal synoptic situation (Wal – Western summer-type anticyclonic situation). Wal in our territory lasted for 6 days from July 21 to 26. The situation was characterised by cloudless, partly cloudy, and sunny weather without precipitation. Clear weather resulted in large daily amplitudes of air temperature and humidity. Air temperatures ranged from 13 °C at night to 38 °C during the day. 25 July 2022 was a warm summer day with low daytime relative humidity and high daytime air temperature values.

Day 25 July 2022 was a warm summer day with low daytime relative humidity and high daytime air temperature values. During this day relative humidity was highest at 6 AM in all cases and generally reaches its highest values on an open area (this is due to the absence of beech stand compared to the forest stand edge and forest stand interior). The lowest relative humidity values were reached between 4 PM and 6 PM. The trend of the daily air temperature was inversely proportional to the daily relative humidity.

Table 8. Measured and calculated values at 2 PM on 25.7.2022.

	Moisture content of fine fuel (%)	Air temperature (°C)	Relative air humidity (%)	Angström index value (–)
Forest stand edge	2.5	37.44	20.37	–0.02
Forest stand interior	12.1	30.09	29.58	1.16
Open area	–	37.52	22.44	0.07

*All values in the table are measured at 2 PM

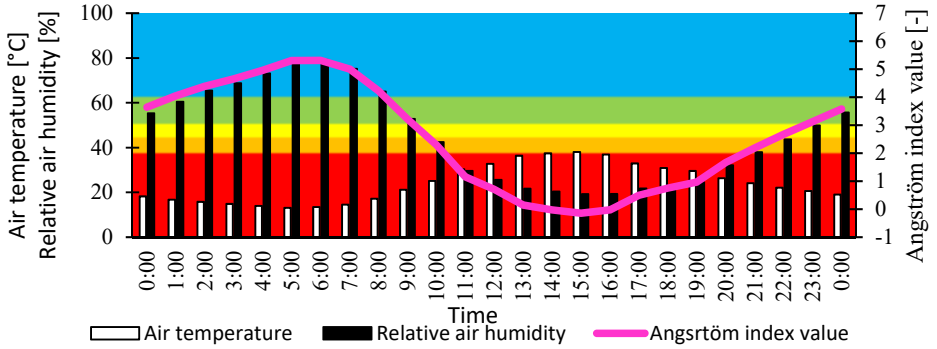


Fig. 4. a) Daily course of air temperature, relative air humidity, and Angström index values during 25 July 2022 at the forest stand edge. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

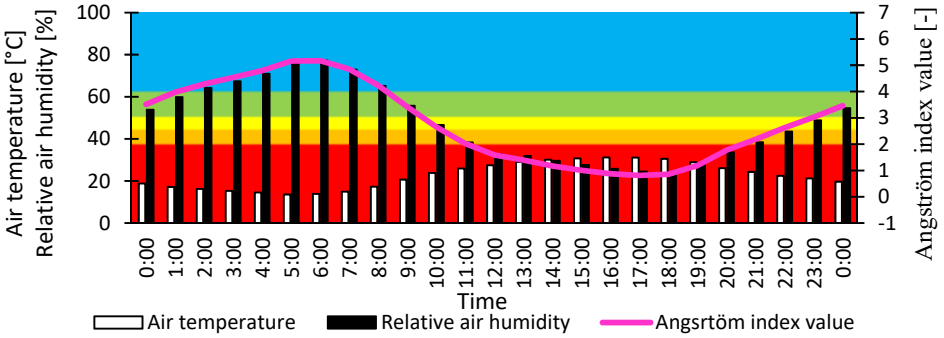


Fig. 4. b) Daily course of air temperature, relative air humidity and Angström index values during 25 July 2022 at the forest stand interior. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

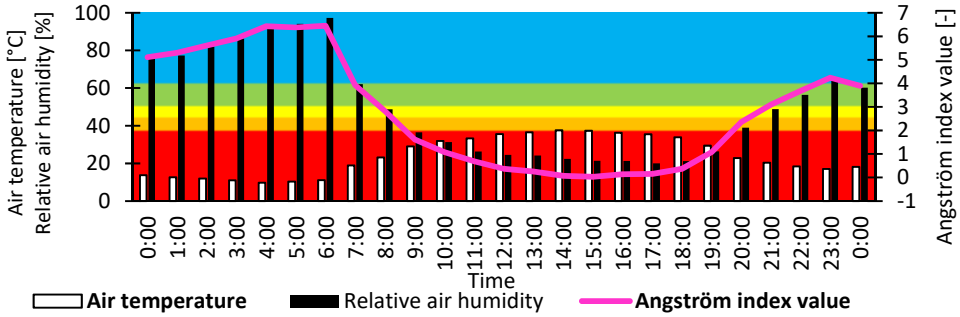


Fig. 4. c) Daily course of air temperature, relative air humidity and Angström index values during 25 July 2022 in the open area. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

The highest air temperature values achieved during the day were between 2 PM and 3 PM. The microclimate of the beech stands influences the Angström index danger class – the highest the Angström index danger class was reached by the open area as early as 9 AM, by the forest stand edge only at 11 AM, and by the forest stand interior only at 12 AM. The trend of the Angström index value in the early morning and evening hours is almost identical to relative humidity during the day. The most extreme Angström index values were reached at 3 PM on an open area and the forest stand edge at 5 PM in and forest stand interior.

During field measurements on **23 July 2017, the highest moisture content of fine fuel** from all measurements was measured **at the forest stand edge, up to 74.0%** (Table 9).

When comparing the forest stand edge (Fig. 5. a), the forest stand interior (Fig. 5. b), and the open area (Fig. 5. c) on 23.7.2017, we see the following facts. The weather was

conditioned by three days of the synoptic situation South-West cyclonic of the 1st type (SWc1), associated with the flow of relatively warm and humid air from the western Mediterranean. The synoptic situation brought abundant precipitation to the study area. The cloudy weather determined small daily amplitudes of air temperature and humidity.

Day 23 July 2017 was a cooler summer day with high daytime relative humidity and maximum daytime air temperature values between 22 and 27 °C. During this day relative humidity was highest at 1 PM in all cases (this is due to a short rain precipitation). The microclimate of the forest stand edge and forest stand interior retains humidity due to its canopy cover and thus prevents a rapid drop in relative humidity. The highest Angström index danger class was level 2 at 10 AM and 6 PM in all areas, and an open area at 3 PM. The daily course of the Angström index value was almost the same in all the areas

Table 9. Measured and calculated values at 2 PM on 23.7.2017.

	Moisture content of fine fuel (%)	Air temperature (°C)	Relative air humidity (%)	Angström index value (–)
Forest stand edge	74.0	22.37	100.00	5.46
Forest stand interior	89.8	21.77	100.00	5.52
Open area	–	26.09	85.94	4.50

*All values in the table are measured at 2 PM

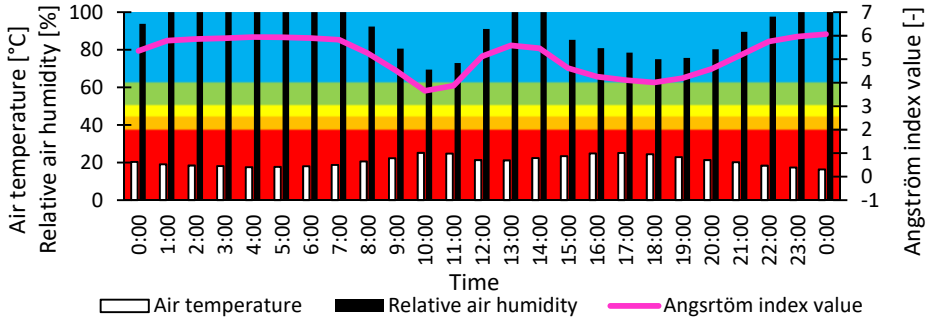


Fig. 5. a) Daily course of air temperature, relative air humidity and Angström index values during 23 July 2017 at the forest stand edge. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

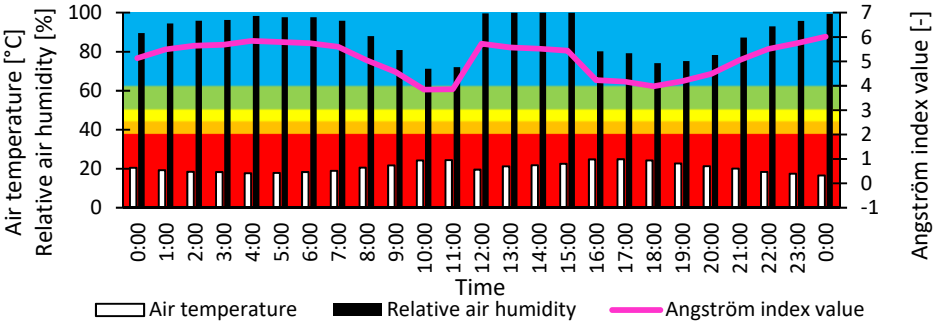


Fig. 5. b) Daily course of air temperature, relative air humidity and Angström index values during 23 July 2017 at the forest stand interior. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

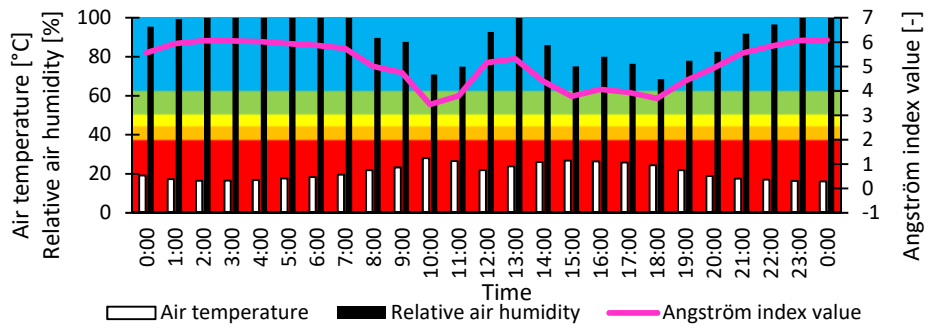


Fig. 5. c) Daily course of air temperature, relative air humidity and Angström index values during 23 July 2017 in the open area. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

compared (more variable in the forest stand edge and open area and more stable in the forest stand interior). None of the areas was at Angström index danger class 3 or above (relative humidity was high and air temperature values were not as high as 25.7.2022).

During field measurements on **12 August 2022, the lowest fine fuel moisture content** of all measurements was measured **in the forest stand interior, only 7.4%** (Table 10).

The weather on this day was influenced by a four-day synoptic period, Northeast anticyclonic type (NEa). The synoptic situation brought warm and dry continental air to the study area, with lightly cloudiness and without precipitation. The lightly cloudy and sunny weather conditioned the high daily amplitudes of temperature and humidity.

When comparing the forest stand interior (Fig. 6. a), forest stand edge (Fig. 6. b), and an open area (Fig. 6. c) on 12.8.2022,

Table 10. Measured and calculated values at 2 PM on 12.8.2022.

	Moisture content of fine fuel (%)	Air temperature (°C)	Relative air humidity (%)	Angström index value (–)
Forest stand interior	7.4	24.65	42.93	2.38
Forest stand edge	2.9	28.51	34.81	1.58
Open area	–	29.24	37.22	1.70

*All values in the table are measured at 2 PM

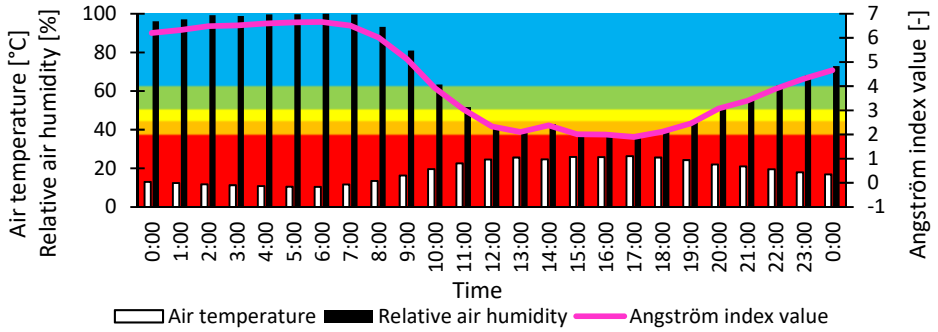


Fig. 6. a) Daily course of air temperature, relative air humidity and Angström index values during 12 August 2022 at the forest stand interior. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

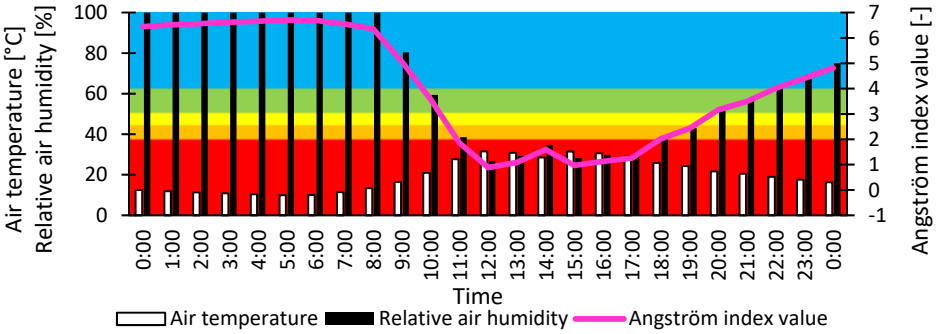


Fig. 6. b) Daily course of air temperature, relative air humidity and Angström index values during 12 August 2022 at the forest stand edge. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

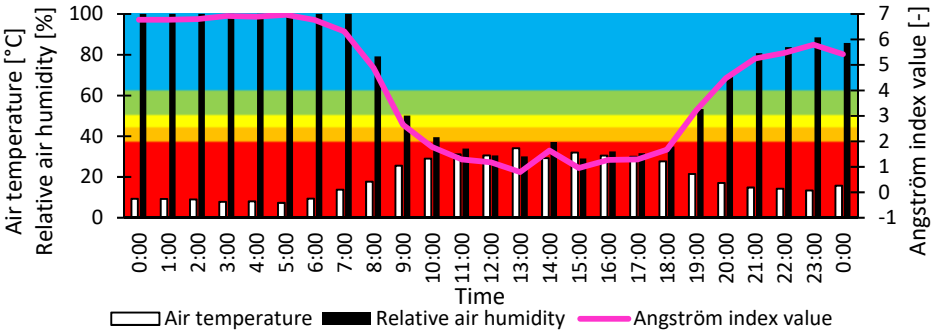


Fig. 6. c) Daily course of air temperature, relative air humidity and Angström index values during 12 August 2022 in the open area. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

we see the following facts. Day 12 August 2022 was a relatively warm summer day with low relative humidity and high air temperature values (but not as high as 25.7.2022). During this day the relative humidity was 100% in an open area by 6 AM and up to 8 AM on the forest stand edge, the forest stand interior was protected by canopy and therefore the relative humidity value was below 100% and only rose to 100% at 6 AM. On the contrary, during the day the lowest relative humidity values are reached in an open area and the canopy cover prevents the relative humidity in the forest stand interior from decreasing (e.g. the difference in relative humidity at 12 AM between the forest stand interior and the forest stand edge is up to 15%). The trend of the daily air temperature is inversely proportional to the daily relative humidity. The highest air temperature values achieved

Table 11. Measured and calculated values at 2 PM on 20.9.2017.

	Moisture content of fine fuel (%)	Air temperature (°C)	Relative air humidity (%)	Angström index value (–)
Forest stand interior	90.1	14.44	87.78	5.64
Forest stand edge	59.6	14.25	95.46	6.05
Open area	–	15.53	84.00	5.34

*All values in the table are measured at 2 PM

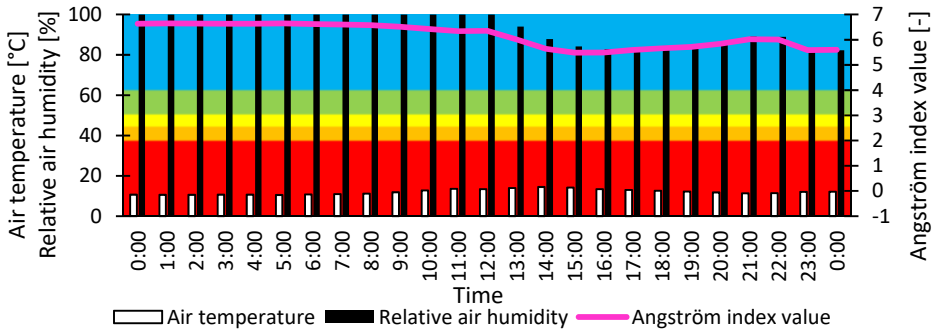


Fig. 7. a) Daily course of air temperature, relative air humidity and Angström index values during 20 September 2017 at the forest stand interior. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

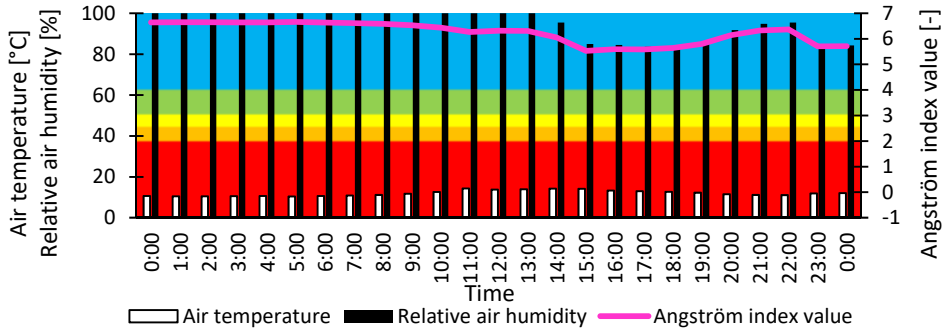


Fig. 7. b) Daily course of air temperature, relative air humidity and Angström index values during 20 September 2017 at the forest stand edge. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

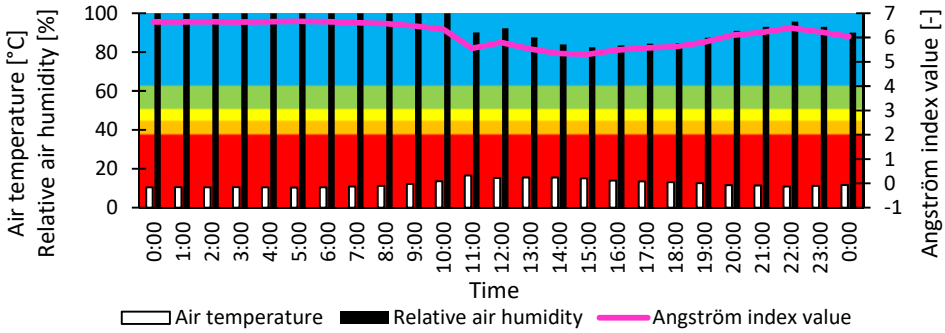


Fig. 7. c) Daily course of air temperature, relative air humidity and Angström index values during 20 September 2017 in the open area. Legend: Angström index danger class (blue part – first class, green part – second class, yellow part – third class, orange part – fourth class and red part – fifth class)

during the day were at 1 PM in an open area, at 12 AM in the forest stand edge and 3 PM in the forest stand interior. The trend of the Angström index value in the early morning is identical in all areas. Angström index values were lowest in the forest stand edge, slightly higher in an open area and highest in the forest stand interior. Angström index danger class 5 in an open area from 10 AM to 6 PM and in the forest stand edge from 11 AM to 5 PM In the forest stand interior, the highest Angström index danger class 5 was reached only between 4 PM and 5 PM. In the evening, the Angström index values rose faster in the open area and on the forest stand edge compared to the forest stand interior.

During field measurements on **20 September 2017, the highest fine fuel moisture content** of all measurements was measured **in the forest stand interior, up to 90.1%** (Table 11).

The weather on this day was influenced by a Northeast cyclonic type (NEc) synoptic situation, which came after a two-day-long precipitation-rich travelling through (Bp). The synoptic situation brought the study area cooler and humid air with high cloud cover. The cloudy weather conditioned small daily amplitudes of air temperature and humidity.

When comparing the forest stand interior (Fig. 7. a), forest stand edge (Fig. 7. b) and open area (Fig. 7. c) on 20.9.2017, we see the following facts. Day 20 September 2017 was an average autumn day with high relative humidity and air temperature up to 17 °C. During this day relative humidity was 100% in all areas by 10 AM, longer only in the forest stand edge and in the forest stand interior. Relative humidity values declined fastest in the open area and reached a minimum value of 83%. The daily temperature rose slightly during the day and reached a maximum of 16.52 °C in an open area. The highest air temperature values reached during the day were at 11 AM in an open area and the forest stand edge and at 2 PM in the forest stand interior. The trend of the Angström index value is very similar throughout the day without significant differences and did not reach a value lower than 5 in any of the areas (none of the areas compared had an Angström index danger class higher than 1).

4 DISCUSSION

Statistical analysis of the measured data agrees with the hypotheses. Differences in the measured values of the variables considered, i.e. air temperature, relative humidity and fine fuel moisture content, can be observed at the forest stand edge and forest stand interior. Compared to the forest stand edge, the interior is characterised by a physically but also chemically different microclimate. The differences are mainly due to the different position of the stands. The different position of the stands under consideration is manifested by different vertical and horizontal coupling. The denser canopy cover and its higher covering capacity absorbs solar radiation penetrating the interior of the stand and thus prevent temperature increases. As Vanwalleghem and Meentemeyer (2009) note denser stands are associated with lower daytime temperatures. Probable causes are higher light shading and secondary effects such as lower wind velocities (Matejka et al., 2004). These facts have been found not only in forest stands but also in apple orchards (Středa et al., 2011) and also in dense stands of maise (Rožnovský et al., 2002). This fact, in the case of investigating and comparing experimental plots on the forest edge and the forest interior, has a significant influence and significantly affects the moisture content of the fine fuel (Matthews, 2010).

Another factor that differentially affects the microclimate of the plots under consideration is air flow and its velocity, which, together with air temperature, contributes to the drying of the fine fuel (Střelcová et al., 2003; Tužinský et al., 2003). The moisture content of fine fuels that is the limiting parameter in the spread of terrestrial forest fires (Stolina et al., 1985; Veľas et al., 2021). If the fuel is largely moist it may even stop the spread of the fire (Chatto and Tolhurst, 1997). The uppermost layer of the fallout and its moisture content measured during this experiment plays the most important role. It largely contributes to the development of the fire in the initiation phase (Vida and Škvarenina, 2010). The fine fuel of beech stands, composed of leaves, has a large surface area to particle volume ratio and comes into contact with the vent and therefore dries out faster than other fuels (Tamai and Goto, 2003). The main factors influencing the desiccation of fine litter are air temperature and relative humidity (Schaap and Bouten, 1997).

Measured meteorological parameters characterise and influence the evolution in different parts of the microclimate of the observed areas. Even a small change in the meteorological conditions is quickly reflected in the moisture content of the fine fuel. This means that the fine fuel adapts its moisture content to its surroundings (Gibos, 2010). In Russian literature, analyses have been conducted where the measured values of fine fuel moisture content were classified into danger classes according to Nesterov's index. For instance, according to Gusev (2015), it's possible to determine the danger class based on intervals created from the values of fine fuel moisture content. This author classifies fuel moisture below 18% as a high level of danger and values below 11% as a very high danger of forest fires. Despite the fact that they determined the danger class based on a different type of index, our results are largely the same. From the selected four observation dates at the forest stand edge and forest stand interior, the danger class was the same in 6 out of 8 cases. The measured results show that during all the selected dates, the moisture content of fine litter was measured to be lower at the edge of the forest stand compared to the forest stand interior. The forest stand edge is subject to greater wind action. The wind causes the forest edge to dry out more rapidly from the open forest stand wall, causing the fine fuel to dry out more quickly. In addition to the wind, the decrease in the moisture content of fine fuel is also related to the changing relative humidity of the air. The same findings are reported in a study investigating the effect of weather on the moisture content of beech fine fuel (Vida and Škvarenina, 2010). Among all fine fuel moisture measurements, the average difference between the forest edge and the forest interior was 7.9%. The largest differences in measured values of fine fuel moisture content occurred on August 2, 2018. The forest stand interior had 35.7% greater fine fuel moisture content than the forest stand edge on this day.

Compared to the average value of the difference in fine fuel moisture content between the forest stand edge and forest stand interior, this was a significantly above-average difference. In contrast, the smallest difference and nearly equal values of fine fuel moisture content were on 19 September 2018. On this day, the forest stand interior had only 0.1% more fine fuel moisture content than the forest stand edge. The lowest moisture content of fine fuel was recorded on July 25, 2022, during the Wal - Western summer-type anticyclonic situation. Kveták (1986) associates this situation with 'desiccative weather,' which denotes extremely dry conditions characterised by low humidity levels and a lack of moisture in the air. On the other hand, the highest value of fine fuel moisture content was recorded on September 20, 2017, during the Northeast cyclonic type (NEc) synoptic situation. Mészáros et al. (2022) assess this synoptic situation as the most precipitation-rich for the windward slopes of the Western Carpathians.

Climate change processes are occurring faster in the boreal

and temperate territories (Melo et al., 2013). Although global warming increases the length of the vegetation season (Gordeev and Pyzhev, 2023; Ziernicka-Wojtaszek, 2019) it also poses a threat of increased frequency and severity of drought and forest fires (Jokanović et al., 2020; Shvidenko et al., 2023; Živanović et al., 2020), increased pest infestations (Ivantsova et al., 2019; Mezei et al., 2017) and shortening of the winter period of snow water accumulation (Bartík et al., 2014, 2016; Jeníček et al., 2017). Based on the above, we understand the issue of forest fires in the context of environmental changes taking place in the landscape under conditions of emerging climate change.

5 CONCLUSION

The moisture content of dead fuels is an important factor that determines many aspects of forest fire behaviour. Understanding fuel moisture relationships with weather, fuels, and stand microclimate is useful for fire managers and models fuel moisture is an integral part of fire risk predictions as well as fire behaviour models.

The moisture of fine fuel organic matter, in this case, moisture of dead beech leaves of the top litter layer, we measured with a special field moisture meter ME 2000, TH Fine Fuel Moisture Meter from Wiltronics Ltd. The Meter measures the electrical resistance of a fine fuel sample and converts this to a moisture content. This meter was developed specifically for the measurement of vegetation fuels. Relationships between fuel moisture content and electrical resistance were established for beech leaves in the first year (through the summer) after their fall off. Two linear relationships were found, one for moisture contents less than 9% oven-dry weight, and the other for moisture contents between 9 and 200% oven-dry weight.

To demonstrate the objectives above and to explain the findings, four days based on the moisture content of fine fuel was selected as the main assessment criterion in this work. These were the days with the lowest but also the highest values of fine fuel moisture content for both experimental forest stands selected in the paper. The selected most extreme days were compared between stand locations and the open area. The study demonstrates many predicted facts such as higher air temperature values, fire danger degree, and conversely lower values of relative humidity and fine fuel moisture content at the stand edge compared to the stand interior. Use statistical methods to determine the degree of interdependence of individual variables. Our results show that edge beech stands are significantly more susceptible to fires, lower air humidity and fine fuel moisture content, and higher air temperatures than forest interiors.

We have found that our applied Angström Fire Index responds operationally to rapid changes in stand microclimate (changes in air temperature and air humidity) caused by changes in cloud cover and crown canopy. The index is non-cumulative, is based solely on daily weather, and reacts quickly to weather fluctuations. We found that its values are highly correlated with litter moisture (fine fuel moisture content).

In the future, we will expand our research on the influence of meteorological factors on the moisture content of fine forest fuels to other woody species in larger research areas.

Acknowledgment. This publication was funded by FOMON project ITMS2014+313011V465 from EFRD and by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport in Slovakia by project VEGA 1/0443/23, and the projects of the Slovak Research and Development Agency Nos APVV-19-0340; APVV-18-0347; APVV-19-0183; APVV-21-0224, APVV-19-0612, APVV-18-0390.

REFERENCES

Adámek, M., Bobek, P., Hadincová, V., Wild, J., Kopecký, M., 2015. Forest fires within a temperate landscape: a decadal and millennial perspective from a sandstone region in Central Europe. Forest Ecology and Management, 336, 81–90.

Aussenac, G., 2000. Interactions between forest stands and microclimate: ecophysiological aspects and consequences for silviculture. Annals of Forest Science, 57, 3, 287–301.

Bartík, M., Jančo, M., Střelcová, K., Škvareninová, J., Škvarenina, J., Mikloš, M., Vido, J., Dagsson Waldhauserová, P., 2016. Rainfall interception in a disturbed montane spruce (*Picea abies*) stand in the West Tatra Mountains. Biologia, 71, 9, 1002–1008.

Bartík, M., Sitko, R., Oreňák, M., Slovik, J., Škvarenina, J., 2014. Snow accumulation and ablation in disturbed mountain spruce forest in West Tatra Mts. Biologia, 69, 11, 1492–1501.

Bradshaw, R. H., Lindbladh, M., Hannon, G.E., 2010. The role of fire in southern Scandinavian forests during the late Holocene. International Journal of Wildland Fire, 19, 8, 1040–1049.

Brown, T.P., Hoylman, Z.H., Conrad, E., Holden, Z., Jencso, K., Jolly, W.M., 2022. Decoupling between soil moisture and biomass drives seasonal variations in live fuel moisture across co-occurring plant functional types. Fire Ecology, 18, 1, 1–14.

Camia, A., Libertá, G., San-Miguel-Ayanz, J., 2017. Modeling the impacts of climate change on forest fire danger in Europe. Joint Research Centre (JRC) Technical Reports, 1, 22.

Carter, V.A., Moravcová, A., Chiverrell, R.C., Clear, J.L., Finsinger, W., Dreslerová, D., Halsall, K., Kuneš, P., 2018. Holocene-scale fire dynamics of central European temperate spruce-beech forests. Quaternary Science Reviews, 191, 15–30.

Cerdà, A., Ebel, B.A., Serpa, D., Lichner, Ľ., 2022. Introduction to the special issue on fire impacts on hydrological processes. Journal of Hydrology and Hydromechanics, 70, 4, 385–387.

Chatto, K., Tolhurst, K.G., 1997. Development and testing of the Wiltronics TH moisture meter. Research Report 46. Department of Natural Resources and Environment, Fire Management Branch, Australia, Victoria. 40 p.

Davis, K.T., Dobrowski, S.Z., Holden, Z.A., Higuera, P.E., Abatzoglou, J.T., 2019. Microclimatic buffering in forests of the future: the role of local water balance. Ecography, 42, 1–11.

Dohnal, M., Votrubová, J., Tesar, M., 2014. Rainfall interception and spatial variability of throughfall in spruce stand. Journal of Hydrology and Hydromechanics, 62, 4, 277.

Ellenberg, H., 1996. Vegetation Mitteleuropas mit den Alpen. 5th Ed. Eugen Ulmer, Stuttgart.

Fajković, H., Ivanić, M., Nemet, I., Rončević, S., Kampić, Š., Vazdar, D.L., 2022. Heat-induced changes in soil properties: fires as cause for remobilisation of chemical elements. Journal of Hydrology and Hydromechanics, 70, 4, 421–431.

Geiger, R., Aron, R.H., Todhunter, P., 1995. The Climate near the Ground. Vieweg & Sohn, Braunschweig / Wiesbaden. 528 p.

Gessler, A., Jung, K., Gasche, R., Papen, H., Heidenfelder, A., Börner, E., Metzler, B., Augustin, S., Hildebrand, E., Rennenberg, H., 2005. Climate and forest management influence nitrogen balance of European beech forests: microbial N transformations and inorganic N net uptake capacity of mycorrhizal roots. European Journal of Forest Research, 124, 95–111.

Gibos, K.E., 2010. Effect of slope and aspect on litter layer moisture content of lodgepole pine stands in the eastern slopes of the Rocky Mountains of Alberta. MSc Thesis. University of Toronto.

Gömöry, D., Kukla, J., Schieber, B., 2011. Taxonomy, phylogeny and distribution of beech in Europe and Slovakia. In: Barana, M., Kulfan, J., Bublinec, E. (Eds.): Beech and Beech Ecosystems of Slovakia. Veda, Bratislava, pp. 19–36. (In Slovak.)

Gordeev, R.V., Pyzhev, A.I., 2023. Impact of trade restrictions on the Russian forest industry: Evidence from Siberian timber producers. Forests, 14, 12, 245.

Gusev, V.G., 2015. O metodakh izmereniya vlazhnosti lesnykh goryuchikh materialov v zavisimosti ot meteorologicheskikh usloviy. Izvestiya Sankt-Peterburgskoy lesotekhnicheskoy akademii, 212, 185–197. (In Russian.)

Hinkle, D. E., Wiersma, W., Jurs, S.G., 1998. Applied Statistics for the Behavioral Sciences. 4th Ed. Houghton Mifflin. 749 p.

Hofmeister, J., Hošek, J., Brabec, M., Střalková, R., Mýlová, P., Bouda, M., Svoboda, M., 2019. Microclimate edge effect in small fragments of temperate forests in the context of climate change. Forest Ecology and Management, 448, 48–56.

Hološ, S., Šurda, P., Lichner, Ľ., Zvala, A., Píš, V., 2022. Fire-induced changes in soil properties depend on age and type of forests. Journal of Hydrology and Hydromechanics, 70, 4, 442–449.

Holsten, A., Dominic, A.R., Costa, L., Kropp, J.P., 2013. Evaluation of the performance of meteorological forest fire indices for German federal states. Forest Ecology and Management, 287, 123–131.

Ivantsova, E.D., Pyzhev, A.I., Zander, E.V., 2019. Economic consequences of insect pests outbreaks in boreal forests: A literature review. J. Sib. Fed. Univ. Humanit. Soc. Sci. 2019, 4, 627–642.

Jeníček, M., Hotový, O., Matějka, O., 2017. Snow accumulation and ablation in different canopy structures at a plot scale: using degree-day approach and measured shortwave radiation. Acta Universitatis Carolinae Geographica, 52, 61–72.

Jokanović, V.N., Vulević, T., Lazarević, K., 2020. Risk assessment of forest decline by application of geostatistics and multi-criteria analysis. Journal of Hydrology and Hydromechanics, 68, 3, 285–292.

Kane, J.M., 2021. Stand conditions alter seasonal microclimate and dead fuel moisture in a Northwestern California oak woodland. Agricultural and Forest Meteorology, 308, 108602.

Klamerus-Iwan, A., Błońska, E., 2017. Seasonal variability of interception and water wettability of common oak leaves. Annals of Forest Research, 63–73.

Kofroňová, J., Šípek, V., Hnilica, J., Vlček, L., Tesař, M., 2021. Canopy interception estimates in a Norway spruce forest and their importance for hydrological modelling. Hydrological Sciences Journal, 66, 7, 1233–1247.

Korená Hillayová, M., Holécy, J., Korísteková, K., Bakšová, M., Ostrihoň, M., Škvarenina, J., 2023. Ongoing climatic change increases the risk of wildfires. Case study: Carpathian spruce forests. Journal of Environmental Management, 337, 117620.

Korísteková, K., 2018. Analysis of meteorological conditions of forest and landscape fires in Slovakia. PhD Thesis. Faculty of Wood Sciences and Technology, Technical University in Zvolen, Zvolen. 106 p. (In Slovak.)

Kveták, S., 1986. Desiccative and sultry weather in Hurbanovo. Geografický časopis, 38, 1, 24–42. (In Slovak.)

Leštianska, A., Fleischer, P., Merganičová, K., Střelcová, K., 2020. Interspecific variation in growth and tree water status of conifers under water-limited conditions. Journal of Hydrology and Hydromechanics, 68, 4, 368–381.

Lindner, M., Fitzgerald, J.B., Zimmermann, N.E., Reyer, C., Delzon, S., van der Maaten, E, Schelhaas, M.J., Lasch, P., Eggers, J., van der Maaten-Theunissen, M., Suckow, F., Psomas, A., Poulter, B., Hanewinkel, M., 2014. Climate change and European forests: what do we know, what are the uncertainties, and what are the implications for forest management? Journal of Environmental Management, 146, 69–83.

Lukáčik, I., Čížová, M., Ježovič, V, Škvareninová, J., 2005. Arboretum Borova hora 1965–2005. Technical University in Zvolen. 91 p. ISBN:80-228-1479-2. (In Slovak.)

Lukasová, V., Bucha, T., Škvareninová, J., Škvarenina, J., 2019. Validation and application of European beech phenological metrics derived from MODIS data along an altitudinal gradient. Forests, 10, 1, 60.

Lukasová, V., Škvareninová, J., Bičárová, S., Sitárová, Z., Hlavatá, H., Borsányi, P., Škvarenina, J., 2021. Regional and altitudinal aspects in summer heatwave intensification in the Western Carpathians. Theoretical and Applied Climatology, 146, 1111–1125.

Lukasová, V., Vido, J., Škvareninová, J., Bičárová, S., Hlavatá, H., Borsányi, P., Škvarenina, J., 2020. Autumn phenological response of European Beech to summer drought and heat. Water, 12, 9, 2610.

Matejka, F., Janous, D., Hurtalova, T., Roznovsky, J., 2004. Effects of thinning on microclimate of a young spruce forest. Ekologia Bratislava, 23, 30–8.

Matthews, S., 2010. Effect of drying temperature on fuel moisture content measurements. International Journal of Wildland Fire, 19, 800–802.

Melo, M., Lapin, M., Kapolková, H., Pecho, J., Kružicová, A., 2013. Climate trends in the Slovak part of the Carpathians. In: Kozak, J., Ostapowicz, K., Bytnerowicz, A., Wyżga, B. (Eds): The Carpathians: Integrating Nature and Society Towards Sustainability. Springer-Verlag, Berlin Heidelberg, pp. 131–150.

Mészáros, J., Halaj, M., Polčák, N., Onderka, M., 2022. Mean annual totals of precipitation during the period 1991–2015 with respect to cyclonic situations in Slovakia. Időjárás – Quarterly Journal of the Hungarian Meteorological Service, 126, 2, 267–284.

Mezei, P., Blaženec, M., Grodzki, W., Škvarenina, J., Jakuš, R., 2017. Influence of different forest protection strategies on spruce tree mortality during a bark beetle outbreak. Annals of Forest Science, 74, 4, 1–12.

Mráček, Z., 1989. Beech Silviculture (Pěstování buku). SZN, Prague, 224 p. (In Czech.)

Nalevankova, P., Ježík, M., Sitkova, Z., Vido, J., Leštianska, A., Střelcová, K., 2018. Drought and irrigation affect transpiration rate and morning tree water status of a mature European beech (*Fagus sylvatica* L.) forest in Central Europe. Ecohydrology, 11, 6, e1958.

Nečas, P., Kollár, D., 2018. The EU security strategy and its importance for the sectoral safety. In: Baculáková, K., Čech, L. (Eds.): Proc. 19th Int. Sci. Conf. International relations 2018: current issues of world economy and politics. Ekonóm, Bratislava, pp. 519–529.

Ostrihoň, M., Škvarenina, J., Korísteková, K., 2021. Effect of selected meteorological factors on forest litter moisture content and fire danger degree. Delta, 15, 1, 58–70.

Packham, J.R., Thomas, P.A., Atkinson, M.D., Degen, T., 2012. Biological flora of the British Isles: *Fagus sylvatica*. Journal Ecology, 100, 1557–1608.

Peterken, G.F., Mountford, E.P., 1996. Effects of drought on beech in Lady Park Wood, an unmanaged mixed deciduous woodland. Forestry, 69, 2, 125–136.

Petrík, M., Havlíček, V., Uhrecký, I., 1986. Forest Bioclimatology. Príroda, Bratislava, 352 p. (In Slovak and Czech.)

Rajczak, J., Pall, P., Schär, C., 2013. Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region. Journal of Geophysical Research: Atmospheres, 118, 9, 3610–3626.

Rožnovský, J., Chalupníková, B., Hurtalová, T., Matejka, F., 2002. Stratification of air temperature and air humidity in maise stand. Contributions to Geophysics and Geodesy, 32, 3.

Rožnovský, J., Litschmann, T., Středová, H., Středa, T., Salaš, P., Horká, M., 2017. Microclimate evaluation of the Hradec Králové city using HUMIDEX. Contributions to Geophysics and Geodesy, 47, 3, 231–246.

Schaap, M.G., Bouten, W., 1997. Forest floor evaporation in a dense Douglas fir stand. Journal of Hydrology, 201, 367–383.

Shvidenko, A., Mukhortova, L., Kapitsa, E., Kraxner, F., See, L., Pyzhev, A., Gordeev, R., Fedorov, S., Korotkov, V., Bartalev, S., Schepaschenko, D., 2023. A modelling system for dead wood assessment in the forests of Northern Eurasia. Forests, 14, 45.

Šípek, V., Hnilica, J., Vlček, L., Hnilicová, S., Tesař, M., 2020. Influence of vegetation type and soil properties on soil water dynamics in the Šumava Mountains (Southern Bohemia). Journal of Hydrology, 582, 124285.

Škvarenina, J., Mindáš, J., Holécy, J., Tuček, J., 2004a. An analysis of the meteorological conditions during the two largest forest fire events in the Slovak Paradise National Park. Meteorological Journal, 7, 167–171.

Škvarenina, J., Križová, E., Tomlain, J.N., 2004b. Impact of the climate change on the water balance of altitudinal vegetation stages in Slovakia. Ekologia-Bratislava, 23, 13–29.

Škvareninová, J., 2009. The dynamics of vegetative phenophases observed at the autochton population of Norway spruce (*Picea abies* [L.] Karst.) in Slovakia. Central European Forestry Journal, 55, 1, 13–27.

Škvareninová, J., 2010. The course of spring phenological stages observed for the generative organs of Norway spruce (*Picea abies* [L.] Karst.) from its autochthonous populations in Slovakia. Central European Forestry Journal, 56, 4, 369–381.

Šraj, M., Brilly, M., Mikoš, M., 2008. Rainfall interception by two deciduous Mediterranean forests of contrasting stature in Slovenia. Agricultural and Forest Meteorology, 148, 121–134.

Stanová, V., Valachovič, M., 2002. Catalog of Slovak biotops. DAPHNE – Institute of Applied Ecology, Bratislava, 225 p. (In Slovak.)

Stašiov, S., Michalková, E., Lukáčik, I., Čiliak, M., 2017. Harvestmen (Opiliones) communities in an arboretum: Influence of tree species. Biologia, 72, 2, 184–193.

Stolina, M., Čapek, M., Gogola, E., Hešková, A., Kodrík, J., Křístek, J., Vaník, K., 1985. Forest Protection. Príroda, Bratislava, 473 p. (In Slovak.)

Středa, T., Středová, H., Rožnovský, J., 2011. Orchards microclimatic specifics. In: Bioclimate: Source and Limit of Social Development. Nitra, pp. 132–133.

Střelcová, K., Kurjak, D., Leštianska, A., Kovalčíková, D., Ditmarová, Ľ., Škvarenina, J., Ahmed, Y.A.R., 2013. Differences in transpiration of Norway spruce drought-stressed trees and trees well supplied with water. Biologia, 68, 1118–1122.

Střelcová, K., Minďáš, J., Škvarenina, J., 2006. Influence of tree transpiration on mass water balance of mixed mountain forests of the West Carpathians. Biologia, 61, 19, 305–310.

Střelcová, K., Minďáš, J., Škvarenina, J., Tužinský, L., 2003. Study of mountain microclimate and bioclimate forest plants – I. Vertical variability. In: Rožnovský, J., Litschmann, T. (Eds.): Proc. Seminar Microclimate of Stands. Brno, pp. 58–68. (In Slovak.)

Střelcová, K., Škvarenina, J., Leštianska, A., 2018. Biometeorological stations of the Department of Natural Environment. Technical University of Zvolen, Zvolen. www.tuzvo.sk (In Slovak.)

Tamai, K., Goto, Y., 2003. Fuel moisture estimation model for a deciduous secondary forest in Japan - A comparison of parameters under the different canopy. In: Proc. 5th Symposium on Fire and Forest Meteorology and the 2nd International Wildland Fire Ecology and Fire Management Congress, Orlando.

Tarábek, K., 1980. Climatogeographical types. Map No. 43. In: Mazúr, E., Jakál, J., (Eds.): Atlas SSR. Veda, Bratislava, p. 64.

Tuček J., Majlingová, A., 2009. Forest fire vulnerability analysis. In: Střelcová, K., et al. (Eds.): Bioclimatology and Natural Hazards. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-8876-6_19

Tuff, K.T., Tuff, T., Davies, K.F., 2016. A framework for integrating thermal biology into fragmentation research. Ecology Letters, 19, 4, 361–374.

Tužinský, L., Střelcová, K., Škvarenia, J., Tužinský, E., 2003. Study of the microclimate and bioclimate of mountain forest stands – II. The influence of plant density on the microclimate. In: Rožnovský, J., Litschmann, T. (Eds.): Proc. Seminar Microclimate of Stands. Brno, pp. 203–206. (In Slovak.)

Vanwalleghem, T., Meentemeyer, R.K., 2009. Predicting forest microclimate in heterogeneous landscapes. Ecosystems, 12, 1158–1172.

Veľas, R., Majlingová, M., Kačíková, D., 2021. Influence of changes in meteorological conditions on the moisture content of dead fine fuel in the mixed pine forest. Kosice Security Revue, 11, 1, 106–119.

Vida, T., Škvarenina, J., 2010. Influence of weather on litter moisture in selected forest stands of Javorníky Mts. and Slovenský raj National Park. In: Proc. Int. Conf. Bioklima. Prague. (In Slovak.)

Vido, J., Tadesse, T., Šustek, Z., Kandrík, R., Hanzelová, M., Škvarenina, J., Škvareninová, J., Hayes, M., 2015. Drought occurrence in central european mountainous region (Tatra National Park, Slovakia) within the period 1961–2010. Advances in Meteorology, 2015, 248728. https://doi.org/10.1155/2015/248728

Watts, A.C., Kobziar, L.N., 2015. Hydrology and fire regulate edge influence on microclimate in wetland forest patches. Freshwater Science, 34, 4, 1383–1393.

Zabret, K., Lebar, K., Šraj, M., 2023. Temporal response of urban soil water content in relation to the rainfall and throughfall dynamics in the open and below the trees. Journal of Hydrology and Hydromechanics, 71, 2, 210–220.

Ziernicka-Wojtaszek, A., 2019. Pluviothermal regionalisation of Poland in light of present-day climate change. Polish Journal of Environmental Studies, 29, 1, 989–996.

Ziernicka-Wojtaszek, A., 2021. Summer drought in 2019 on Polish territory – A case study. Atmosphere, 12, 11, 1475.

Živanović, S., Ivanović, R., Nikolić, M., Đokić, M., Tošić, I., 2020. Influence of air temperature and precipitation on the risk of forest fires in Serbia. Meteorology and Atmospheric Physics, 132, 869–883.

Received 19 January 2024
Accepted 20 February 2024