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Variability of surface temperatures in various development stages of mountain forest (Belianske Tatras)

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Abstract. Our research was conducted over a period of two years, with a focus on microclimate conditions of the dominant forest stand in the Tatra Mountains. Several types of forest stands have been studied, including young mixed forest - mountain alluvial forest, mixed forest, young spruce forest, old natural spruce stands, and calamity areas (mixed forest and spruce forest) left for natural development. The primary aim of this study is to analyse the temperature differences of the surface temperature in individual forest stands as well as observe daily and seasonal changes, including humidity. We continuously monitored surface temperature and surface humidity in selected forest stands with an infrared camera from October 2021 to October 2023. We also focused on increases or decreases in surface temperature over time. We have examined the influence of local climate characteristics and the type of forest stand, considering naturality or management practices. Results confirmed higher surface temperature variations in young and calamity forests, than in well-preserved forests. In addition, coniferous forest (Pod Muráňom) had higher surface moisture levels conferring the ability to dampen temperature variabilities more than broadleaf or mixed forests. Coniferous forest maintains warmer conditions in winter and cooler conditions in summer. These results are especially important when contemplating future climate change and adaptation mitigation strategies implemented by forest management in protected areas.

Key words: microclimate condition, mountain forest, surface temperature, surface humidity, seasonal changes, Belianske Tatras

Introduction

A map of the world's mountain ranges, defined by elevation, slope and relative relief, shows that 24% (35,813,437 km^2) of the earth's surface is covered by mountains. The map was then overlaid with a global forest database. The result was that mountain forests alone, constitute 28% (5,179,248 km^2) of the world's forests. The results demonstrate that mountain forests cover a significant portion of the earth's surface (Kapos *et al.* 2000; Price 2005). As we already know, mountain forests have been negatively impacted by human activities for a long time (Minďáš *et al.* 2011). Air pollution and climate change are atmospheric forces that influence and affect mountain forests (Innes 2000). However, past deforestation of woodlands for grazing or industrial purposes has also had a significant impact. With the subsequent industialisation of the 1970s, overland and long-distance transport of pollutants expanded, affecting high mountain areas the most, whether through the deposition of acidic substances or photo-oxidants (Minďáš *et al.* 2011). Nowadays, the worst pollutant is proving to be greenhouse gases in the atmosphere exacerbated by global warming (Shugart 1984, 1993; Smith and Shugart 1993). With the increasing intensity of heat waves caused by climate change and global warming, other negative phenomena have become more prevalent. The rising heat will affect the individual functions of trees. At the leaf level, as photosynthesis decreases, photo-oxidative stress increases, leading to leaf abscission and a decrease in the growth rate of remaining leaves. At the whole-plant level, heat stress can reduce growth and shift biomass allocation. If drought stress is imposed on the plant together with heat stress, it can cause tree death (Teskey *et al.* 2015).

Large disturbances not only affect forests but have a significant impact on mountain forests, where effects of warming may be pronounced (Beniston 2002). Wind, fire, avalanches, animals, insects, fire, wind, snow storms, etc., can all negatively impact mountain forests (Svoboda 2007; Kulakowski and Bebi 2004; Peterson *et al.* 2000; Fischer *et al.* 2002). Due to the impact of human activity in most of the temperate zone, the density of mountain forests is generally stable, as a result oh spontaneous activities such as afforestation and planting of (Piussi 2000). Conversely, mountain forests have been negatively affected by direct and indirect anthropogenic activities for a long time. Ecological balance of forest ecosystems is influenced by various disturbances (Fischer *et al.* 2002), resulting in changes to forest structure and microclimate conditions (Baker *et al.* 2014), as well as affecting the overall water balance in the forest ecosystem (Kopáček *et al.* 2015).

Damaged forests with canopy loss had lower humidity conditions, and they are more affected by rising sunlight and direct solar radiation at ground-level (Hojdová *et al.* 2005; Royer *et al.* 2011). As solar radiation is generally bound to water vapor, which helps maintain daily variation of temperatures (Hojdová *et al.* 2005). From the perspective of temperature conditions, forests, as an ecosystem are particularly sensitive to disturbance factors. For example, in an unmanaged montane forest that has been affected by a disturbance, compared to a nearly intact forest, there has been an increase in average daily soil temperature and air temperature due to climate-related factors (Kopáček *et al.* 2020). A calamitous factor can be due to co-participation of wind and insects (bark beetles), as they commonly influence forest dynamics jointly. However, a negative result can occur when wind disturbed wood also serves as a food source for bark-consuming insects (e.g., *Ips typographus*). The insects will subsequently multiply and increase their population, and this can lead to the insects attacking living vegetation and trees in the event of a huge overpopulation. This will cause forest disturbance on a much larger scale than the area originally damaged by the wind (Svoboda 2007).

Microclimate is unique to each area. Because the soil is wetter for longer periods of time in forests, this makes the microclimate more stabilized (Rouse 1984). Mature forests have more stable microclimates (Baker *et al.* 2014). This can be due to a range of factors, for example, the tree canopy, as coniferous forests retain more water in the tree canopy by keeping water droplets between the needles, where their crucial function in forest ecosystems is water storage and water distribution (Klamerus-Iwan and Błońska 2018). Calamities can disrupt the water balance in forest ecosystems by causing a loss of needles and small branches, leading to a decrease in sedimentation and impaction of water droplets from low clouds, mist, and fog (Kopáček *et al.* 2015). As coniferous forests receive less sunlight, water is retained in the soil for a longer period of time without evaporating, aided by needles, which retain water droplets for a longer period of time (Kantor and Šach 2003; Volková 2010). Forest cover plays a crucial role in the rainfall-runoff process. It retains rainfall through the tree canopy, slows surface runoff, increases soil water retention, and reduces evaporation and evapotranspiration. Water accumulation in the environment can occur both in the short-term and long-term. For example, a coniferous forest covered in snow during winter approximately 20% longer to melt, which can be attributed to either the shading effect or high tree density (Cudlín *et al.* 1999).

Forests play a crucial and irreplaceable role in mitigating the warming of the Earth's surface and distributing water resources. It is imperative to maintain and protect forests to ensure this continued and significant contribution to the environment. The interconnectedness of forests, water, and energy in their ability to sequester carbon dioxide (CO_2) highlights the critical importance of preserving these natural resources. By taking these actions, we can confidently and diplomatically reduce the impact of climate change and secure a sustainable future for future generations. It is widely acknowledged that forests play a crucial role in regulating the water, energy, and carbon cycles (Ellison *et al.* 2017)

In this work we analysed temperature differences in individual forest, taking into consideration both daily and seasonal changes. We focussed on several types of forest stands, including young mixed forest - mountain alluvial forest, mixed forest, young spruce forest, old natural spruce stands as well as calamity areas (mixed forest and spruce forest) left for natural development.

Material and Methods

Study area

The research took place in the northern part of the Belianske Tatras, a part of the Tatra Mountains (Western Carpathians). For our research, we chose two sites where post wind-bark beetle calamite areas and different forest stands were present (Fig. 1). The investigated sites are located within the Tatra National Park (TANAP). Climate conditions for individual months are presented in Table 1.

Our first measurement site (L1) was the western slope of Pod Koňom hill (1163 m a.s.l.), near the village of Tatranská Javorina. The slope was found to be on Allgäu Formation, characterized by dark-

		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Air temperature	2019	-6.1	-0.5	1.9	5.8	7.4	16.8	14.6	15.7	10.6	7.6	4.3	-0.4
	2020	-1.4	-0.2	0.2	5.2	6.6	13.4	14.2	16.1	11.5	6.5	1.9	-0.4
	2021	-4.5	-2.4	-1.1	1.7	8.0	15.0	17.0	13.2	10.4	**5.2**	**1.7**	**-3.4**
	2022	**-3.3**	**-1.0**	**-0.9**	**2.7**	**10.6**	**15.1**	**15.0**	**15.9**	**8.9**	**8.5**	**1.6**	**-2.2**
	2023	**-1.4**	**-2.8**	**1.3**	**2.7**	**8.7**	**12.8**	**15.6**	**16.2**	**13.7**	**8.5**	0.9	-0.8
Precipitation	2019	93.0	38.9	54.6	123.5	217.9	85.6	118.2	125.2	99.6	58.1	142.9	95.2
	2020	24.8	105.5	41.3	22.8	186.5	191.2	215.7	129.2	183.4	152.0	35.7	46.8
	2021	71.7	55.6	43.8	92.9	192.5	109.1	194.0	243.7	105.2	**15.8**	**45.9**	**62.2**
	2022	**78.0**	**65.9**	**27.3**	**62.7**	**49.7**	**79.3**	**128.9**	**157.3**	**123.6**	**71.3**	**48.6**	**61.2**
	2023	**119.4**	**102.4**	**60.7**	**109.2**	**105.4**	**160.4**	**130.8**	**208.6**	**112.2**	**111.7**	120.2	56.7

Table 1. Monthly averages of air temperature and precipitation for each month of the year at meteorological station Tatranská Javorina. Data provided by the Slovak Hydrometeorological Institute (Source: SHMI 2019, 2020, 2021, 2022, 2023), Values in period of investigation are in bold.

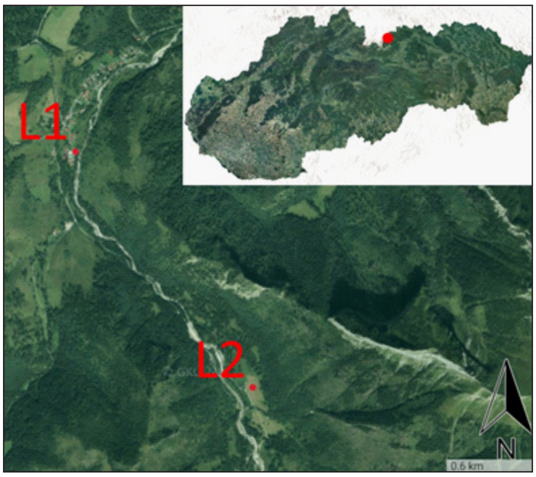

Fig. 1. Measured localities, L1 (Pod Koňom) and L2 (Pod Muráňom) (Source: ÚGKK SR, 2022).

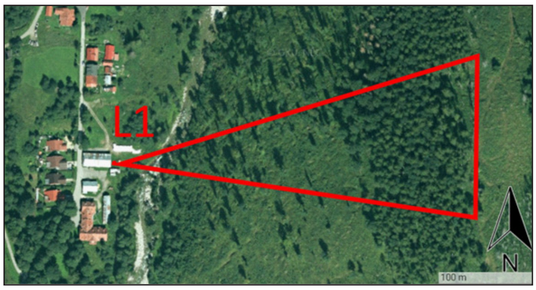

Fig. 2. Measure point with view to locality L1 Pod Koňom. Post-calamity forest with removed trees (Source: ÚGKK SR, 2022).

Fig. 3. Photo and investigated parts (red square) of the slope at locality L1 Pod Koňom. Post-calamity forest with removed trees (Photo: D. Inšpektor, 2022).

Fig. 4. Measure point with view to locality L2 Pod Muráňom. Post-calamity forest with removed trees (Source: ÚGKK SR, 2022).

Fig. 5. Photo and investigated parts (red square) of the slope at locality L2 Pod Muráňom. Post-logging forest with trees retained to ensure natural regeneration of the forest (Photo: D. Inšpektor, 2022).

grey to black, sometimes mottled, fine-grained ± clayey limestones and calcareous claystones (Early Jurassic Period). The point (N: 49.263726° E: 20.141856°; 1005 m a.s.l.) from which we collected infrared images is located behind the mountain stream Javorinka on the edge of the village (Fig. 2). When measuring, we focused on three parts of the slope (Fig. 3). In the first part (L1-1) there is a young mixed forest - mountain alluvial forest (*Picea abies* - 40%, *Alnus incana* - 40%, *Acer pseudoplatanus*; age 50 years). In the second part (L1-2) there is a post calamity mixed forest where spruce trees were removed, and trees of *Acer pseudoplatanus* stay there. In the third part (L1-3) there is mixed forest (*Picea abies* - 50%, *Acer pseudoplatanus* - 25%, *Larix decidua* - 20%) approximately 80 years in age.

The second measurement site (L2) represented western slopes beneath Muráň peak (1890 m a.s.l.). This site is approximately 2250 m away from site L1. The slopes consist of various Mesozoic formations (Mráznica, Jasenine, Ždiar, Allgäu) of limestones with shales and glaciogenic sediments near the foothill. The position from which we measured (Fig. 4) was in a meadow just before the forest (N: 49.249626° E: 20.158250°; 1090 m a.s.l.). When measuring, we focused on three portions of the slopes (Fig. 5). The first part (L2-1) consists of young spruce forest (*Picea abies* - 50%, *Sorbus aucuparia* - 20%, *Acer pseudoplatanus* - 20%, *Fagus sylvatica* - 5%, *Abies alba* - 5%; age 50 years). The second part (L2-2) represents calamity area of spruce forest (*Picea abies* - 60%, *Sorbus aucuparia* - 30%, *Acer pseudoplatanus* 10%; age 5 years) left for natural development. The third part (L2-3) is comprised of a dominant old natural spruce stand (*Picea abies* - 100%; age 165 years).

Field measurement

Field measurement took place between October 2021 and October 2023. During this period, we performed measurements monthly on one carefully chosen day according to weather conditions connected to suitable visibility (i.e., a day without fog or rain). The weather was checked using the meteograms (model ALADIN and ECMWF) of the Slovak Hydrometeorological Institute (SHMI). A regular pre-measurement weather check ensured we had optimal conditions in advance of each measurement. In the case of deteriorating weather, the measurement was cancelled and postponed to the next day. On suitable days, the infrared pictures of the study sites were taken by Thermocamera testo 882

(Testo SE & Co. KGaA, Germany). The thermal imager has a detector with an infrared resolution of 320 x 240 pixels. The temperature sensitivity is less than 50mK, i.e., 0.05 °C. The temperature range is from -20 to 100 °C. The lens has a viewing angle of 32° x 23°. The spectral range is 8 to 14 µm. During measurement, we focused on a consistent schedule. We started in the morning (7:00), then in the afternoon (13:00), evening (19:00), night (01:00) and finally again in the morning (7:00) of the next day. Throughout each day six pictures were taken. Of these, three images recorded the thermal temperature, and the other three images recorded the actual humidity. Attention was given to focus and to record the same image for each measurement. Travel distance between our study was estimated at 30 minutes, therefore, images captured at Pod Muráňom were taken with a half-hour delay.

Data processing

We recorded images 60 infrared images from two sites in total (3 thermal and 3 humidity images, 5 times at 2 sites). The processing and editing of the images was performed using Testo software (Testo IRSoft Software version 3.4). Only the best images from each series (with regard to position, relative smoothness and contrast) were chosen for further analysis. We determined the maximum, minimum and average temperature (°C) and humidity (%) using Square function, which helped us define measured parameters in selected parts of the investigated slopes (Fig. 6 and Fig. 7). Final data were plotted in a matrix using Excel. For each measurement the actual air temperature and relative humidity were recorded from databases of SHMI displayed on their web page and which provided mean hourly values for last 10 days. After measurement, three-day average air temperatures and relative humidity were computed from the same source (SHMI). Data were evaluated by Statistica 8.0 (StatSoft Inc., USA). To compare groups of data, we used the Kruskal-Wallis test and for relationships, Spearman's rank correlations, because data did not have normal distribution based on the Shapiro-Wilk test.

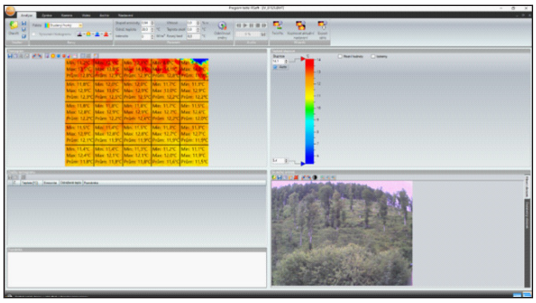

Fig. 6. Data processing in Testo software on example of site L1 Pod Koňom, Tatranská Javorina 29.7.2022 (Photo: D. Inšpektor, 2022).

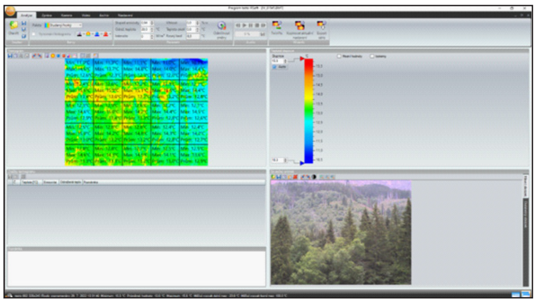

Fig. 7. Data processing in Testo software on example of site L2 Pod Muráňom, Belianske Tatras 29.7.2022 (Photo: D. Inšpektor, 2022).

Results

Temperature and humidity conditions during measuarement

The maximum average air and surface temperatures were measured in August 2023 (25.0; 23.7 °C). August and June were the warmest months in 2022, but in 2022, the average air temperature was lower than usual in June (see Table 1). During our survey (October 2021 to October 2023) we reached an average air temperature of 6.8 °C, and air humidity of 75.5%. In detail view (Fig. 8), the values of surface

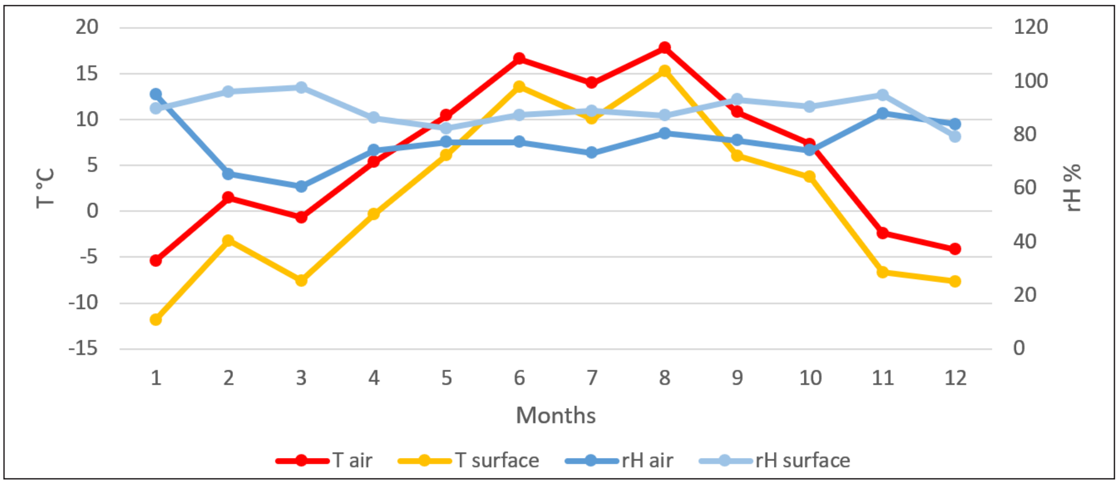

Fig. 8. Annual air and surface temperature (T) and humidity (rH) in both study sites (L1 and L2). Average values represent four measurements from individual parts of the day (morning, afternoon, evening and night) during survey (from October 2021 to October 2023).

temperatures respect air temperatures during year. When we look at the trend of the air and surface temperature, we can see that our temperatures rose from January to June. With a small decrease in July. In September we started to see a significant drop in temperatures, and this continued until January. When looking at air and surface humidity, we have the highest average air humidity in January, which started to drop extremely in February, then it stabilized in March. What is remarkable is that surface humidity was similar to air humidity in January, but in February and March surface humidity was higher than air humidity. However, the humidity at the surface was higher in the air during in all months apart from December and January.

The average surface temperature measured at individual parts of the sites during survey ranged from 1.8 ˚C to 3.0 ˚C (Table 2). The lowest average surface temperature was measured (1.8 ˚C) in the post calamity mixed forest (L1-2) at Pod Koňom (L1). The highest average surface temperature (3.0 ˚C) was measured in the old natural spruce stand (L2-3), then (2.7 ˚C) in the calamity area of spruce forest (L2-2) at Pod Muráňom (L2), and in the old mixed forest (L1-3) at Pod Koňom (L1). The highest maximal surface temperature was measured in the young mixed forest (L1-1) and then in the calamity area of spruce forest (L2-2). The lowest minimal surface temperature was measured in post calamity forest stands (L1-2 and L2-2). The highest average surface humidity was measured in lowest-elevation parts (L1-1 and L2-1) of the hills and the lowest in the higher parts (L1-3 and L2-3) of the hills at both sites. The values of minimal surface humidity were lower at the first site L1 (Pod Koňom), especially in post calamity mixed forest (L1-2).

Comparison of the all data without grouping according to season or individual measured sections of the day, shows that forest stands were not significantly different in surface temperature (K-W H (5, 693) = 1.6251, p = 0.8982) but significantly different by surface humidity (Fig. 9) as well as in case of minimal surface humidity (K-W H (5, 546) = 32.63619, p = 0.0001).

		L1-1	L1-2	L1-3	L2-1	L2-2	L2-3
T surface ˚C	Mean	2.0	1.8	2.7	2.1	2.7	3.0
	Min.	-15.2	-17.0	-16.6	-16.1	-17.2	-17.1
	Max.	23.7	22.7	21.7	22.9	23.4	21.8
	SD	9.6	9.7	9.3	8.8	9.0	8.7
	SE	0.9	0.9	0.9	0.8	0.8	0.8
rH surface %	Mean	89.8	88.7	85.4	92.5	89.6	88.3
	Min.	39.2	38.5	42.7	64.2	60.5	45.4
	Max.	100	100	100	100	100	100
	SD	11.2	11.0	11.0	8.8	10.2	13.5
	SE	1.2	1.2	1.2	0.9	1.1	1.4

Table 2. Average surface temperature and humidity conditions in investigated parts of the two study sites (L1-1 – young mixed forest - mountain alluvial forest; L1-2 – post calamity mixed forest; L1-3 – mixed forest; L2-1 – young spruce forest; L2-2 – calamity area of spruce forest; L2-3 – old natural spruce stand). Measured, T surface (Average surface temperature); rH (Average surface relative humidity), min (Minimum average values), max (Maximum average values), SD (Standard Deviation), SE (Standard Error of Mean).

Difference in surface humidity in studied forest stands at the Pod Koňom and Pod Muráňom sites. The minimum humidity values at Pod Muráňom (old forest) were higher than those at Pod Koňom (young forest), while the maximum values were also higher. The data from Pod Muráňom indicates that not only the median, but also 25% - 75% of the data showed higher humidity values.

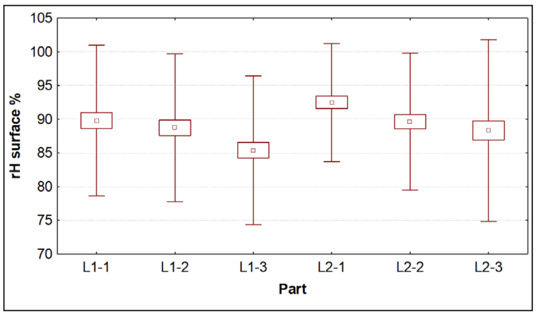

Fig. 9. Differences in surface humidity (rH %) in studied forest stands (L1-1 – young mixed forest - mountain alluvial forest; L1-2 – post calamity mixed forest; L1-3 – mixed forest; L2-1 – young spruce forest; L2-2 – calamity area of spruce forest; L2-3 – old natural spruce stand). K-W H (5, 546) = 26.78, p = 0.0001 (Middle points - means; Boxes - +/- standard errors of mean; Whiskers - +/- standard deviations of mean).

Seasonal changes of the surface temperature and humidity

In the spring, the average air temperature rose from 4 ˚C in the morning to 9.2 ˚C in the afternoon. Overnight, air temperature dropped to 2 ˚C from 5 ˚C in the evening (Fig. 10). The lowest average surface temperatures in the morning, were measured at site L1. Upon closer inspection of individual parts of the sites, the highest parts represented by mixed forest (L1-3) and old natural spruce stands (L2-3) had the lowest surface temperature compared to other stands at the sites. In the afternoon, the highest average surface temperatures were measured in lower areas at both sites. Sites that were colder in morning had the lowest average surface temperatures in the afternoon. If we compare the higher parts with well-preserved forest stands and middle parts with calamity forest stands the differences are 2.1 ˚C at L1 and 1.9 ˚C at L2. The middle parts (L1-2 and L2-2) had quite similar average surface temperatures at both sites. In the evening, the average surface temperatures at Pod Koňom (L1) were above 0 ˚C while those at Pod Muráňom (L2) were below 0 ˚C. The lower surface temperature was observed most often in old natural spruce stands (L2-3). In the night, average surface temperatures were below 0 ˚C at all parts, but lower parts which were the warmest in afternoon were the coldest during the night.

In the summer, the air temperatures ranged from 13 ˚C (in the night) to 19.8 ˚C (afternoon). Morning surface temperatures started from 10 ˚C (L1-1) to 12.4 °C (L1-3). Afternoon surface temperatures ranged from 14.4 °C (in L2-3) to 18.3 °C in (L1-1). In the evening, the surface temperature ranged from 13.3 °C (L2-1) to 15.4 °C (L1-2). During the night, surface temperatures ranged from 9.1 °C (L2-1) to 11.9 °C (L1-3). In the morning, similar surface temperatures were observed when we compared study sites L1 and L2 (Fig. 11). Well-preserved forest stands (L1-3) had a higher surface temperature especially at site L1 (Pod Koňom). At site L2 (Pod Muráňom), similar surface temperatures were observed between old natural spruce stand (L2-3) and the calamity area of spruce forest (L2-2). The lowest surface temperatures were measured in lowest parts of study sites (L1 and L2). In the afternoon, higher surface temperatures were observed at site L1, especially in the lower part of the site L1. At site L2 higher surface temperatures were measured in lower and middle parts of the hill. Well-preserved forest stands in higher parts of the hills (L1-3 and L2-3) had lower surface temperatures despite higher morning temperatures. The surface temperatures at Pod Muráňom (L2) maintained lower surface temperature values during the afternoon. In the evening, surface temperatures were quite similar, but slightly higher at site L1. The lowest drop of surface temperature is visible in old natural spruce stands (L2-3). During the night, well-preserved forest stands (L1-3, L2-3) had higher surface temperatures. That means that in the summer, old natural forest had the ability to maintain more stable temperatures compared to other types of forest stands.

After the warmer summer, air temperature dropped to the highest average air temperature 10 °C in autumn. In this season, the air temperature ranged 2.5 °C in the morning to warmer temperatures in the afternoon with a high of 10.3 °C (Fig. 12). Surface average temperatures were below zero in the morning. Forest stands in lower and middle parts of the hills at both sites (L1 and L2) had lower/colder temperatures than higher elevation areas with older well-preserved forest stands (L1-3 and L2-3). In the afternoon, surface temperatures rose to positive values, with a maximum of 7.6 °C in lowest area at Pod Koňom (L1-1). At both sites, ca-

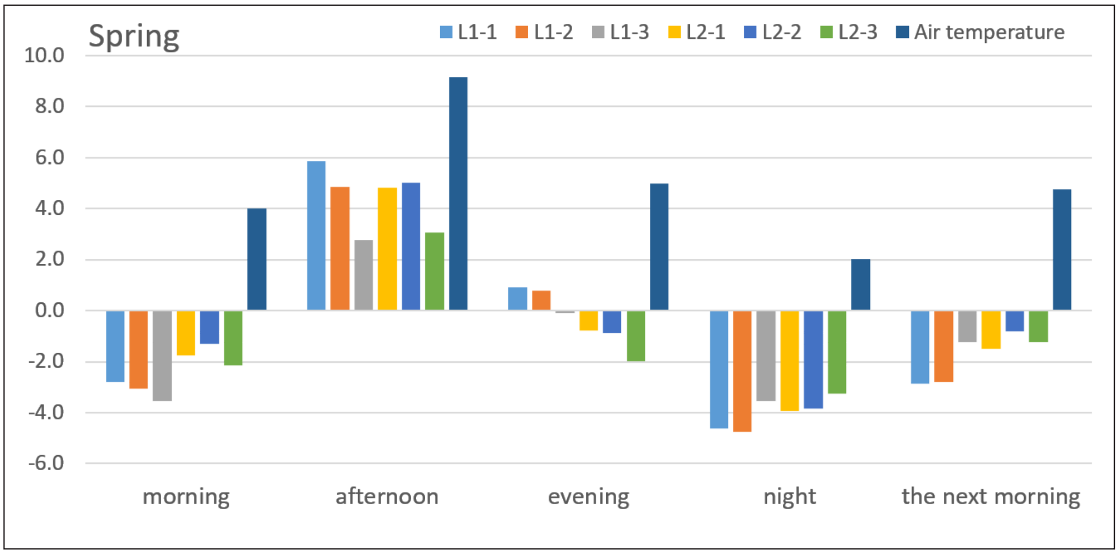

Fig. 10. Spring average surface temperatures in the selected forest stands (L1-1 – young mixed forest - mountain alluvial forest; L1-2 – post calamity mixed forest; L1-3 – mixed forest; L2-1 – young spruce forest; L2-2 – calamity area of spruce forest; L2-3 – old natural spruce stand) during individual parts of the day.

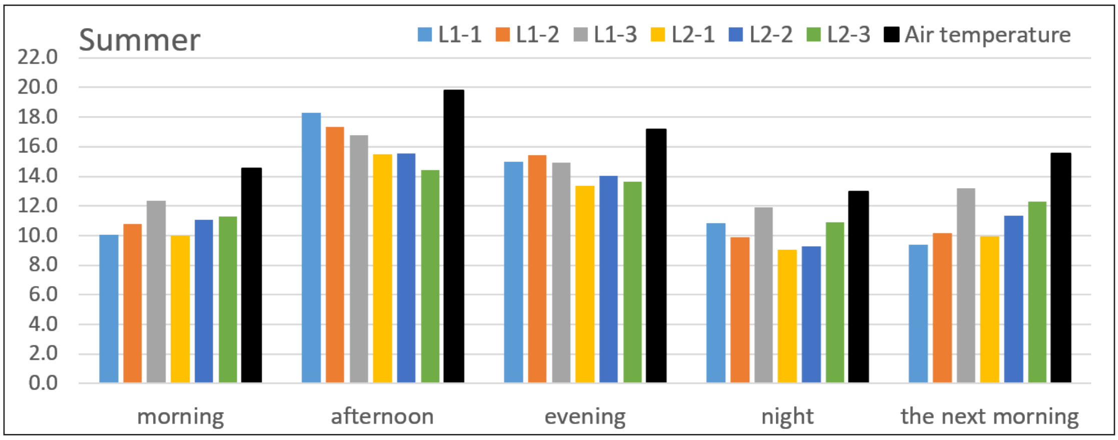

Fig. 11. Summer average surface temperatures in the selected forest stands (L1-1 – young mixed forest - mountain alluvial forest; L1-2 – post calamity mixed forest; L1-3 – mixed forest; L2-1 – young spruce forest; L2-2 – calamity area of spruce forest; L2-3 – old natural spruce stand) during individual parts of the day.

lamity forest reached a surface temperature of 6.9 °C. The colder surface temperatures were measured at well-preserved forest stands (L1-3 and L2-3) and in young spruce forest in the lower part of Pod Muráňom. In the evening, average surface temperatures dropped below 0 °C except in well-preserved forest stands at both site (L1-3 and L2-3). Despite quite similar air temperatures in the evening and in the night, surface air temperatures surprisingly increased in the night at all parts, particularly at Pod Muráňom (L2), and in well-preserved forest stands at both site (L1-3 and L2-3).

In the winter, the average air temperature ranged from -4.7 °C in the morning to 1.4 °C in the afternoon (Fig. 13). During the winter, the lowest surface temperatures were measured in each part of the day at pod Koňom (L1). The lowest surface temperatures were observed especially in young forests (lower parts) and then calamity forests (middle parts). Afternoon average surface temperatures increased. Only the highest positioned areas (L2-3) represented by old natural spruce stand reached a positive surface temperature (0.4 °C). Evening air temperature dropped slightly, and at this hour it was already dark, so the surface temperature started to cool down more. Site L1 had a higher temperature drop compared to site L2. Therefore, we can assume that at Pod Muráňom (L2) we always have more stable conditions in the forest and older forest stands hold, and are able maintain a warmer surface temperature. The parts with calamity forests (L1-2 and L2-2) represented the coldest parts of the hills at both sites during each part of the day. Surface temperatures at Pod Muráňom (L2) lowered to an identical temperature (-5.6 °C) overnight.

When we focused on increasing or decreasing surface temperature in our study sites (Fig. 14), we confirm that the biggest increases in temperatures were observed from morning to afternoon due to rising air temperature and solar radiation, as increases in surface temperatures were higher then increases in air temperature (mainly in spring and winter). Overall, this increases in temperatures was the highest in autumn, and the lowest in summer. Slight differences were observed between our two sites, with higher increases at Pod Koňom (L1). The largest increases were observed in young mixed forest (L1-1) followed by young spruce forest (L2-1). The smallest increases were observed in old natural spruce stands (L2-3) as well as in mixed forest

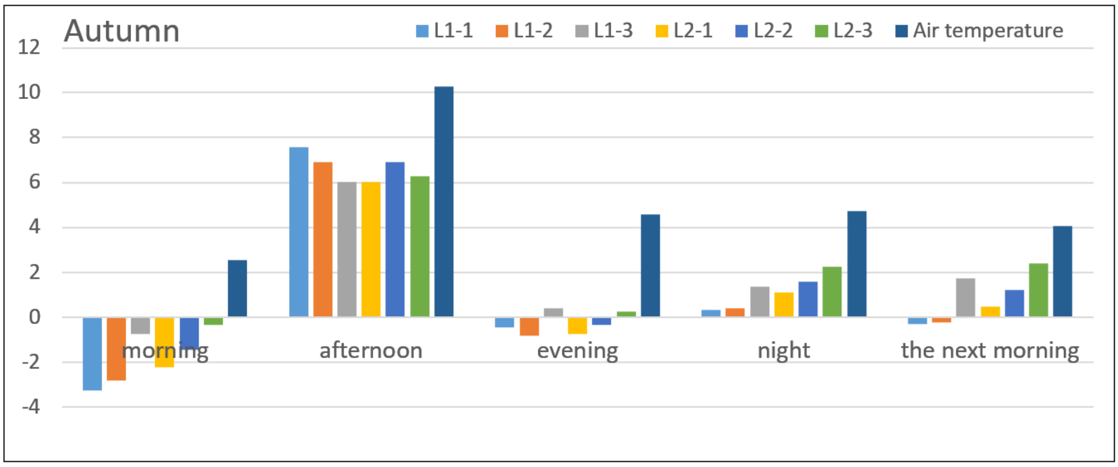

Fig. 12. Autumn average surface temperatures in the selected forest stands (L1-1 – young mixed forest - mountain alluvial forest; L1-2 – post calamity mixed forest; L1-3 – mixed forest; L2-1 – young spruce forest; L2-2 – calamity area of spruce forest; L2-3 – old natural spruce stand) during individual parts of the day.

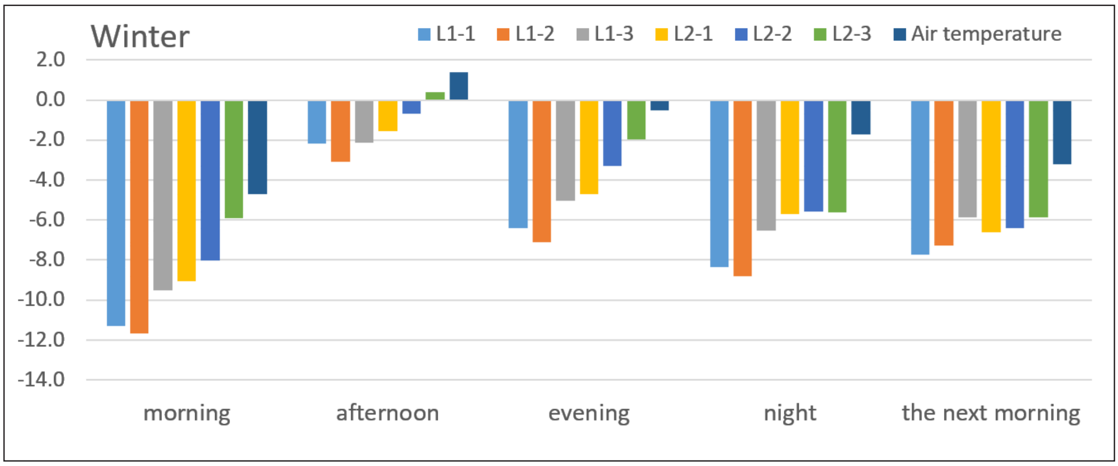

Fig. 13. Winter average surface temperatures in the selected forest stands (L1-1 – young mixed forest - mountain alluvial forest; L1-2 – post calamity mixed forest; L1-3 – mixed forest; L2-1 – young spruce forest; L2-2 – calamity area of spruce forest; L2-3 – old natural spruce stand) during individual parts of the day.

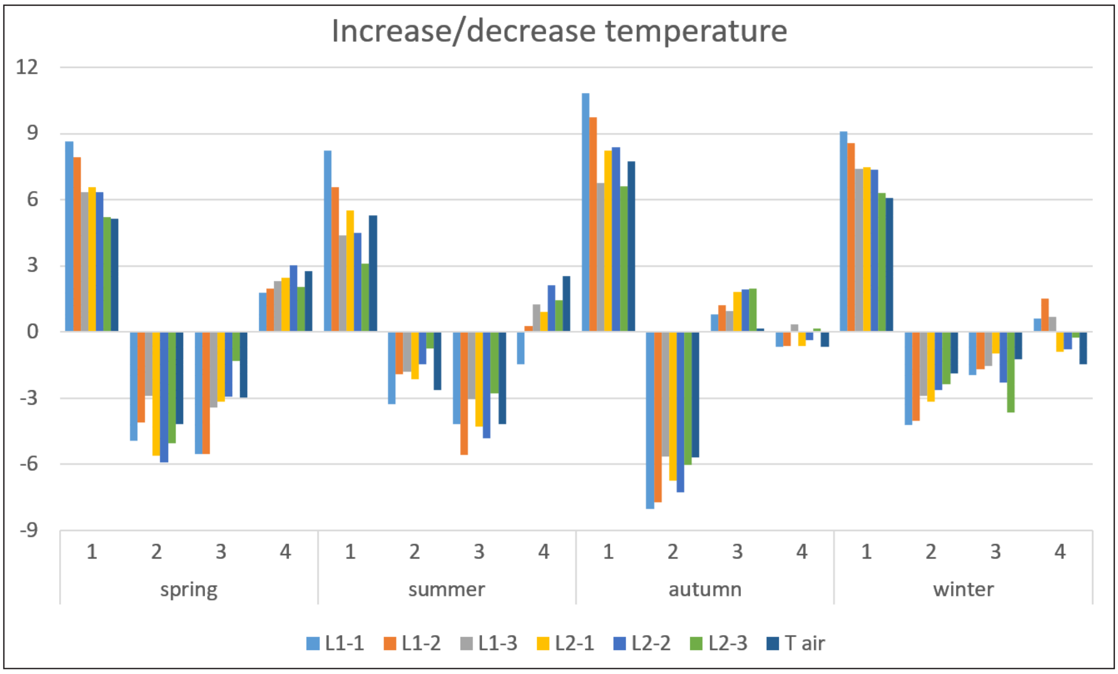

Fig. 14. Increase and decrease of surface temperatures between measured part of the day (1 - morning to afternoon; 2 - afternoon to evening; 3 - evening to night; 4 - night to the next morning) in each season (spring, summer, autumn, winter).

(L1-3). Between afternoon and evening(2), temperatures decreased due to advancing sunset and subsequent cooling of the earth's surface. Higher decreases in surface temperature were observed in autumn and the lowest in summer. Young forest stands and calamity areas had higher decreases of surface temperatures than older well-preserved forest stands (L1-3 and L2-3). Afternoon increases and evening decreases in surface temperatures support the theory of increased thermoregulation abilities of old mountain forests. Between afternoon to night, decreases of surface temperatures were visible in winter, spring and summer, but not in autumn, when increases of surface temperatures were observed. Decreases of surface temperatures were mostly visible in young forest or in calamity areas. In summer, overnight decreases of surface temperatures were higher than evening decreases. In the winter, the opposite was observed, and night decreases were lower than evening decreases. Autumn night increases of surface temperatures were unexpectedly observed and could be connected to radiative cooling delay or specific wind conditions such as a temperature inversion.

Relationships of air and surface temperature in forest stands

The relationship between air and surface temperature is extraordinarily strong (Table 3) and actual air temperature (T) have higher impact on surface temperature than air temperature before three-days (T3). Slight differences between investigated forest stands were observed, with a focus on correlation

	Annual n=115		**Spring** n=30		**Summer** n=30		**Autumn** n=35		**Winter** n=20	
	T	T 3	T	T 3	T	T 3	T	T 3	T	T 3
All parts	0.95	0.84	0.94	0.77	0.81	0.51	0.95	0.69	0.77	0.44
L1-1	0.97	0.85	0.95	0.73	0.73	0.33	0.98	0.70	0.95	0.66
L1-2	0.97	0.86	0.96	0.77	0.84	0.47	0.98	0.71	0.89	0.64
L1-3	0.96	0.87	0.96	0.82	0.82	0.65	0.95	0.73	0.81	0.48
L2-1	0.96	0.84	0.94	0.78	0.86	0.52	0.97	0.73	0.83	0.51
L2-2	0.95	0.82	0.93	0.77	0.88	0.53	0.95	0.69	0.76	0.39
L2-3	0.90	0.79	0.91	0.78	0.81	0.68	0.87	0.60	0.50	0.02

Table 3. Correlation coefficients between surface temperature and air temperature (T - mean air temperature) or three-day mean temperatures before measuring (T 3 - mean air temperature during three-days) in investigated parts of the two study sites. Average temperature (all parts) and other seasons such as (spring, summer, autumn, winter) and number of samples marked as (N). Naming of our parts: (L1-1 - young mixed forest - mountain alluvial forest, L1-2 - post calamity mixed forest, L1-3 - mixed forest, L2-1 - young spruce forest, L2-2 - calamity area of spruce forest, L2-3 - old natural spruce stand). Minimal correlation coefficients are in bold and maximal in bold italic.

coefficients. During all seasons, we observed that summer correlation coefficients were lowest (from 0.73 to 0.88). We can also say that surface temperatures were more dependent on air temperature during spring and autumn. The means of three-day temperatures were especially important for their relationship with surface temperatures in spring. In assessing annual temperatures, old natural spruce stands (L2-3) were less influenced by air temperatures, especially in the winter (0.50), autumn (0.87) and in the spring (0.91). In summer, the young mixed forest was less influenced. On the other hand, calamity areas of spruce forest most influenced by air temperature (L2-2) in summer (0.88), as well as post calamity mixed forest in summer (0.84) and in autumn (0.98). In the winter, young forest stands (L1-1 and L2-1) were most influence by air temperatures.

Focusing on individual parts of the day (Table 4), morning temperatures influenced surface temperatures less (0.89) in old natural spruce stands (L2-3). In the young forest stand (L1-1 and L2-1), air temperature mostly influenced surface temperatures in the afternoon and in the evening. Overnight, forest stands at Pod Koňom were influenced more.

Pod Muráňom (L2) had lower values of correlation coefficients of air dependence to surface temperature compared to Pod Koňom (L1). That means that the forest stands there had a better ability to reduce not only the maximum temperature but also the minimum temperature. Therefore, we can assume that site L2 creates its own microclimatic conditions beneath Muráň peak.

Discussion

The variations of surface temperatures were highest in forest stands affected by biotic or abiotic factors (areas of calamity forests). These surface temperatures in areas of calamity forests were more influenced by air temperature than in well-preserved forest stands. In addition, we can confirm that during the day, when the sun is on the horizon, the calamity areas are warmer in certain cases. Kopáček *et al.* (2020), noted that disturbances in the forests led to rising daily average temperatures in both soil and air. After canopy loss, the ground is impacted by increased sunlight. The greater the openness of the canopy, the greater the amount of radiation at ground level, and the greater the amount of direct rather than diffuse radiation (Royer *et al.* 2011). This means that more direct solar radiation reaches calamity forest stands, passing through the open space to generate more heat. Whereas in an undisturbed healthy forest, or well-preserved forest stand, diffuse radiation is predominant, scattering in the forest and refracting in different directions through the dense canopy of trees and leaves. Diffuse radiation thus creates a more moderate and uniform light environment compared to direct radiation, which can be more intense and concentrated.

The results of land-based measurements provided by Hojdová *et al.* (2005) show that living forest (in Šumava NP) better manages temperature fluctuations than dry or clearcut forests, where the climatic effect of trees is missing. Our results supporting these findings. In addition, we observed that young forests showed the highest variability in maximum daily temperatures, while old-growth forests showed the lowest variability in daily temperatures. Also, younger forests were characterized not only by the highest daytime temperatures, but also by the coolest nighttime temperatures, as well as the most variable daily and nighttime temperature patterns. Lindenmayer *et al.* (2022) investigated the forest microclimate in relation to differences of forest stand age. They found that temperature variability decreased with increasing stand age, both during the day and at night. That indicates that the older forest tends to have cooler daytime temperatures and warmer nighttime temperatures. Hojdová *et al.* (2005) explained that damping of daily maxima and night minima temperatures in forests could be driven by evapotranspiration during the day and reduction of reflexive radiation at night and creation of dew. That means the daily temperature maximum is damped by the binding of solar radiation to water vapor while the night temperature minimum is damped by condensation of the latent heat under vegetation cover.

If shading is missing or limited, temperature variations are higher. Findings from Lindenmayer *et al.* (2022) can support this explanation based on age classes differing in stand structure such

	Morning		Afternoon		Evening		Night	
	T	T 3	T	T 3	T	T 3	T	T 3
All parts	0.94	0.90	0.96	0.86	0.96	0.87	0.95	0.86
L1-1	0.97	0.94	0.98	0.92	0.99	0.92	0.97	0.87
L1-2	0.97	0.93	0.97	0.91	0.98	0.92	0.99	0.90
L1-3	0.95	0.91	0.96	0.89	0.97	0.89	0.97	0.88
L2-1	0.95	0.91	0.98	0.87	0.97	0.87	0.96	0.86
L2-2	0.94	0.88	0.97	0.84	0.96	0.84	0.95	0.84
L2-3	0.89	0.83	0.92	0.76	0.91	0.78	0.91	0.82

Table 4. Correlation coefficients between surface temperature and air temperature (T - mean air temperature) or three-day mean temperatures before measuring (T 3 - mean air temperature during three-days) in investigated parts of the two study sites during different measuring time intervals such as: (morning, afternoon, evening, night and the next morning). Minimal correlation coefficients are in bold and maximal in bold italic.

as canopy height, dominance of large old trees, and dense, moist, understorey. They also identified that young to 12-years-old forest (Mountain ash) were characterised by the hottest day-time temperatures and the coldest night-time temperatures. Our results confirmed that younger forest stands (young mixed forest - mountain alluvial forest with alder and spruce) had higher increases of surface temperatures in summer, as well as in spring, autumn, and winter. In addition to the night-time temperature, we observed the coldest values in areas of calamity forests, especially in mixed forest stands (*Picea*, *Larix* and *Acer*).

We measured surface temperatures of forest stands in western slopes of two hills, Pod Koňom and Pod Muráňom. Even though Pod Muráňom was closer to the main mountain ridge of Tatra Mountain and partly in higher elevations (approximately 100 metres), where we can expect the coldest conditions, the lowest minimal surface temperatures were measured at Pod Koňom. This may be due to species composition of these forest stands, where broadleaved trees or a mixed forest are present, while forest stands at Pod Muráňom are characterised predominantly by coniferous trees. Therefore, we can consider coniferous forest to be less impacted by variation in surface temperatures, due to maintaining additional moisture in their canopies. Broad-leaved forests can be affected by temperature fluctuation more, especially during early spring, late autumn and winter, when leaves are absent (Lindner *et al.* 2010). In this context, evapotranspiration may also play a crucial role. Evapotranspiration of broad-leaved forests can be nearly equal to evapotranspiration of young coniferous forests and higher than evapotranspiration of old coniferous forests (Komatsu *et al.* 2007).

Our disturbed plots displayed significantly lower air humidity levels. Kopáček *et al.* (2015) found that, the loss of needles, fine twigs and small branches caused by calamity, led to reduced surface area of canopies. This reduction resulted in decreasing occult precipitation deposition (e.g., water droplets from wind driven low clouds, mist and fog, and formation of rime and hoar frost on foliage) and had a significant impact on the amount of water entering the soil, which consequently increases evaporation following tree dieback (Kopaček *et al.* 2020). In addition, trees that were left to naturally decompose on the ground without any interference had the highest levels of soil moisture (Fleischer 2008). Thus, calamity forests without any interference can better deal with surface temperature fluctuations.

We mentioned a that decrease in canopy cover resulting from tree mortality not only decreases transpiration and interception, but also enhances the penetration of radiation and wind at ground level. These changes collectively lead to elevated levels of soil evaporation and transpiration in the understory (Anderegg *et al.* 2013). Well-developed mature forests with their understory plants release a lot of water through transpiration and better maintain temperature conditions in the forest and its surrounding, before they are disturbed, like deforestation or tree loss. After the disturbance, the soil and understory plants usually release more water into the air and impact how quickly water moves through the ecosystem (Beudert *et al.* 2018). This could impact soil wetness and how much water runs off (Bearup *et al.* 2014), as well as further forest recovery and development (Caldwell *et al.* 2016).

We observed an increase in surface temperature overnight during autumn; there were instances of temperature inversion. Specifically, between 19:00 to 1:00, temperatures were expected to fall but instead rose, including surface temperature. This phenomenon occurred five times out of a total of 7 measurements recorded in autumn (on 29th October and 26th November in 2021, then on 23rd September and 21st October in 2022, and finally on 19th September in 2023). Only two out of 7 measurements in the night had a lower temperature than in evening. That indicates that this type of night inversion in mountain valleys can occur frequently in autumn. Groundwater and an abundance of precipitation can also play a crucial role in influencing the processes of evaporation and air temperature within an ecosystem. Research conducted by Miller (1977) indicates that a significant amount of the water vapor in the atmosphere originates from the upper layers of soil, where groundwater is most accessible. This process of evaporation not only helps regulate air temperature by releasing heat energy into the atmosphere, but also plays a key role in the water cycle by replenishing moisture in the air and contributing to the formation of clouds and precipitation. According to research conducted by Koreň *et al.* (1997), the northern side of the Tatra Mountain range receive approximately 60% more precipitation due to their exposure to northwest air flows. The higher precipitation rate or number of days with precipitation can increase the occurrence of mist or fog. Fog forms when cool air mixes with warm moist air over water. This moist air cools until its humidity reaches 100% and a fog forms. Hůnová *et al.* (2021), mentioned in their study how the forest influences the occurrence of fog. Not only does the forest increase the number of fog occurrences, but it also produces higher humidity in the air and higher humidity can reduce the temperature of the forest. The influence of fog differs between coniferous and broad-leaved forests.

Fog not only lowers temperatures but also reduces evaporation. This behaviour can help prevent drought. Moisture from fog droplets, deposited on plant leaves, is subsequently absorbed into the soil, providing an important source of water for young trees and other plants on the understory (Rastogi *et al.* 2016). Greater humidity levels may be also attributed to the tree canopy, as coniferous forests trap more water in the canopy by capturing water droplets amidst the needles (Klamerus-Iwan and Błońska 2018). In a thriving, undisturbed forest, the canopy collects water from clouds and mist, which then either drips down into the soil through the overflow and stems or is taken up by the leaves and transported downward through the plant xylem, contributing extra water to the forest ecosystem. At the same time, the increased occurrence of clouds, and the retention of water in clouds or fog, leads to a reduction in differences in water potential in the forest (Tognetti 2015).

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