Oecologia Montana 2022, **31,** 27-34

The impact of forest management on the microclimate - a case from the Belianske Tatry, Slovakia

D. SUROVČÍK and M. KOMPIŠ

Institute of High Mountain Biology, Žilina University, Tatranská Javorina 7, SK-059 56, Slovak Republic; e-mail: surovcik.david@gmail.com

Abstract. Temperature is a crucial driver of ecosystem dynamics in forests. Thermal changes within forests can be highly variable and are dependent on multiple factors, such as forest type, soil composition, edge orientation, slope, humidity and climate conditions. In this study we focused on temperature measurement of forest stands using a thermal camera, in three different localities within the Belianske Tatras. These localities were selected based on slope orientation and differentiated by vegetation type. The main aim of the study was to determine the surface temperature of the forest area in terms of seasonal and diurnal/night temporal changes. Field measurements were carried out continuously for two years. The results suggested significant temperature differences between the measured localities and also showed in which locations the most heat accumulates, the influence of slope orientation on tree growth, and the response of vegetation to seasonal changes. If the forest is significantly damaged, it cannot function properly to mitigate large temperature fluctuations. The forest must inhabit a particular footprint and utilize the correct management strategy for proper growth and regeneration in order to maintain a mild microclimate. From an ecological perspective, it preferable to leave old mixed forests as intervention free as possible. Intervention may include logging, planting of monocultures, or drainage of slopes with the help of heavy machinery, and contributes to long-standing problems that persist for decades. Belianske Tatras, as an eastern locality with unique dolomites and rare vegetation, fully captures the nature of the Tatras and is a prime example of the microclimate within this region. This microclimate is crucial to this mountain complex for the prevention of periphery drought, whereby water resources will be lost. Additionally, within this study, thermal imaging proved to be a suitable tool to understand ecosystem response to temperature extremes This technique still has its flaws, and must be fine-tuned to fully determine temperature, thermal conductivity, specific heat and emissivity within these environments.

Key words: Belianske Tatry, forested areas, daily and seasonal time scales, climatic conditions, forest temperature

Introduction

Forests are an important part of our lives, providing beauty, recreation, and an ecosystem that helps us to combat climate change, but deforestation is still a widespread issue worldwide. Deforestation is not limited to rainforests alone; approximately 3.7 million hectares of forest in Europe has been damaged by insects, fires and human activity. An additional threat to this ecosystem is forest fragmentation (Ledig *et al.* 1992), which occurs due to the continuous development of cities and related infrastructure. Every day we lose an area of forest equal to double the area of the High Tatras due to deforestation. Forests produce oxygen, which is requisite for life; they capture and filter water; provide sustenance and shelter for fauna and flora; and propagate medicinal substances. As the human population grows every year, more and more food crops need to be grown. Agriculture causes 80 % of deforestation. When forests are clear-cut to create more land for growing crops, especially in rainforests during the dry season, the soil becomes poorly nourished, dry, and infertile, leading to a loss in value. Nutrients are often supplemented with chemical sprays that are unnatural to the environment, or "cutting and burning" is relied on as an agricultural technique. This land is fertile, but only for a short period, and farmers quickly abandon fallow land for new areas.

Fortunately, in many countries, emissions are falling as a result of the introduction of new laws and policies, such as fuel standards, stricter building regulations and emission limits for power plants. Also contributing to this are developments in technology and lifestyle trends, and increasingly incorporating the principles of sustainable use of resources, partly in response to the growing interest of governments, business and the general public about the threat of social unrest and conflict, and from worsening environmental problems (Gallopin *et al.* 1997). Many countries signed the Paris Agreement in December 2015 and committed themselves to better policies to combat climate change. This change will be reflected in investment in cleaner energy sources, such as wind turbines, solar panels, hydropower and power plants that burn natural gas instead of coal. Countries also set carbon taxes on emissions, which could have a profound impact on and convince industries to start using cleaner energy sources faster. However, in Slovakia, use of forest resources is largely an issue of economy, often due to the necessity for construction of new human dwellings, tourism and transport. Increasing deforestation in national parks, nature reserves, and protected landscape areas continue to occur due to state support and fundraising. Harvested wood is also used in house construction, paper production and heating. In addition, the loss of such habitats in Slovakia also causes significant negative effects, including: a reduction in biodiversity, contribution to global warming, interruption of water cycles, soil erosion, increase in greenhouse gases and, last but not least, increasing the temperature of the forest and surrounding soils. This last factor was the focus of this study, wherein we sought to evaluate the extent to which this temperature increase has impacted forests and their surrounding soils. The main aim of the study was to obtain data on forest temperature at selected localities, and to find out how the forest temperature fluctuated depending on seasonal changes, daily changes, and depending on how much the given soil substrates overheat to loss of vegetation.

Material and Methods

Study area

We carried out research on measurement of forest temperatures in the Belianske Tatras, which comprise the northeast part of the Tatra Mountains (in North Central Slovakia). We wanted to focus on slopes oriented in different direction, therefore we chose three localities that identify the forest temperature due to the slope's orientation to sun. Localities are affected by various local climate factors.

We chose the first locality L1 Pod Muráňom (measurement from point - N 49.24965°, E 20.15829°) in the Javorová valley (Fig. 1). The slope is south-west oriented, and is located at an altitude of 1084 m a.s.l. This locality was divided into three positions for a better overview of the temperature at different heights with different vegetation composition. The first position is located between 55 and 168 m from the point of measurement, at an altitude of 1100 - 1200 m a.s.l. The first position is composed of young spruce forest that is not exposed to severe weather conditions and is close to the meadow ecosystem. The second position is located between 168 and 461 m from the point of measurement, at an altitude of 1200 - 1300 m a.s.l. The second position is a forest following a natural disturbance. It consists of a mixed stand in which natural disorders occur. It is mainly affected by stronger winds and larger temperature fluctuations due to higher altitudes. At this level of the slope, there is a natural regeneration of the forest, which is composed of nutrients from the previous stand of trees. Restoration in this area began with a young deciduous forest of beech, maple and rowan. The third position is located between 461 and 636 m from the point of measurement, at an altitude of 1300 - 1450 m a.s.l. This position is characterized as an old spruce forest without current human intervention. It withstands the greatest natural conditions and forms the basic floor at this altitude. There are individuals of old age who will later provide a good basis for future generations of young tree species.

We chose the second locality L2 Čierna valley (measurement from point - N 49.24158°, E 20.30701°), near the village Tatranská Kotlina (Fig. 2). This slope is south-east oriented, and is located at an altitude of 793 m a.s.l. In this case, we measured two positions. The first position is located between 60 and 105 m from the point of measurement, at altitude. This position is characterized as a clear-cut forest area. It does not contain any wood residues or trunks. It consists only of soil or low grassland. This area is fully exposed to the sun in the summer and frost in the winter as it is not shielded by any geographical features and has no other protection. The second position is located between 50 and 70 m from the point of measurement, at altitude. This position consists of Norway spruce monoculture and is fully forested with spruce trees that are tall and slender. However, they are exposed from the bottom and have no lower growth below them. The crowns have grown up completely at the ends due to dense growth.

We chose the third locality L3 Kôň (measurement from point - N 49.263752°, E 20.141879°), in the village Tatranská Javorina (Fig. 3). This slope is north-west oriented, and is located at an altitude of 950 m a.s.l. The slope is located on a limestone subsoil.

Fig. 1. Photo from locality L1 pod Muráňom. The image show slope with the relevant tree positions (Photo: D. Surovčík, 2021).

Fig. 2. Photo from locality L2, Čierna valley, Tatranská Kotlina. A preserved fragment of the forest in Čierna Valley, divided into two positions (Photo: D. Surovčík, 2021).

The intervening element during the measurement is the river Javorinka, which flows through the bottom of the hill. This locality was divided into three positions. The first position is located between 70 to 100 m from the point of measurement. This position is comprised of beech clear-cut, along with natural regeneration of other trees. The second position is located between 100 and 134 m from the point of measurement. This position is a fully clear-cut forest area with lonely beeches that are quite bright. The third position is located between 134 and 145 m from the point of measurement. This position is characterised by young mixed forest with a predominance of beech trees.

Fig. 3. Photo from locality L3 Kôň. The locality is characterized by solitary beeches and low, young vegetation (Photo: D. Surovčík, 2021).

Field experiments

Measurements took place between November 2019 and December 2021. Field measurements took place every month, and day/night intervals were recorded in a regular ratio 5 times (morning, afternoon, evening, night, the next morning). They were measured using a thermal imager testo 882 (Testo, USA). Thermal infrared imaging is a powerful tool for ecological studies, providing the possibility of accurate, continuous, real-time measurement of vegetation temperatures. Thermal cameras are analogous to monochrome digital cameras; each pixel in the sensor records a digital number that represents the light intensity it receives. Parameters: Spectral range: 8 - 14 μm; Detector type: 320 x 240 pixels; Thermal sensitivity: 50 mK; Temperature range: -20 - 100 °C.

Three images were recorded for each measurement. Each image was processed by the Testo analysis program (Figs. 4-7) using the true environmental parameters measured at the time the image was recorded. This produces the true temperature value for each pixel. Thermal interference from the atmosphere and surroundings can dramatically affect the recorded temperature of forest area. Therefore, we tried to adhere to following parameters: Emissivity: 0.94; Distance: 55 - 636 m; Relative humidity: 0 - 100 %rF; Reflected object temperature: 50 - 100 °C.

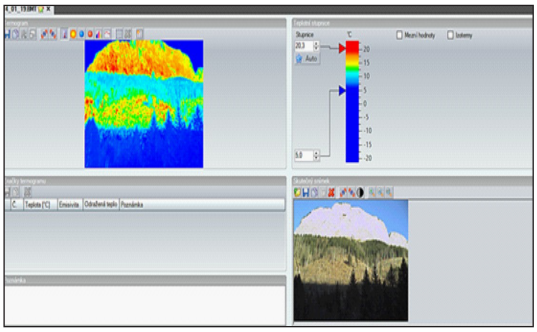

Fig. 4. Image analysis program, Testo IRSoft Software Version 3 (Photo: D. Surovčík, 2021).

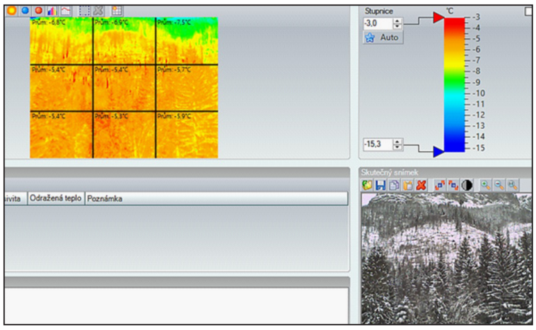

Fig. 5. Evaluated image with average temperature from locality L1 Pod Muráňom, Belianske Tatras 28. January 2021. (Photo: D. Surovčík, 2021).

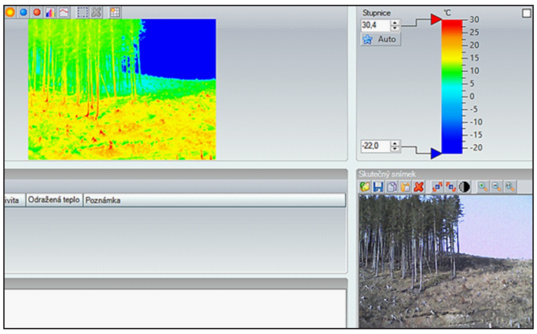

Fig. 6. Locality L2, Čierna valley from date 23. February 2021 (Photo: D. Surovčík, 2021).

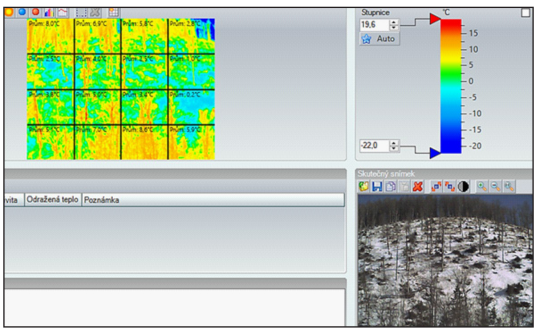

Fig. 7. Locality L3 Kôň, with the Square function displayed, Tatranská Javorina, 23. February 2021 (Photo: D. Surovčík, 2021).

Corrections caused by thermal interference are important, but the quality of image data should be considered before applying any corrections. Careful checking of imaging conditions, parameter ranges, and general accuracy is more important than ultra-accurate measurements of meteorological conditions.

All three measured localities were within the same mountain range (Belianske Tatry). For this reason, we have taken into account the direct and indirect factors that affect forest temperature. The first of these factors is the type of forest. Measuring deciduous and coniferous forests requires an understanding of their inherent differences. While deciduous forests manage water better, and are less dependent (it can withstand larger periods of drought) (like in the case of L1 Pod Muráňom position 2, L3 Kôň all three position), coniferous forests are scavengers (in the case of L1 Pod Muráňom position 1 and 3; L2 Čierna Valley position 2). Additionally, it is colder beneath deciduous trees due to the fact that they have larger leaves and thus shade a larger area of land below. Coniferous forests have smaller needles, which are more likely to withstand winter periods. The second of these factors is soil type. L1 Pod Muráňom, L2 Čierna Valley and L3 Kôň are located on a limestone subsoil. In these mountain localities soils often occur on slopes where there is a high risk of erosion. As a result, there is a lot of semi-natural vegetation in these areas. This contributes to faster drainage and drying of slopes where vegetation is lacking. This is especially the case in the locality of L2 Čierna Valley, where natural vegetation is removed or missing. Slope orientation is another factor influencing forest temperature. L1 Pod Muráňom has a south-west orientation, while L2 Čierna Valley has a south-east orientation, and L3 Kôň has a north-west orientation. The warmest slopes are those with the greatest sun exposure; thus, southern slopes were selected. Meteorological conditions have significant impact on the ability to utilize thermal imaging. Measurements may be distorted by direct sunlight, rain (precipitation) and high humidity, including fog. We attempted to select optimal conditions for measurement (e.g., partial sunlight or cloud). Altitude and slope inclination have an impact on measurement as well. Given that the selected localities are in mountainous terrain, we took into account altitude, slope inclination and land cover. Air temperature also had a significant effect on measurements, and was included in the binding conditions for our measurements.

Preparation and analysis of images

Measurement took place five times per day in intervals of six hours. Previous images were designed based on the same shooting time. There are 830 complete observations with 12 variables in the dataset. The main variables for data evaluation were the type of locality, seasonality, minimal and maximal day/night temperature and type of forest area. Statistical analysis was processed in the environment of programming language "R" version 4.1.2. in the user interface RStudio 2021.09.2 Build+382 "Ghost Orchid" Release.

Results

Temperature of the studied forests from seasonality point of view

The highest median monthly temperature was recorded in all localities in June, and the lowest (depending on the locality) in March (L1 Pod Muráňom), January (L2 Čierna Valley) or December (L3 Kôň) (Figs. 8 and 9). Measured annual temperature at locality L2 Čierna Valley at the "clear-cut forest area" experienced a large range of temperature variation (Fig. 8). We can infer that this unshielded clear-cut area over-heats faster and more significantly on sunny days than the forest position comprised of "Norway spruce monoculture" in the same locality.

Figure 10 shows an evident rise in temperature in the morning and afternoon in some more stable positions like "old spruce forest" and "natural disturbance-based mixed forest", and a drop in temperature at these positions during the evening and night.

For position "clear-cut forest area", the average temperature reached the largest range of variation (it changed the most during the day and within the year). This is likely related to the lower water content in this type of forest area, which would dampen temperature fluctuations when the temperature changes occur. The smallest temperature fluctuations were recorded in the position "old spruce forest", whose humidity can likely cope with temperature fluctuations.

Discussion

We learned that there is high variability of forest temperatures in different localities. In our case, L1 Pod Muráňom, L2 Čierna Valley and L3 Kôň. The Belianske Tatras are part of the Eastern Tatras, and the sun tends to warm this range the most as it rises in the morning. The habitats that occur here are diverse, depending on the type of soil and geological bedrock, but are mostly comprised of spruce forests. We have found that deforested areas like locality L2 with position "clear-cut forest areas" on hillsides are overheating due to increased forest management, when compared to forests left without intervention, like the position "natural disturbance-based mixed forest" in locality L1 (Fig. 8). Temperate forests show moderate cooling in summer and moderate warming in winter with net cooling annually. The cooling or warming effects are mainly influenced by rainfall and snow (Li *et al.* 2015). The forest stands (deciduous and mixed, coniferous) are surfaces that cool the landscape due to evapotranspiration, which is reflected in low surface temperatures (Hesslerová *et al.* 2018).

In our measurement localities we also observed a significant variation due to seasonality. During summer, the most warm days were observed, particularly during the afternoon. In addition, the hottest temperatures at locality L2 were recorded in the morning (Figs. 8 and 9). The habitat in locality L2 was severely disturbed and sufficiently grafted to such an extent that the overall respiratory activity was disturbed and generally drained. The forest in the position "norway spruce monoculture" could

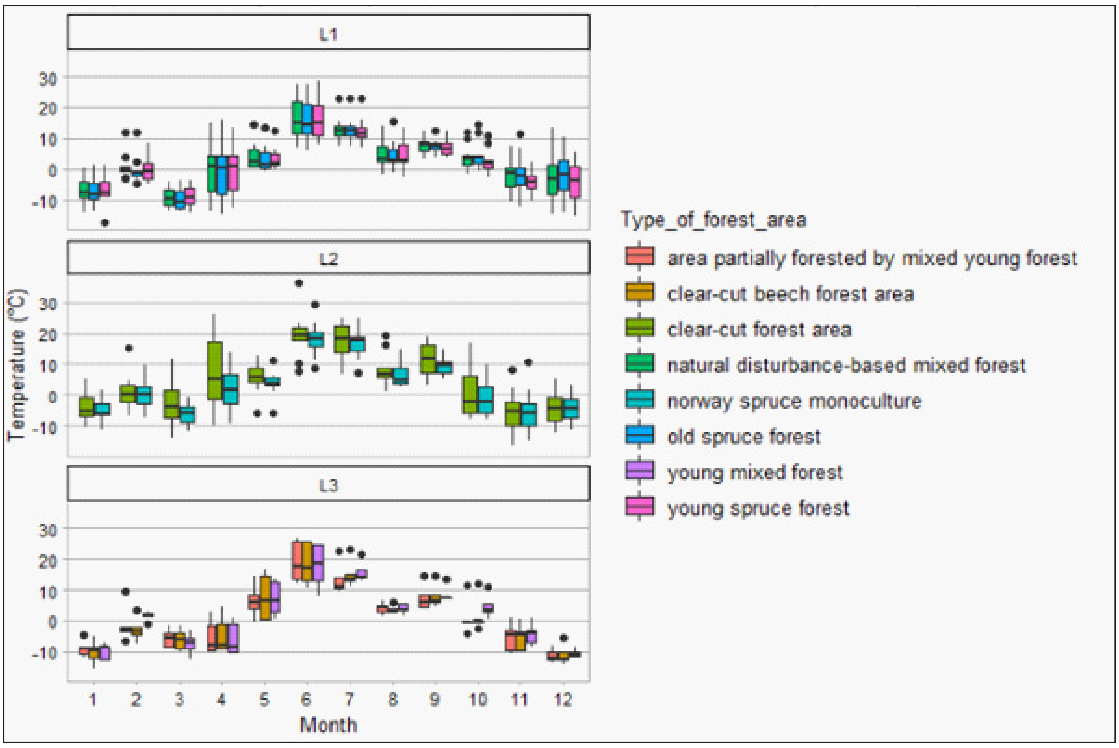

Fig. 8. Boxplot of average monthly temperature of monitored localities by forest types. Locality: L1 Pod Muráňom; L2 Čierna Valley; L3 Kôň. The graph shows the presence of a considerable number of extreme values, which are marked with black dots.

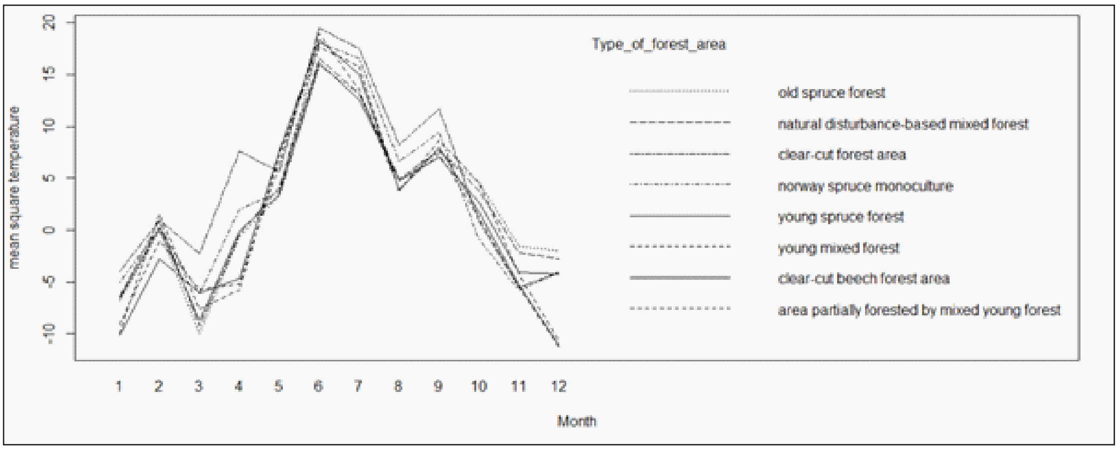

Fig. 9. Interaction plot of month and the square temperature. Square means a precisely defined level in the positions based on the pixel resolution, which was regularly measured.

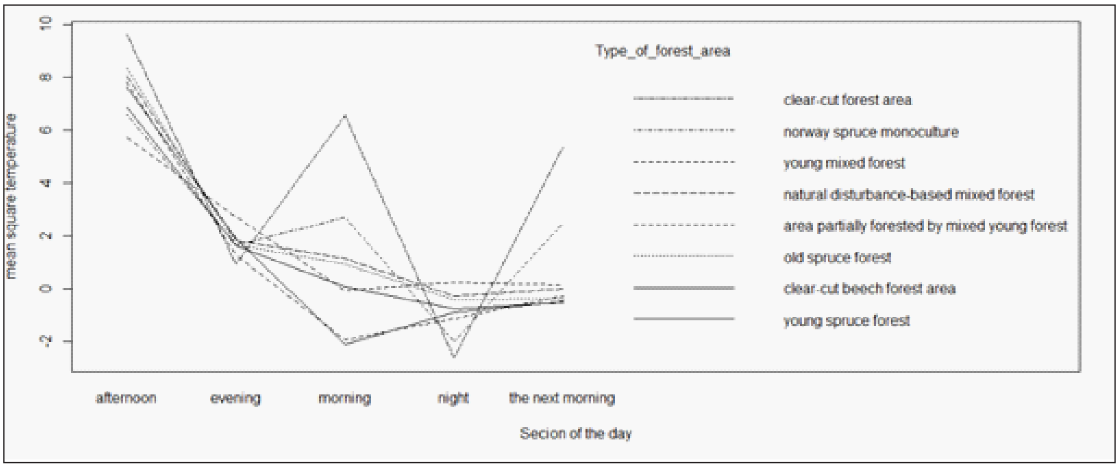

Fig. 10. Interaction plot of section of the day and the square temperature.

not retain moisture that fell several times a month, yet there was a precipitation deficit. The trees lacked middle and lower levels of vegetation in this position, and this effect was further enhanced. The opposite effect occurred in winter, when ambient temperatures dropped deeper below zero. In this case, the vegetation acted as an insulating layer for the bare roots of the trees and protected them from the cold. In the position "clear-cut forest area", only smaller shrubs and weeds were observed. According to Hesslerová *et al.* (2018), an increase in surface temperature is apparent in an area where the forest canopy layer died in the order of 2 - 4 °C. High surface temperature in the harvested forest area indicates production of sensible heat instead of evapotranspiration and cooling like in the case of position "clear-cut forest area".

Comparatively, in the position "old spruce forest" in locality L1, the temperature was completely different throughout the year (Figs. 8 and 9). The forest in this position was complete without serious intervention by anthropogenic activity, it retained moisture, was larger in size and was comprised of a variety of ages of vegetation. A major advantage such as stand density helped to balance the temperature effect, keep the same moisture in the summer and protect it from frost. In the position "natural disturbance-based mixed forest", dead trees, young beech, pioneer trees, rowan trees, and shrubs acted like sponges and supplied the habitat with the necessary water to survive the warm months. The large variability of microclimates in forest undergrowth is one of the most important legacies following natural disturbances (e.g., deadwood, diverse species and age composition) (Swanson *et al.* 2011). In winter, this position also showed only small temperature variations. We found that if the forest is of a mixed nature, and also consists of deciduous trees, it helps to better cope with moisture than a monocultural forest. Deciduous trees can manage the obtained water much more than coniferous forests (Wohlleben 2015). Trees like beech, maple and birch are also able to provide water to the surrounding environment and strengthen the entire ecosystem. The Belianske Tatras also have interesting soil conditions, with a composition of igneous rocks of granitoids and crystalline shales. The casing consists mainly of limestone, dolomite and clayey shales. This area does not have rich nutrient soils and is very often overheated through the earthenware base.

Our findings suggest that a forest without human intervention is far better able to tolerate different temperature fluctuations. The larger the forest ecosystem in terms of area, the more its microclimate and its internal functioning as a whole are affected. If a forest is extremely disturbed, fragmented or logged, it struggles to recover. This claim is also supported by the results which clearly show the differences between winter and summer seasons, daily and night time differences and their large temperature fluctuations. It is clear from our research that the highest temperatures in the areas occurred in June and July. Clear-cut areas displayed the highest values (Figs. 8 and 9), with temperatures ranging on average from 18 - 22 °C. However, it is worth mentioning that gusty temperatures were able to climb up to 38 degrees locally. Soil and air temperature are influenced by plant cover and the extremes within seasons and in day and night-time air temperatures are a function of transpiring vegetation height in hot and dry days and seasonal periods (Tesař *et al.* 2006).

The idea that harvested forests are less equipped to adapt is also supported by findings from the winter, that clearly demonstrate the same result. The average winter temperature was between -8 to -10 °C, but occasionally dipped to -12 (Fig. 8). Other forest areas, such as young mixed forests, tolerated such temperatures somewhat better. However, old coniferous forests based on natural disturbance were the areas that performed best in terms of their microclimate conditions. Soil saturation provides evaporation which in turn cools the forest area. This reflects the general observation that soil respiration rates decrease in saturated soils (Kucera and Kirkham 1971) and very dry soils.

These types of forests also fared better winter where vegetation prevented severe frost from penetrating the ecosystem and causing significant frost dieback of seedlings. Spruce forests and their monocultures are more susceptible to mortality caused by changes in soil temperature. The results of a Swedish study on soil warming (Bergh and Linder 1999; Majdi and Öhrvika 2004) led to the assumption that shallow roots determine the length of the growing season and that root mortality increases with increasing soil temperature. Closer analysis of the results revealed how temperature varies during the day at our studied localities.

In two localities (L1 Pod Muráňom, L3 Kôň) we found the same temperature pattern, namely that the lowest temperature was measured early in the morning when the air was still cool from the night, and gradually began to warm up during the day (Fig. 10). At that time, the sun is usually further from the centre and the accumulated heat is held in the canopy of trees or the sun-charged parts of holly trees. The crucial factor in these results is the elevation of the two localities (L1 Pod Muráňom and L2 Čierna Valley). As the locality Pod Muráňom has a higher altitude, it is colder compared to Čierna Valley (Fig. 8). Where the forest was left undisturbed, whether it was old or young, the air was constantly warming up along with the forest temperature. In this ideal case, heat is accumulated in the forest ecosystem, and as the forest is not in thermal stress, it functions properly (photosynthesis takes place). Transpiration is the plant-regulated evaporation of water from leaves or needles. Transpiration is only switched on when a plant is at risk of overheating due to ambient heat - from absorbed solar radiation and/or from warm air (Liu *et al.* 2016).

If the temperature of the plant drops - due to heat being consumed for evaporation and/or heat being radiated to cooler air, transpiration is switched off. It is thus a control with negative feedback. It is characterised by the fact that the control maintains the maximum temperature of the plant so that it stays within a narrow range of approximately 23 to 27 °C, with an optimum value of 25 °C (Šír *et al.* 2003). The L2 Čierna Valley in Tatranská Kotlina, however, behaved oppositely. There is a predominance of monoculture forest and clear-cut areas, where the temperature of the forest rises faster on sunny days than the air would be able to compensate for. The slope absorbs a greater amount of heat, causing greater evaporation, and the landscape dehydrates faster, resulting in vegetation mortality (Hesslerová *et al.* 2018). The air only later equalizes the temperature of the forest and this marks a non-constant curve. The areas studied are evenly matched in ambient temperatures and strive to maintain the same warming throughout the day. This equilibrium is also due to direct sunlight, which is evenly dispersed in the dense vegetation and thus warms the air equally.

Deciduous, coniferous and mixed forests respond differently to climate and temperature changes through the canopy level, leaves, branches and roots in the soil. The presence of a canopy of trees or litter layer on the soil surface may limit the flux of heat transfer from the atmosphere to the soil during the day, particularly in summer. However, at night, or on cool and cloudy days, a canopy of trees or litter layer may limit the upward trajectory of thermal radiation from the soil to the atmosphere (Paul *et al.* 2004).

Hutchison and Matt (1977) found a decrease in diffuse radiation transmission under cloudy skies. Compared to clear days in hardwood stands, demonstrating the effect of scattered direct radiation (Hutchison and Matt 1976). If the area is open, a greater amount of radiation falls and is immediately absorbed by the surface. If this area is disturbed by any activity, it is all the more vulnerable. Everything that receives the sun's rays heats up. The darker the object, the greater the response. However, nature is more complex and different principles apply. According to the interactions of forest temperatures, we can confirm that the first heat wave had its peak in February, then decreased gently and started to increase again at the end of April until June when it peaked (Figs. 8 and 9). Indirectly, we can argue that summer temperature seasons are becoming both more intense and longer lasting compared to winter seasons. When water was non-limiting, warm and even very warm summers had no negative effect on the canopy of mountain forests exposed to heat waves. The summer water balance partially expands the green period in late summer and early fall (Corona-Lozada *et al.* 2019).

Forest areas responded about the same in the measured mountainous localities with a few exceptions. Some areas have warmed up so much that they have prevented the growth of a new generation of forest. These are forests areas with no vegetation (bare-root areas). The land surface temperature regimes that affect these areas may be subject to changes in the form of altered energy balance, evapotranspiration and precipitation (Culf *et al.* 1996). Deforestation can accelerate climate warming, both directly as a result of the surface and indirectly as a result of increased greenhouse gases. It is also one of the main causes of biodiversity loss worldwide (Cusack *et al.* 2016), including in our measured localities.

Looking at the progression of the months more closely we can analyse the temperature variation during the day. We know that under ideal conditions, the sun is strongest, and thus emits the most light rays between morning to afternoon, and this is exactly what can be observed in our measurements (Fig. 10). The temperature at the localities rises between morning and afternoon, and the areas that are not shaded or have no vegetation cover are the ones that overheat the most. Calmer lower temperatures occur in the evening and at night. Various scientific studies indicate that temperatures during the day are higher than normal and therefore many forest areas are drying out. Plant regeneration and growth are also affected (Frost 1992), as tree mortality (Ruth *et al.* 1953; Gratkowski 1956) and ecosystem processes such as productivity and decomposition are strongly influenced by human encroachment.

Removing tree canopies through harvesting may result in increasing surface and air temperatures and in decreasing humidity. Soil compaction and rut formation by heavy machinery leads to increasing surface flow, enhanced erosion, and accelerated run-off generation in managed areas (Beudert *et al.* 2018). Microclimatic conditions and temperature changes are manifested differently in clear-cut areas compared to those where natural disturbance took place. Our results in two positions, ("clear-cut forest area" in the locality L2 and "natural disturbance-based mixed forest" in the locality L1) present exactly this scenario (Fig. 8). Dead trunks following natural disturbance provide shade and limit wind speed, thus maintaining microclimatic variability in their surroundings and underlying soils (Kopáček *et al.* 2020). Stands regenerating after disturbance in unmanaged areas have a heterogeneous structure due to the predominant association of seedlings with specific microhabitats (Bače *et al.* 2015).

Acknowledgements

We want to express our gratitude to everyone who contributed to our work in other ways, such as scientific opinions or relevant references.

References

Bače, R., Svoboda, M., Janda, P., Morrissey, R.C., Wild, J., Clear, J.L., Čada, V. and Donato, D.C. 2015: Legacy of pre-disturbance spatial pattern determines early structural diversity following severe disturbance in montane spruce forests. *PLoS One*, **10**: 139-214.

Bergh, J. and Linder, S. 1999: Effects of soil warming during spring on photosynthetic recovery in boreal Norway spruce stands. *Glob. Change Biol.*, **5**: 245-253.

Beudert, B., Bernsteinová, J., Premier, J. and Bässler, C. 2018: Natural disturbance by bark beetle offsets climate change effects on streamflow in headwater catchments of the Bohemian Forest. *Silva Gabreta*, **24**: 21-45.

Corona-Lozada, M.C., Morin, S. and Choler, P. 2019: Drought offsets the positive effect of summer heat waves on the canopy greenness of mountain grasslands. *Agr. Forest Meteorol.*, **276**: 107-617.

Culf, A.D., Esteves, J.L., Filho, A.O.M. and Da Rocha, H.R. 1996: Radiation, temperature and humidity over forest and pasture in Amazonia. *Amazonian Deforestation and Climate*, **5**: 175-192.

Cusack, D.F., Karpman, J., Ashdown, D., Cao, Q., Ciochina, M., Halterman, S., Lydon, S. and Neupane, A. 2016:

A Global change effects on humid tropical forests: Evidence for biogeochemical and biodiversity shifts at an ecosystem scale. *Rev. Geophys.*, **54**: 523-610.

Frost, E.J. 1992: The effects of forest-clearcut edges on the structure and composition of oldgrowth mixed conifer stands in the western Klamath mountains. Doctoral dissertation, Humboldt State University, CA, USA.

Gallopin, G.C., Hammond, A., Raskin, P. and Swart, R. 1997: Branch points: global scenarios and human choice. SEI, Stockholm, Sweden.

Gratkowski, H.J. 1956: Wind throw around staggered settings in old-growth Douglas-fir. *Forest Sci.*, **2**: 60-74.

Hesslerová, P., Huryna, H., Pokorný, J. and Procházka, J. 2018: The effect of forest disturbance on landscape temperature. *Ecol. Eng.*, **120**: 345-354.

Hutchison, B.A. and Matt, D.R. 1976: Beam enrichment of diffuse radiation in a deciduous forest. *Agr. Meteorol.*, **17**: 93-110.

Hutchison, B.A. and Matt, D.R. 1977: The distribution of solar radiation within a deciduous forest. *Ecol. Monogr.*, **47**: 185-207.

Kopáček, J., Bače, R., Hejzlar, J., Kaňa, J., Kučera, T., Matějka, K., Porcal, P. and Turek, J. 2020: Changes in microclimate and hydrology in an unmanaged mountain forest catchment after insect-induced tree dieback. *Sci. Total Environ.*, **720**: 137-518.

Kucera, C.L. and Kirkham, D.L. 1971: Soil respiration studies in tallgrass prairie in Missouri. *Ecology*, **52**: 912-915.

Ledig, F.T. 1992: Human impacts on genetic diversity in forest ecosystems. *Oikos*, **63**: 87-108.

Li, Y., Zhao, M., Motesharrei, S., Mu, Q., Kalnay, E. and Li, S. 2015: Local cooling and warming effects of forests based on satellite observations. *Nat. commun.*, **6**: 1-8.

Liu, X., Nie, Y., Luo, T., Yu, J., Shen, W. and Zhang, L. 2016: Seasonal shift in climatic limiting factors on tree transpiration: Evidence from sap flow observations at alpine treelines in southeast Tibet. *Front. Plant Sci.*, **7**: 10-18.

Majdi, H. and Öhrvik, J. 2004: Interactive effects of soil warming and fertilization on root production, mortality, and longevity in a Norway spruce stand in Northern Sweden. *Glob. Change Biol.*, **10**: 182-188.

Paul, K.I., Polglase, P.J., Smethurst, P.J., O'Connell, A.M., Carlyle, C.J. and Khanna, P.K. 2004: Soil temperature under forests: a simple model for predicting soil temperature under a range of forest types. *Agr. Forest Meteorol.*, **121**: 167-182.

Ruth, R.H., Forest, P.N. and Yoder, R.A. 1953: Reducing wind damage in the forests of the Oregon Coast Range. U.S. Department of Agriculture, Portland,Oregon, USA.

Swanson, M.E., Franklin, J.F., Beschta, R.L., Crisafulli, C.M., DellaSala, D.A., Hutto, R.L., Lindenmayer, D.B. and Swanson, F.J. 2011: The forgotten stage of forest succession: earlysuccessional ecosystems on forest sites. *Front. Ecol. Environ.*, **9**: 117-125.

Šír, M., Tesař, M., Lichner, Ľ. and Syrovátka, O. 2002: Klimatická změna a transpirace rostlin. In: Extrémní hydrologické jevy v povodí (eds. A. Patera, J. Váška, and A. Jakubíková), pp. 151-156. Fakulta stavební ČVUT a Česká vědeckotechnická vodohospodářská společnost, Praha, Czech republic.

Tesař, M., Šír, M., Lichner, Ľ. and Zelenková, E. 2006: Influence of vegetation cover on thermal regime of mountainous catchments. *Biologia*, **61**: 311-314.

Wohlleben, P. 2015: Das geheime Leben der Bäume: was sie fühlen, wie sie kommunizieren-die Entdeckung einer verborgenen Welt. Ludwig Verlang, München, Germany.

Received 17 May 2022; accepted 15 June 2022.