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Estimation of the leaf area index in a decline spruce forest in the Western Tatra Mountains for determination of rainfall interception

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Leaf area index (LAI) is an important vegetation leaf structure parameter in forest and agricultural ecosystems. In the paper, we deal with the estimation of leaf area index (LAI) and woody area index (WAI) values in a decline climax spruce forest. The research is conducted on the Červenec research plot at an altitude of 1,420 m a.s.l. in the Western Tatra Mountains in the Jalovecký Creek catchment. We carried out the initial measurements during June, August and October 2023. We estimated the values of the LAI and WAI in the mature living and dead spruce stands using hemispherical photography and HemiView software. LAI and WAI values weren´t corrected with clumping index. The average values in the living and dead forest stands were 4.7 and 3.0, respectively. In addition to the estimation of the spruce canopy layer LAI, we measured the LAI values of the understorey vegetation in the living, dead stand and in an open area using the SunScan instrument and the SunData software. The highest LAI values of the understorey in the living stand (1.9), in the dead stand (5.3) and in an open area (2.9) were obtained in August, when the vegetation was fully leafy. On the other hand, the lowest LAI values in the understorey were reached in the living stand (1.2) and in an open area (1.8) in October, when the vegetation was already without leaves.

KEY WORDS: mountain spruce forest, canopy layer, rainfall interception, Jalovecký Creek catchment

Introduction

Leaf area index (LAI) was defined as the total one-sided area of leaf tissue per unit ground surface area (Chen and Black, 1992; Fasschnat et al., 1994). According to this definition, LAI is a dimensionless quantity characterizing the canopy of an ecosystem, although it is sometimes reported in units of $m^2 m^{-2}$ (Rich et al., 1995; Scurlock et al., 2001). In forestry, LAI is often defined as the area of one side of green leaves per unit area for deciduous stands. For conifers, the determination of LAI is more complex and the following three definitions are usually used: a) total surface of needles per unit area, b) total surface of needles per unit area divided by two, c) projected area of needles per unit area (Pavlendová, 2010; Pokorný, 2015). The long-term monitoring of LAI can provide understanding of dynamic changes in productivity and climate impacts on forest ecosystems. In addition, LAI can serve as an indicator of stress in forests, e.g. to investigate the relationships between environmental stress factors and forest insect damage (Zheng and Moskal, 2009).
Several studies divided the LAI assessment methods into direct and indirect (Chason et al., 1991; Fasschnat et al., 1994; Dufrêne and Bréda, 1995; Chen et al., 1997b). Direct methods are based on the collection of leaves from trees and the subsequent calculation of their area. Direct methods are further divided into harvesting and non-harvesting (Jonckheere et al., 2004). The harvesting method is a destructive method and consists in removing all the leaves from the vegetation and evaluating the area of the leaves, e.g. using optical measuring devices (Baret et al., 2010, White et al., 2019). This method is more suitable for agricultural crops than for forest stands (Jonckheere et al., 2004). The non-harvesting method is a direct non-destructive method based on the collection of fallen leaves during one season. Spontaneously falling leaves of deciduous trees are caught in nets. Direct methods are very accurate albeit extremely time-consuming and laborious. The use of direct methods for larger areas and in the forestry, practice is therefore inappropriate (Pokorný, 2015).
When using indirect methods, the LAI value is derived from the observation of other variables. Indirect methods are faster compared to direct methods, measurements can be automated and used in larger areas (Jonckheere et al., 2004). Indirect methods derive LAI from measurements of solar radiation transmission through the canopy using efficient and nondestructive optical instruments (e.g. LAI-2000 Plant Canopy Analyzer, Tracing Radiation and Architecture of Canopies (TRAC) or Digital Hemispherical Photographs). We can also call these indirect methods as optical indirect methods. Indirect methods estimate the LAI based from the relationship

with other vegetation characteristics (Bréda, 2003; Yan, 2019). The development of remote sensing methods brought more progressive methods of determining the LAI. One of them is the airborne laser scanning system, commonly known by the acronym LiDAR (Light Detection and Ranging) (Sabol et al., 2014) The LiDAR system provides effective tools for estimating the spatial distribution of LAI for large areas, and its advantage in remote sensing is that it directly provides three-dimensional coordinates (Jung and Crawford, 2011; Alonzo et al., 2015; Xu et al., 2020). Indirect methods have been rapidly developed and used since the 1990s. They are highly recognized in the scientific community, and are used in several fields and industries (Yan, 2019).
In recent years, the forests in the spring areas of the Tatras have undergone significant changes related to dying and subsequent regeneration. These changes also affect the hydrological cycle, but estimating their impact at the catchment scale is only possible through hydrological modeling. Therefore, it is necessary to express these changes by changes in the parameters of hydrological models, which represent the influence of vegetation on the hydrological cycle. One such parameter of hydrological models is the leaf area index, which is used in the calculation of rainfall interception and estimation of the amount of precipitation that can infiltrate into the soil.
In the Jalovecký Creek catchment, which represents the hydrological conditions of the highest Tatras catchments, at the Červenec site since 2006 are ongoing measurements characterizing the rainfall interception of the mountain spruce forest. After 2012, the living spruce forest began to disintegrate and dieback initiated by windfalls and bark beetle outbreaks, which made it possible to perform comparative measurements of some characteristics (rainfall interception, snow water equivalent, surface runoff) in dead (the regeneration has already started) and living spruce stand (Bartík et al., 2019; Jančo et al., 2021; Holko et al., 2022a; Holko et al., 2022b) Currently, the living spruce stand is gradually being completely reduced.
The aim of this study was to propose and evaluate a method of estimating the leaf area index of living and dead stand (spruce forest), as well as the understorey, which began to develop significantly after the spruce forest dieback. The paper presents the results of the first measurements that were carried out in the summer of 2023. The understorey LAI was also estimated for the open area.

Material and methods

Study area

The Červenec study site (latitude 49.183617°N, longitude 19.641944°E) is situated at an altitude of 1,420 m a.s.l. in a mature climax spruce stand in the Jalovecká valley in the Western Tatra Mountains (Slovakia) (Fig. 1.). The whole research site is located within a geologic boundary between the Crystallinic and Mesozoic zones in the Inner Western Carpathians. The predominant crystalline rocks are granodiorites and rules covered with cambisol podsoles and accompanied with lithosols and rankers. From the Mesozoic rocks, the dominant types include calcites and dolomites with developed cambisol rendzinas (Bartík et al., 2014). This part of the Western Tatras belongs to the cold climatic region, the cold mountain district (Klimatický atlas Slovenska, 2015). The annual average air temperature at Červenec for the period of years 1988–2017 is 3.0°C and long-term annual precipitation is 1,450 mm (Danáčová et al., 2019). According to Stanová and Valachovič (2002), forest communities belong to Alpine and Carpathian subalpine (*Picea)* forests; Acidophilous spruce forests (*Vaccinio-Piceetea*). According to Hančinský (1972), the research site is situated in the 7th spruce (*Picea*) altitudinal vegetation zone, types: *Sorbeto-Piceetum* (60%) and *Acereto-Piceetum* (40%).
The predominant tree species is Norway spruce (*Picea abies*, L. Karst.), accounting for 100% of the tree species coverage. The age of the mature stands is up to 150 years. In the living forest, the understorey is represented by the European blueberry (*Vaccinium myrtillus* L.). The open area is predominantly represented by European blueberry (*Vaccinium myrtillus*, L.) as well, but the red raspberry (*Rubus idaeus*, L.), rowan (Sorbus aucuparia, L.), red campion (*Silene dioica*, L.) and natural spruce regeneration occurs there too. In the dead stand, where the succession takes place, the understorey is the most diverse. It is formed by the European blueberry (*Vaccinium myrtillus*, L.), red raspberry (*Rubus idaeus*, L.), rowan (*Sorbus aucuparia*, L.), ragwort (*Senecio sp.*, L.), rattlesnake root (*Prenanthes purpurea*, L.), and great wood-rush (*Luzula sylvatica*, L.) species, to a lesser extent red campion (*Silene dioica*, L.) and narrow buckler-fern (*Dryopteris cartusiana*, L.).
The site has a south-east exposition with a slope of 20°–33°. Currently, the research site has an area of about 1000m^2 (which of living stand – 360 m^2, dead stand – 220 m^2, open area – 450 m^2). The average tree height is 26.8 m and the average stem diameter at breast heigh in the stands is 40.5 cm. Directly below the upper tree line, stocking density in the stands is significantly reduced to value 0.6.

Estimation of the canopy layer effective leaf area index in the living stand and woody area index in the dead stand

The LAIe and WAI estimation at all stands were carried out during the growing season 2023 on June16, August 8 and October 19. It is also important to realize that in dead forest, the value determined as the leaf area index (LAI) doesn't correspond to the area of leaves ("needles") that are no longer there, but rather to the "woody area index" (WAI).
When determining the canopy layer LAIe and WAI using the hemispherical photography, we first established one transect in the living and dead stand. On the transect in the living stand (length 28 m), we marked 7 points at a distance of 3–6 m. On the transect in the dead stand (length 16 m), we marked 4 points at a distance of 5–6 m. On these points where we took photographs, we marked these points with wooden pegs to ensure that

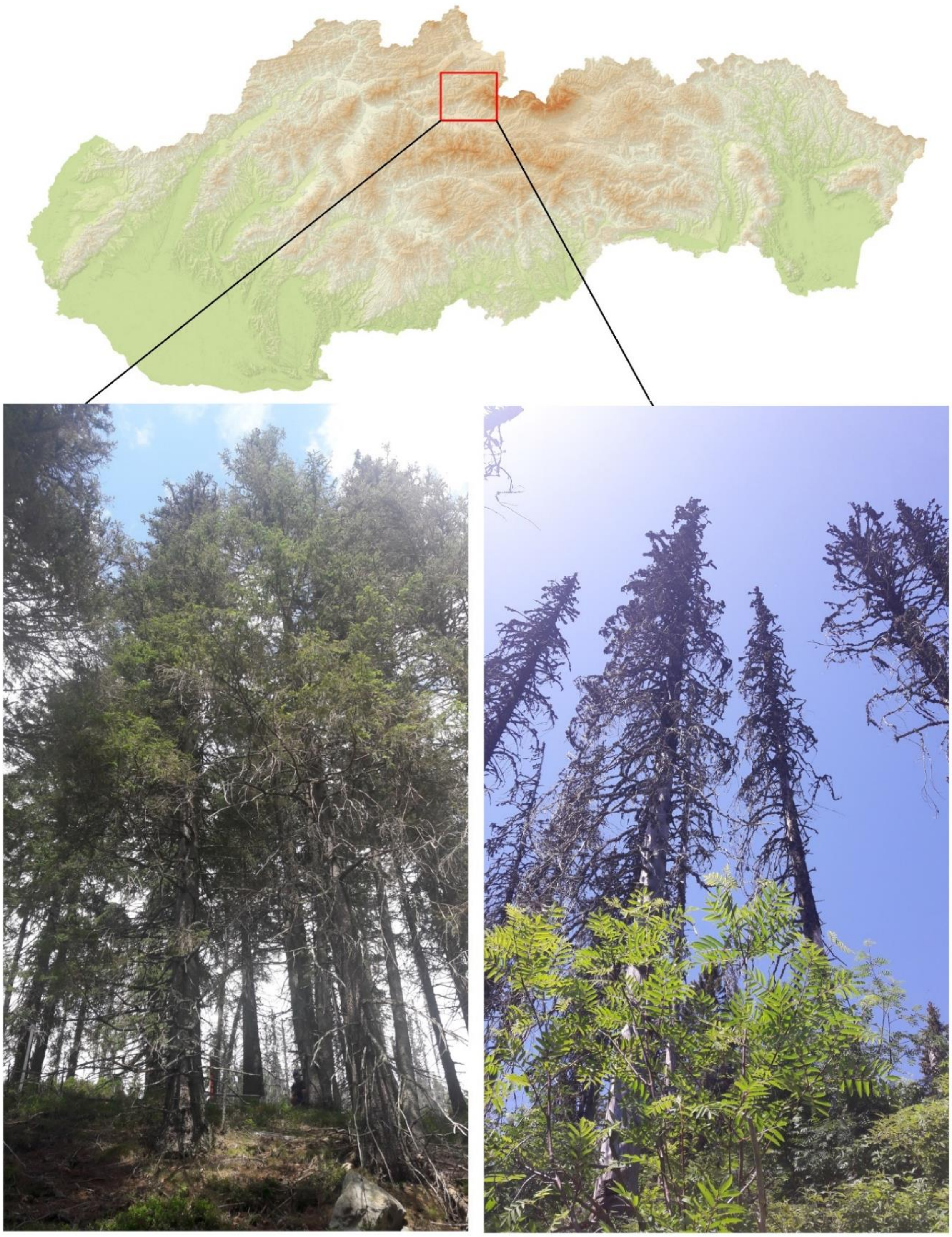

Fig. 1. Research plot Červenec (left: living spruce stand, right: dead spruce stand).

the photographs on other dates were shot on the same points. The number of these points wasn´t the same and depended on the size of the area covered by the rest of the living and dead forest. Unlike traditional measurements, which are usually carried out in forestry, we didn´t have the opportunity to make them in a homogeneous forest of a large area. Due to the slope, the orientation of the transects was chosen along the contour line in both stands. The height of the trees in both stands was approximately the same. Within the transect, we tried to capture all tree crowns.

The photographs were taken by Canon EOS 50D digital camera with a sigma EX DC lens with a focal length of 4.5 mm (fisheye) and a resolution of 15 MB (Fig. 2.). The camera was placed on a tripod (1.3 m from the soil surface), its horizontal position, which ensures that the lens is directed vertically upwards, was controlled by a spirit level, and the camera was oriented using a compass so that the upper edge of the photograph was pointing to north. The photographs were taken with aperture priority (F 8.00) with bracketing.

Of the three photographs obtained in this way, the one with the subjectively best contrast was selected for the processing (Danko et al., 2018). Photographs in the jpg. format was processed in the HemiView software (Delta-T Devices, 1999) with the surrounding terrain (recorded understorey) filtered out. The final processing was done with the photographs, cropped according to a circular template that was the same for all sites (Fig. 3.). The threshold value that separates the visible sky from the vegetation cover (needles) was the same for all evaluated photographs. The LAI values obtained in this way in living stand weren´t corrected with clumping index. The clumping effect is an important factor complicating indirect LAI measurements. This index at different scales quantifies the spatial pattern of leaf distribution and is a transforming factor for calculating the true LAI from the effective LAI (Bao et al., 2018). Therefore, in our case, it is appropriate to term the leaf area index as effective LAI (LAIe).

Estimation of the leaf area index of the understorey vegetation

The understorey LAI estimation at the living and dead forest stands and in an open area was carried out using the SunScan instrument (Delta T) (Fig 2.). The wooden pegs used to mark the points for taking hemispherical photographs determined the transect lines for the SunScan measurements. The transects were marked also in the open area. The SunScan instrument consists of a portable probe, which is a one meter long and contains 64 calibrated photodiodes, which are evenly distributed along its entire length and measure the flux of photosynthetically active radiation (PAR) below the canopy of the given crop or type of vegetation. Another part of this instrument is the Beam fraction sensor (BFS) – a sunshine sensor that measures direct and diffuse incident radiation above the canopy of the given crop, or type of vegetation, which is which is necessary for the computation of LAI. During each measurement, the BFS sunshine sensor was placed near to the living stand and dead stand in an open space. The probe and the BFS sensor are equipped with small antennas, which are connected via the radio waves. The probe is also equipped with a cable connected to the personal digital assistant (PDA) via the RS232 serial port connector. The PDA (Trimble) is a small portable electronic device where the SunData software is installed, in which the measured values of LAI or PAR are stored. It is necessary to set the leaf absorption value in the SunData software before the measurement. Absorption is the percentage of incident PAR absorbed by the leaf. Most leaves have the absorption values in the range of 0.8–0.9, so the standard value used in most cases is 0.85. Another parameter whose value we had to enter before the measurement was the ellipsoidal leaf angle distribution parameter (ELADP), that characterizes the horizontal or vertical direction of the leaves in the canopy of a given type of vegetation. For most crops have ELADPs in the range 0.5–2.0. In our case, we used the value 1.0, which was prescribed in the Delta T manual.

All analyses and plot displays were performed using Statgraphics Centurion 16 and Microsoft Excel 2016 software.

Fig. 2. Digital camera Canon EOS 50D and SunScan instrument (BFS sensor, SunScan probe and PDA Trimble).

Fig. 3. An example of photograph processing (left: original photograph in the living and dead stand and right: circular cropped photograph for processing in HemiView software)

Results and discussion

Effective leaf area index and woody area index of the canopy layer in the living and dead stand

Fig. 4. shows that seasonal variability of LAIe at the majority of 7 points in the living forest where the hemispheric photographs were taken, was negligible. We noted an exception at point number 2, where the LAIe values differed significantly in individual terms. The inspection of the photographs suggested that some error was made during the shooting (e.g. different height of the tripod, or failure to point the camera to the north). Significant changes of the LAIe in the living spruce forest occur in this area at the beginning of the growing season, approximately in April and May, depending on the air temperature and the duration of the snow cover (Škvareninová, 2009), when we can observe the following vegetative phenophases based on the Slovak Hydrometeorological Institute methodology (Kolektív, 1984): a) flushing of the buds of needles, b) burst of the buds of needles, c) first May sprouts, d) mature needles. Considering that all three measurements were already carried out in the phenophase of "mature needles" and our previous measurements in the Jalovecká valley (Danko et al., 2018) showed a relatively small seasonal variability of spruce stands of different ages, we consider the results obtained for point 2 to be unusual. Similar results for a 30-year-old spruce monoculture stand are also reported by Pokorný et al. (2008), where no significant differences between subsequently obtained values were found within the 2 months (August to September) right after reaching the seasonal maximum. The mean values of LAIe in the individual measurement dates were 5.0 in June, 5.1 in August and 4.8 in October. Therefore, this point wasn´t taken into account in further processing. The mean values of LAI values in the individual measurement dates, excluding point 2, were 4.7 in June, 4.6 in August and 4.5 in October. The average value in the living forest stand was 4.7.

The WAI values estimated for the dead forest stand is shown in Fig. 5. The values remained rather stable and ranged from 2.9 to 3.2. It follows that the mean values of WAI were 2.9 in June, 3.1 in August and 3.0 in October. The average value in the dead forest stand was 3.0.

The estimation of the leaf area index (LAI) of forest stands has been the subject of a large number of studies in the world. LAI is a key parameter for global and regional models of biosphere/atmosphere exchange of carbon dioxide, water vapor, and other materials. It also plays an integral role in determining the energy balance of the land surface. This data set provides a benchmark of typical values and ranges of LAI for a variety of biomes and land cover types, in suport of model development and validation of satellite-derived remote sensing estimates of LAI and other vegetation parameters (Scurlock et al., 2001). Determination of LAI in stands of forest trees depends mainly on the species composition and structure of the stand (Pokorný and Opluštilová, 1999). Vose et al. (1994) report that the LAI values of coniferous trees in most cases reach maximum values of 6 to 8. The highest values are achieved by coniferous forests, which consist of Douglas-fir, fir, hemlock and spruce species. Chen et al. (1997a) reported LAI values from 1 to 6 for boreal forests (*Picea marina*, L.) in Canada of various ages.

In addition to the structure, the age of the stand is an important parameter in determining LAI. The relationship between LAI and stand age in spruce stands showed that LAI gradually decreases with increasing stand age. A 15-year-old spruce stand reached LAIe 8.2, while a 100-year-old spruce stand reached a value of 4.35 (Pokorný and Stojnič, 2012). Similar results, when LAI decreases with increasing age of spruce stands, are also reported by Homolová et al. (2007) and Kram (1998).

Stocking density is another important parameter in determining LAI. Küßner and Mosandl (2000) report LAIe values in the range of 0.68 – 4.84 for mature spruce stands of about 100 years of different stocking density. Determination of LAI in an 80-90-year-old spruce forest in the Liz catchment (Šumava) was also dealt with by Dohnal et al. (2014), LAIe reached values ranging from 3.54 to 3.75. Our results of determining LAIe (mean value 4.7) in a living 150-year-old spruce stand coincide with the range of LAIe values that are given in foreign studies dealing with the estimation of LAI in spruce stands or boreal forests.

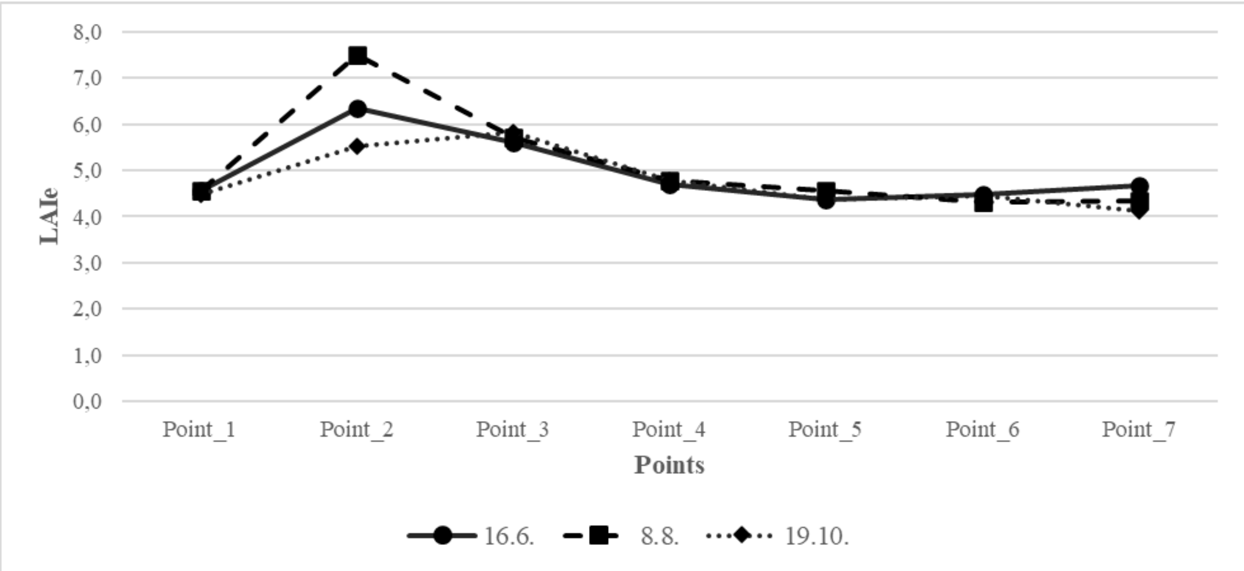

Fig. 4. LAIe values in the living stand using a hemispherical photograph.

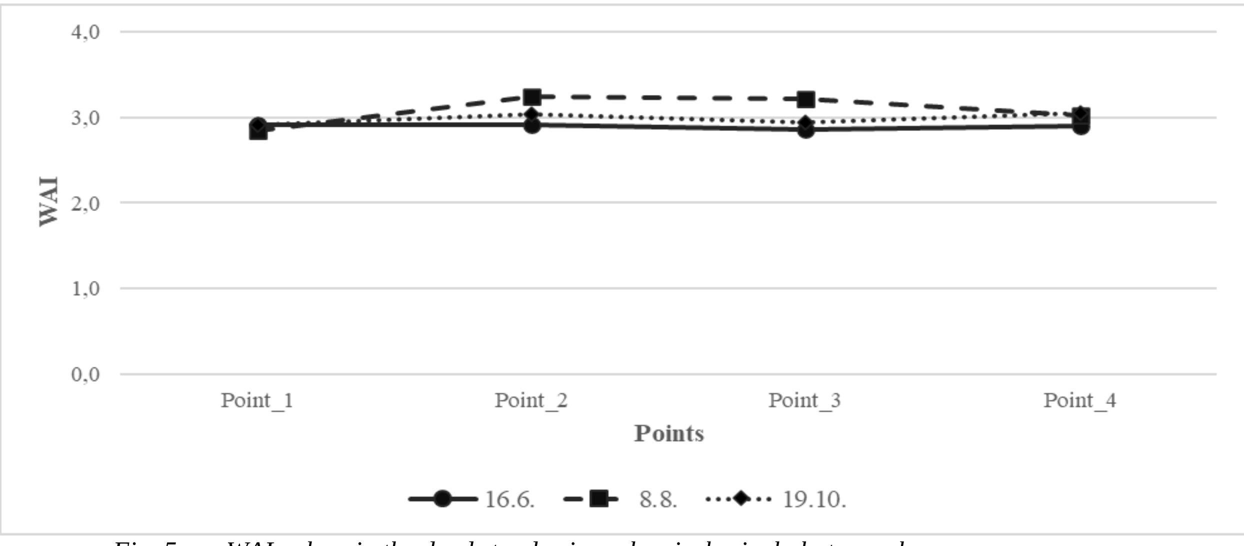

Fig. 5. WAI values in the dead stand using a hemispherical photograph.

Leaf area index of the understorey in the living, dead stand and in an open area

Table 1. shows that during the first measurement on June 16, the mean LAI values of the understorey in the living and dead stand (living – 1.6, dead – 1.7) were very similar. The highest range of values was found in the open area, the smallest in the dead forest. During the measurements on August 8, we started measuring LAI below *Sorbus aucuparia* in an open area, in addition to the understorey of *Vaccinium myrtillus*. The obtained LAI values were in the following order: dead forest (5.3) > rowan (3.9) > open area (2.9) > living forest (1.9). The highest range of values was again in the open area, the smallest in the living forest. On October 19, the highest mean LAI value was obtained in the dead forest (2.3), followed by the open area (1.8), living forest (1.2), and rowan (0.8). The highest range of values occurred again in the open area, the smallest in rowan.
The statistical characteristics of the measured understorey LAI values are shown in Table 1.

At the first measurement on June 16, the understorey was the least developed in the dead forest. Therefore, the LAI values were almost identical values with the ones in the living forest. In the living forest and also in an open area, the *Vaccinium myrtillus* was already 100% leafy. When comparing the *Vaccinium myrtillus* in an open area and in the living forest, a higher coverage and stature were found in an open area which is why the LAI in an open area was higher (Fig. 7.). In August, the LAI has increased in all sites. We noticed the most significant increase in the dead forest. The herbs that form this understorey were fully developed (Fig. 6.). In an open area and in the living forest, the *Vaccinium myrtillus* had already grown fruits at full maturity. It resulted in a slight increase in the LAI values at these two sites.
During the last measurement, we observed a decrease in LAI values at all monitored locations. The leaf fall occurred on the *Vaccinium myrtillus* in the living forest and in an open area, and the *Sorbus aucuparia* also had fallen leaves. In the dead forest stand, the leaves of *Rubus idaeus* have not yet fallen completely.

Table 1. Statistical characteristics of the understorey LAI values

	Count	Arithmetic mean	Median	Standard deviation	Coeff. of variation	Minimum	Maximum	Range
Living (June 16)	18	1.6	1.6	0.52	31.85	0.5	2.6	2.1
Dead (June 16)	10	1.7	1.6	0.25	15.45	1.3	2.1	0.8
Open (June 16)	9	2.4	2.4	1.07	44.02	1.2	5.0	3.8
Living (August 8)	18	1.9	1.8	0.65	33.57	0.9	3.4	2.5
Dead (August 8)	10	5.3	5.4	1.27	24.25	3.3	7.1	3.8
Open (August 8)	9	2.9	2.6	1.36	46.53	1.8	6.2	4.4
Rowan (August 8)	5	3.9	4.2	1.23	31.46	2.1	5.2	3.1
Living (October 19)	18	1.2	1.2	0.38	30.97	0.7	1.9	1.2
Dead (October 19)	10	2.3	2.1	0.50	22.18	1.7	3.2	1.5
Open (October 19)	9	1.8	1.7	0.57	31.80	0.9	2.7	1.8
Rowan (October 19)	5	0.8	0.8	0.22	26.44	0.5	1.1	0.6

Fig. 6. Understorey in the living stand (left), in dead stand (in the middle) and in an open area (right) during August.

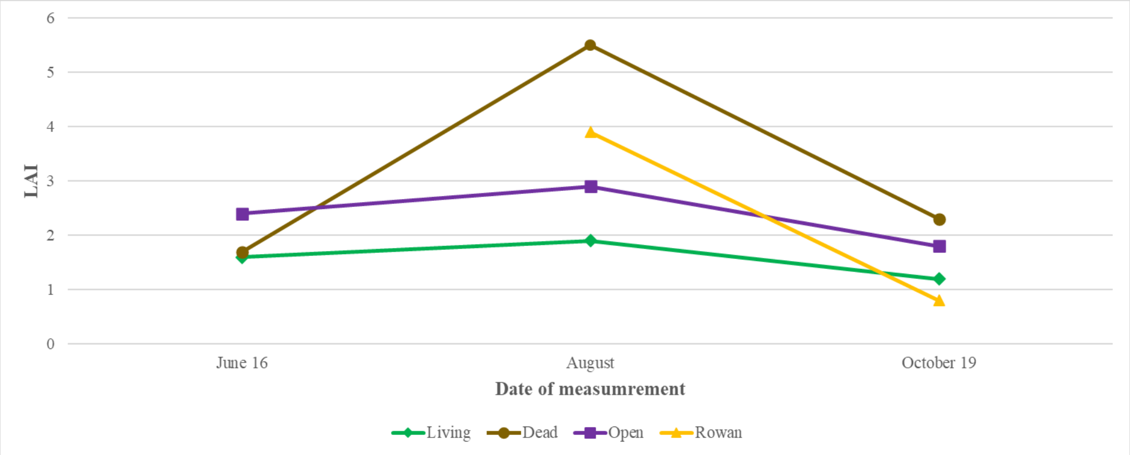

Fig. 7. LAI values in the understorey at the observed sites.

Conclusion

At the research plot, which is similar to other localities with ongoing forest dieback, we obtained characteristics by indirect methods enabling the parameterization of hydrological models in the calculation of rainfall interception. Higher values, which represent leaf area index (approx. 4.1-5.8), were found for living forest and didn´t have much seasonal variability in the observed period. Lower values (approx. 3.0), which represent the woody area index were found for dead spruce stand. The understory leaf area index has the most significant seasonal variability in the dead stand compared to the understory in the living stand and in the open area. At all evaluated sites, we recorded the highest understory LAI values in summer (August) as a result of the development of the phenophases of the individual observed species.

The preliminary results of the initial measurements presented in the paper will enable the adjustment of the measurements in the next season (capturing the beginning of the growing season, slightly more measurements during the season). The number of measuring points in individual localities is limited by their small area.

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