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Effect of mature spruce forest on canopy interception in subalpine conditions during three growing seasons

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Abstract: The interception process in subalpine Norway spruce stands plays an important role in the distribution of throughfall. The natural mountain spruce forest where our measurements of throughfall and gross precipitation were carried out, is located on the tree line at an elevation of 1,420 m a.s.l. in the Western Tatra Mountains (Slovakia, Central Europe). This paper presents an evaluation of the interception process in a natural mature spruce stand during the growing season from May to October in 2018–2020. We also analyzed the daily precipitation events within each growing season and assigned to them individual synoptic types. The amount and distribution of precipitation during the growing season plays an important role in the precipitation-interception process, which confirming the evaluation of individual synoptic situations. During the monitored growing seasons, precipitation was normal (2018), sub-normal (2019) and above-normal (2020) in comparison with long-term precipitation (1988–2017). We recorded the highest precipitation in the normal and above-normal precipitation years during the north-eastern cyclonic synoptic situation (NEc). During these two periods, interception showed the lowest values in the dripping zone at the crown periphery, while in the precipitation sub-normal period (2019), the lowest interception was reached by the canopy gap. In the central crown zone near the stem, interception reached the highest value in each growing season. In the evaluated vegetation periods, interception reached values in the range of 19.6–24.1% of gross precipitation total in the canopy gap, 8.3–22.2% in the dripping zone at the crown periphery and 45.7–51.6% in the central crown zone near the stem. These regimes are expected to change in the Western Tatra Mts., as they have been affected by windstorms and insect outbreaks in recent decades. Under disturbance regimes, changes in interception as well as vegetation, at least for some period of time, are unavoidable.

Keywords: Precipitation; Interception; Synoptic types; Norway spruce (*Picea abies* L. Karst.); Growing season.

INTRODUCTION

In the conditions of the Western Carpathians, atmospheric precipitation is almost the only income component of the water balance (Minďáš, 2003). Forest canopies standing up in the air impede precipitation from reaching the ground. A portion of precipitation is inevitably intercepted by the canopy (canopy interception), flows along the stem to the ground surface (stemflow), drips from the foliage and branches or passes through canopy openings to the ground (throughfall), or is further intercepted by ground plants or the forest floor (litter interception). These processes cause a reduction in precipitation quantity and a redistribution of precipitation towards the soil (Arnell, 2002; Chang, 2013; Klamerus-Iwan et al., 2020; Sadeghi et al., 2020; Střelcová et al., 2006). The water regime of forest stands is also determined by the precipitation conditions of a given locality as well as by the properties of soils. Out of the many properties of a stand, the amount and distribution of the assimilation area is the most important factor for affecting the water balance in an ecosystem. Indeed, it determines the amount of transpiration as well as the retention of precipitation on the surface, i.e. interception (Bruijnzeel, 2004; Landsberg and Waring, 2014; Pypker et al., 2011; Shelton, 2009; Zabret et al., 2018). Interception is the process in which part of the rainwater is used or retained on the surface of trees or plants. This water neither infiltrates into the soil nor drains in the form of surface runoff. Therefore, the amount of intercepted precipitation that returns to the atmosphere upon evaporation is often referred to as interception loss (Dohnal et al., 2014; Gregersen et al., 2007; Llorens and Gallart, 2000; Šraj et al., 2008; Ward and Trimble, 2003).

From the point of view of the water balance, the interception of precipitation in spruce stands is quite significant. However, its magnitude varies in an orographically and vertically divided area. Interception plays a significant negative role in spruce forests at lower altitudes. By contrast, in mountain locations, the interception process of liquid precipitation changes due to occult precipitation from fog and interception may be perceived very differently, from a significantly negative item of the water balance of stands up to a positive item, depending on the local conditions (Bartík et al., 2016; Chroust, 1997; Kantor, 1981; Krečmer, 1973; Krečmer et al., 1981; Valtýni, 1986).

The topic of interception losses in forest hydrology has long received considerable attention. Nevertheless, we do not yet have enough reliable quantitative data, particularly from specific mountain habitats. One such habitat consists of climax mountain spruce trees growing in extreme mountain climate conditions below the tree line (Minďáš et al., 2018; Šípek et al.,

2020). Mountain spruce forests perform a number of important ecosystem services in the country (e.g. snow accumulation, protection against avalanches and soil erosion, a headwater function) as stated by, for instance, Fleischer et al. (2017), Holko et al. (2021), Pichler et al. (2010) and Seidl et al. (2019). The long-distance transport of air pollution and acid deposition from the 1970s through the 1990s in many mountain massifs, particularly in Western and Central Europe, caused a decline in natural mountain spruces (e.g Fazekašová et al., 2016; Minďáš and Škvarenina, 1995; Oulehle et al., 2013; Rehfuess, 1985; Vacek et al., 2015). The onset of climate change, accompanied by natural hazards such as extreme temperatures, drought, storms and the consequent calamities of bark beetles, has instigated thelarge-scale decline of fragile mountain spruces (Grodzki et al., 2006; Hroššo et al., 2020; Mezei et al., 2017; Seidl et al., 2011). Many recent works have also pointed to changes in the basic hydrological and ecological functions of affected areas (Bartík et al., 2019; Bernsteinová et al., 2015; Černohous et al., 2018; Gömöryová et al., 2017; Homolák et al., 2020; Hotový and Jeníček, 2020; Iovino et al., 2018; Jeníček et al. 2017; Lichner et al. 2020; Švihla et al., 2016). Due to the aforementioned reasons, it has become necessary to examine in detail the water balance of mountain spruces, including with regard to canopy interception.

The present research was conducted in a natural mountain Norway spruce (*Picea abies* L. Karst.) forest in the Western Tatra Mountains (Slovakia). It was designed to: (i) examine estimation of spruce canopy interception including the description of its small-scale spatial variability; (ii) determine the interception losses of spruce stands based on data from three consecutive growing seasons with different precipitation amounts (average, dry, wet) and determine the impact of atmospheric synoptic types on gross precipitation; and (iii) analyze the spatial and temporal variability of throughfall in the three growing seasons and to compare these values with those published for spruce ecosystems with similar ecological conditions.

MATERIAL AND METHODS

Study site

The Červenec study site is situated in a mature (climax) spruce stand in the Jalovecká valley in the Western Tatra Mts. (latitude 49.183617°N, longitude 19.641944°E, altitude 1,420 m a.s.l.) (Fig. 1.). This valley is characterized with its quaternary glacial terrain modelling. The whole research plot 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, 2016; Holko et al., 2020). This part of the Western Tatras belongs to the cold climatic region, the cold mountain and very wet district (Lapin et al., 2002). The annual average air temperature at Červenec is 3.0 °C and long-term annual precipitation is 1,450 mm (Danáčová et al., 2019).

The main vegetation cover of the study plots comprises forest ecosystems, predominantly following forest types: *Sorbeto-Piceetum* (9410 Acidophilous spruce forests (*Vaccinio-Piceetea*)); *Cembreto-Piceetum* (9420 Alpine *Larix decidua* and *Pinus cembra* forests); above the timberline (4070 Bushes with *Pinus mugo*) (Hančinský, 1972; Stanová and Valachovič, 2002).

The predominant tree species is Norway spruce (*Picea abies* L. Karst.), accounting for 100% of the tree species coverage. Sites characterized by loosened canopy and the understorey include rowan (*Sorbus aucuparia* L.), raspberry brushes (*Rubus ideaus* L.), bilberry (*Vaccinium myrtillus* L.) and natural spruce regeneration. The plot has a south-east exposition with a slope of 20°–33° and an area of about 0.3 ha. In the over-130-year-old stand the average tree height is 26.8 m, the average stem diameter at breast heigh is 40.5 cm and the stocking density, at about 0.6, is low (Oreňák et al., 2013).

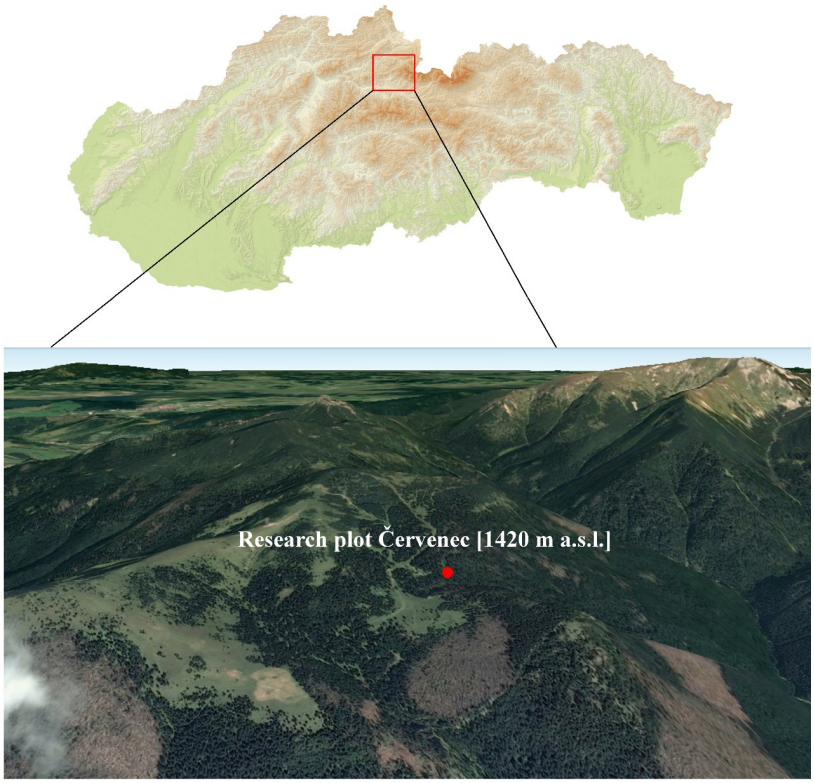

Fig. 1. Research plot Červenec.

Precipitation measurements

The amount of precipitation was recorded in the growing seasons of 2018–2020. The growing season in these areas begins in early May and concludes around the end of October, depending on the weather conditions. The data were sampled in approximately two-week intervals, as the research plot is rather remote. Water precipitation was collected in ten standard Czechoslovak rain gauges METRA (an orifice area of 500 cm^2 (Fig. 2.). The primary categorization of the measurements of precipitation was in an open area vs. in the forest stand. Daily precipitation totals were recorded by means of automatic weighing rain gauge TRwS 504 with an orifice area of 500 cm^2, we based our evaluation of synoptic situation on this metric. One standard METRA rain gauge was located on an open area, situated at a sufficient distance from the forest stand to limit or eliminate the influence of the surrounding standing trees on the amount of precipitation as a result of the air flow. Due to the structure of the forest stand, the rain gauges were installed in the canopy gap (GAP), in the dripping zone at the crown periphery (CROWN) and in the central crown zone near the stem (STEM) (Fig. 2.). In the forest, three METRA rain gauges were located in each of these three localities. We considered this research design sufficient for preliminary research on canopy interception in mountain forest, mainly due to rough terrain and accessibility regarding periodical measurements.

The canopy gap was characterized as an unconnected area by trees or their branches in a stand without trees with an area of about 20–30 m^2. Rain gauges were placed in the middle of this space. The dripping zone at the crown periphery represented precipitation, which was caught in the surface parts of the crown and dripped into the sub-canopy space after canopy saturation. In the central crown zone near the stem, rain gauges were located near the stem (Bartík et al., 2016; Dohnal et al., 2014; Minďáš et al., 2018; Oreňák et al., 2013).

Data analysis

In the period from 1 May to 31 October in years 2018, 2019 and 2020, each day was assigned the appropriate type of synoptic situation (Slovak Hydrometeorological Institute, 2021) and, in the case of precipitation on a given day,the appropriate precipitation total as well.Atmospheric circulation was characterized by the synoptic types according to Ballon et al. (1964) and Brádka et al. (1961), updated by Racko (1996), which are extensively used in synoptic and climatological practice in the Czech and Slovak republics. Czech and Slovak types are basically a modification of the catalogue of Hess and Brezowsky (1977) to optimally suit the conditions in the former Czechoslovakia (Beranova and Huth, 2005). The Czech and Slovak catalogue consists of 28 types, leaving no days unclassified. For the list of types see Table 1. Similarly, the synoptic types were applied to characterize pollutant concentrations in precipitation (Fišák and Tesař, 2015; Fišák et al., 2004).

The recorded totals of throughfall in individual measurements were first expressed as the arithmetic mean for each locality in the stand. Interception loss (I_L)in mm was calculated as the difference between gross precipitation (P_G) and throughfall (T_F)using the following equation:

$$I_L = P_G - T_F \quad (1)$$

The interception ratio (I) in % was then calculated as follows:

$$I = \left(\frac{I_L}{P_G} \right) \times 100 \quad (2)$$

All analyses and plot displays were performed using Statgraphics Centurion 16, Statistica 12 and Microsoft Excel 2016



Fig. 2. Throughfall measurements in the mature spruce forest in the research plot Červenec: in the canopy gap „GAP“ (A), in the dripping zone at the crown periphery „CROWN“ (B) and in the central crown zone near the stem „STEM“ (C).

software. When comparing the equality of the mean of the two dependent samples, we first needed to ascertain whether the data (interception in %) showed a normal distribution. To determine whether the data came from a normal distribution, we used the Shapiro–Wilk test. If the p-value ≥0.05, the data showed a normal distribution, while if the p-value <0.05 the data did not come from a normal distribution. If the compared samples showed a normal distribution, we used Student's paired t-test. If the distribution of one of the compared samples was not normal, we used the non-parametric Wilcoxon paired test. The level of significance (α) in the test was set at 95% in all cases, so if the p-value ≤0.05, we were able to state that the difference between the individual samples was statistically significant.

We used correlation and regression analysis to determine the dependence of interception losses in the stand (mm) on gross precipitation. The statistical significance of the linear relationship between the samples was tested with analysis of variance at a 95% confidence level. If p-value ≤0.05, the relationship was not significant.

RESULTS AND DISCUSSION

Evaluation of synoptic situations and precipitation totals

The occurrence of precipitation in individual synoptic types is presented in Table 1. For an illustration of the occurrence of individual synoptic types during the monitored periods in 2018–2020, the absolute frequency of these types is also given in Table 1 (column 1 (days)).

Table 1. Frequency of synoptic types (ST) in days, gross precipitation total (P_G) and percentage contribution (PC) of each synoptic situation to the precipitation total of the months May–October in the years 2018, 2019 and 2020.

	2018			2019			2020		
Synoptic types	ST (days)	PG (mm)	PC (%)	ST (days)	PG (mm)	PC (%)	ST (days)	PG (mm)	PC (%)
B	21	83.2	10.7	22	17.1	28.5	17	90.5	8.8
Bp	20	119.7	15.5	24	86.7	14.1	5	72.0	7.0
C	4	28.2	3.6	5	112.2	18.3	6	105.1	10.3
Cv	11	26.9	3.5	2	7.8	1.3	19	155.6	15.2
NWc	13	131.5	17.0	1	5.8	0.9	3	72.7	7.1
NEc	17	288.4	37.3	7	10.0	1.6	12	247.3	24.2
Nc	2	23.7	3.1	10	26.5	4.3	3	33.3	3.3
Wc				3	6.2	1.0	7	48.5	4.7
Wcs				7	33.8	5.5	5	31.0	3.0
SWc1				3	5.2	0.8	8	41.9	4.1
SWc2				7	38.6	6.3	4	2.2	0.2
SWc3							2	24.4	2.4
SEc	10	32.2	4.2	3	11.9	1.9	5	15.7	1.5
Ec				3	0.2	0.0	3	4.7	0.5
Vfz				3	19.1	3.1	2	20.2	2.0
A	2	0.0	0.0	7	10.6	1.7	9	0.2	0.0
Ap1				8	31.6	5.1	7	9.2	0.9
Ap2	13	4.7	0.6	7	1.8	0.3	8	4.2	0.4
Ap3				5	0.5	0.1			
NWa	8	0.9	0.1	13	8.9	1.4	11	5.2	0.5
NEa	13	8.7	1.1	1	0.1	0.0	9	6.3	0.6
Wa	2	1.4	0.2	7	3.0	0.5	8	0.7	0,1
Wal	20	6.3	0.8		0.0	0.0	14	18.6	1.8
Sa	11	0.2	0.0	16	0.5	0.1	3	0.1	0.0
SEa	1	2.4	0.3	7	16.6	2.7	3	11.4	1.1
SWa	7	0.3	0.0	10	0.8	0.1	6	2.6	0.3
Ea	9	15.2	2.0	3	0.5	0.1	5	0.0	0,0
Sume of type c	98	733.7	94.8	100	539.1	87.8	101	965.0	94.3
Sume of type a	86	40.1	5.2	84	74.9	12.2	83	58.6	5.7
Sume of c+a	184	773.8	100.0	184	614.0	100.0	184	1023.6	100.0

Synoptic situations: **Wc**, west cyclonic; **Wcs**, west cyclonic with southern pathway; **Wa**, west anticyclonic; **Wal**, west anticyclonic of summer type; **NWc**, north-west cyclonic; **NWa**, north-west anticyclonic; **Nc**, north cyclonic; **NEc**, north-east cyclonic; **NEa**, north-east anticyclonic; **Ec**, east cyclonic; **Ea**, east anticyclonic; **SEc**, south-east cyclonic; **SEa**, south-east anticyclonic; **Sa**, south anticyclonic; **SWc1**, south-west cyclonic of the 1st type; **SWc2**, south-west cyclonic of the 2nd type; **SWc3**, south-west cyclonic of the 3rd type; **SWa**, south-west anticyclonic; **B**, trough over Central Europe; **Bp**, travelling trough; **Vfz**, entry of the frontal zone; **C**, cyclone over Central Europe; **Cv**, upper cyclone; **A**, anticyclone over Central Europe; **Ap1**, travelling anticyclone of the 1st type; **Ap2**, travelling anticyclone of the 2nd type; **Ap3**, travelling anticyclone of the 3rd type

Year 2018: a so-called normal/average year (102% of the long-term precipitation average for May–October). Almost 95% of the precipitation from May to October 2018 fell in cyclonic weather types. The highest total precipitation fell on days with the synoptic situation of NEc, namely 288 mm, representing 37% of the total in the observed period. In the NEc situation, the highest daily total (129 mm) recorded in 2018 fell on 18 July. Subsequently, large amounts of precipitation fell in NWc 132 mm (17%), Bp 120 mm (16%) and B 83 mm (11%). Types C, Cv SEc and Nc contributed only marginally (3–4%). The anticyclonic types, Ea, NWa and Wal, altogether contributed about 4% to the total precipitation.

Year 2019: a relatively dry year (85% of the long-term precipitation average for May–October). Precipitation in 2019 fell in the following proportion: 88% for cyclonic types and 12% for anticyclone types of weather situations. During the period with synoptic situations B, almost 175 mm, representing 29% of the total in the observed period. Then there were the following situations C 112 mm (18%) and Bp 87 mm (14%), together SWc 44 mm (7%) and Wcs 34 mm (5.5%), and other cyclonic types were below 5%. The highest daily total (64.2 mm) fell on 22 May in situation C. This situation C cyclone over Central Europe lasted for five days from 19 to 23 May, during which a total of 132 mm fell, representing about 21% of the precipitation in the observed period. In 2019, in comparison with the other years evaluated, there was more precipitation even in anticyclonic synoptic situations, mostly precipitation of a storm nature. The types Ap (together) accounted for about 34 mm (5%), SEa for about 17 mm (3%) and A for 11 mm (2%).

Year 2020: an above-normal year of precipitation (135% of the long-term precipitation average for the months of May–October). In this year, cyclonic synoptic types predominated (94% of the precipitation total), while anticyclonic types accounted for only 6%. As in 2018, the synoptic type NEc contributed the most to the total, with a total of 247 mm (24%). The highest daily total precipitation (77 mm) was reached again in the NEc situation on 30 September. It is worth mentioning that the second-highest daily total (64 mm) was reached in the same synoptic situation NEc on 22 June. Synoptic types (Cv 156 mm, 15%; C 105 mm (10%) also accounted for a more significant share of the total, so in summary, situations C and Cv represented up to 25% of the total. Regarding the othercyclonic types, B and Bp should be mentioned, as they collectively contributed to a total of about 160 mm (15%). Out of the rest of the types, only the anticyclonic situations Wal and Ap contributed above 1% of the total.

The Western Tatras, as a massive mountain range, form the north-western edge wall for precipitation-bearing western, northern and partly also north-eastern cyclonic situations. Compared to the other parts of Slovakia (Petrovič, 1972), the character of precipitation hereis different. Indeed, in other regions of Slovakia, the most precipitation was brought by synoptic situations with a western and north-western flow (Bp, Wc, NWc and SWc). In the study area, the largest amount of precipitation wasobserved in the north-eastern cyclonic situation (NEc) in 2018 and 2020. As mentioned by Krečmer (1973), the mountain locality Šerlich (elevation 960 m a.s.l.) in the Orlické Mountains also classified the NEc type as the rainiest. The Orlické Mountains are located on the north-eastern border of the Czech Republic and Poland, where the geographical effects of air flow and movement of active frontal and air masses manifest similarly to those on the edge of the Western Tatras. A similar opinion was expressed by Konček and Orlicz (1974) for the Polish side of the Western Tatras, when they analyzed the summer precipitation conditions of the mountain obsevatory at Kasper Peak (elevation 1987 m a.s.l.). In addition to the synoptic situation of NEc in the summer rain totals, the situation of Nc predominates. Compared to other, southern parts, the south-western cyclonic situations (SWc1 to SWc3) bringgreater precipitation to the marginal northern parts of our territory only sporadically (Polčák and Mészáros, 2018).

Comparison of interception in individual zones of stand measurement during growing seasons (2018–2020)

The amount of precipitation had a significant effect on the values of interception during the analyzed growing seasons of 2018, 2019 and 2020. The distribution of sub-canopy precipitation within the natural spruce stand with reduced stocking density showed considerable heterogeneity. The recorded values of interception during vegetation periods fluctuated considerably. In the canopy gap, we recorded interception values of the gross precipitation total in the range of 4.4–40.0% in the growing season of 2018, 7.0–39.3% in 2019 and 13.3–32.3% in 2020 (Fig. 3.). Furthermore, in the canopy gap, there were two situations in the growing season of 2019 and one situation in the growing season of 2020 when the measured precipitation total in the stand exceeded the gross precipitation. These situations could have been caused by the influence of the wind, which transported precipitation captured in the canopy space into the area of the canopy gap.

In the dripping zone at the crown periphery, we recorded the highest variability of interception. One of the factors influencing values of interception during the vegetation period is the occurrence of occult precipitation (Holko et al., 2009; Krečmer, 1973; Minďáš et al., 2018; Vorčák et al., 2009). This effect was most pronounced in the studied locality, when we recorded five cases in all evaluated periods with the throughfall exceeding the gross precipitation. High levels of throughfall always occurred at the beginning of each growing season during a two-week period: for example, on 21 May 2020 we recorded up to 42.9% higher throughfall than gross precipitation (Fig. 3.). We also registered significantly higher throughfall on 28 July 2018 at the highest recorded two-week gross precipitation total (232.4 mm) of all three evaluated periods. In addition, occult precipitation by its interaction reduces canopy storage capacity. The range of interception values in the dripping zone at the crown periphery ranged from –17.9 to 53.7% in the growing season of 2018, from –17.3 to 64.3% in 2019 and from –42.9 to 56.7% in 2020 (Fig. 3.). Out of 12 measurements in the dripping zone at the crown periphery, Bartík et al. (2016) reported up to 8 times higher throughfall than gross precipitation in a living spruce stand at this locality during the growing season of 2014. In a spruce forest in the Orlické Mountains (960 m a.s.l.) in the growing seasons 1962–1966 during individual months, Krečmer (1968) reported a significant variability of interception, ranging from an improvement of throughfall by 28.0% up to the canopy interception of 25.0%. Fojt and Krečmer (1975) reported an enrichment of 15% by occult precipitation at the same locality during the growing season (6 months). Kantor (1981) reported a negative interception of 2.0% in the growing season of 1978 during rainfall events with the occurrence of fog. In research conducted in North America, Lovett et al. (1982) reported enrichment with rainwater of 450 mm per year (20% of the annual gross precipitation) at an elevation above 1,200 m a.s.l. in a Douglas fir stand (*Pseudotsuga menziesii*), while Harr et al. (1982) reported an improvement of 880 mm (30% of the annual gross precipitation) in Oregon, also at an elevation above 1,200 m a.s.l. in Douglas fir forests.

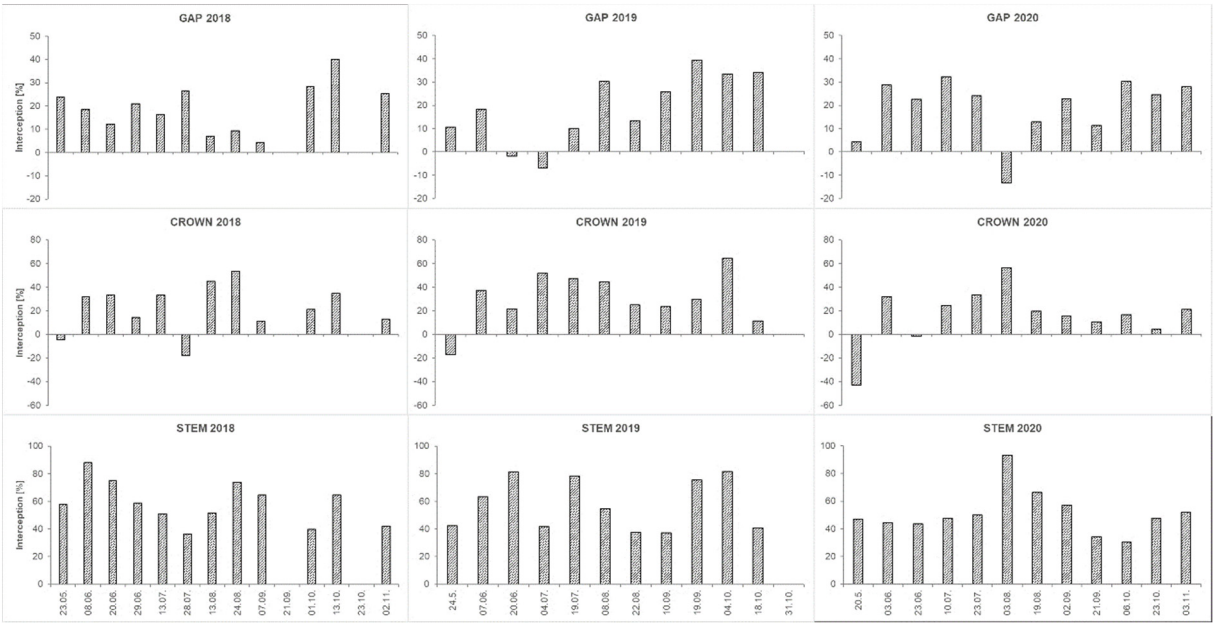

Fig. 3. Interception (%) in the canopy gap (GAP), in the dripping zone at the crown periphery (CROWN) and in the central crown zone near the stem (STEM) during the growing seasons of 2018–2020.

In the central crown zone near the stem, interception reached the highest values in most cases. In this locality, which is not identical with the stemflow, the lowest amount of precipitation was able to penetrate due to the shape of the growing branches. In the growing seasons, we recorded interception in the range of 36.2–87.8% in 2018, 37.1–81.7% in 2019 and 30.5–93.3% in 2020 (Fig. 3.).

The calculated sums of throughfall (mm), interception losses (mm), interception (%) and gross precipitation (mm) during the evaluated periods are given in Table 2. The canopy gap reached a total interception loss of 163.7 mm (21.2% of the gross precipitation total) in 2018, 120.5 mm (19.6%) in 2019 and 246.4 mm (24.1%) in 2020. The dripping zone at the crown periphery reached a total interception loss of 64.1 mm (8.3% of the gross precipitation total) in 2018, 136.4 mm (22.2%) in 2019 and 156.3 mm (15.3%) in 2020. The central crown zone near the stem reached a total interception loss of 395.2 mm (51.1% of the gross precipitation total) in 2018, 300.9 mm (49.0%) in 2019 and 467.8 mm (45.7%) in 2020. When comparing individual localities, we recorded the lowest interception losses in the growing seasons of 2018 and 2020 in the following order: the dripping zone at the crown periphery > canopy gap > the central crown zone near the stem. An exception was the poorest precipitation period of 2019, when we recorded the lowest interception in the following order: the canopy gap > the dripping zone at the crown periphery > the central crown zone near the stem. This could have been caused either by two recorded situations, when the throughfall reached higher values than the gross precipitation, or by very warm weather, especially in the period June–October. The year 2019 was the warmest in Europe since at least 1980, with the warmest period being June–August (European Centre for Medium-Range Weather Forecasts and Copernicus Climate Change Service, 2020). The warm growing season was also manifested by the highest values of interception in the dripping zone at the crown periphery in comparison with the growing seasons 2018 and 2020. Regarding this study site in the living forest during the growing seasons of 2007–2011, Oreňák et al. (2013) reported that average interception was 27.0% in the canopy gap, 20% in the dripping zone at the crown periphery and 63% in the central crown zone near the stem. Also concerning this study site in the living forest during the growing seasons of 2012–2015, Jančo et al. (2017) reported that average interception was 10.1% in the canopy gap, 1.6% in the dripping zone at the crown periphery and 70.6% in the central crown zone near the stem. Regrettably, both of the living stands used in the past with which we compared our results are now dead. Expressing interception as the average of these three localities (GAP, CROWN, STEM) during each evaluated growing season, interception reached 26.8% in 2018, 30.3% in 2019 and 28.3% in 2020. These interception values obtained in spruce forest support numerous previous findings from Europe and North America that average coniferous forest interception ranges from 25.0 to 35.0% of the gross precipitation total (Robinson and Ward, 2017) Furthermore, the values of average interception obtained here correspond to the results of other authors, who have reported values in the range of 23.0–38.0% for older spruce stands (e.g. Grelle et al., 1997; Grunicke et al., 2020; Halmová et al., 2006; Kofroňová et al., 2021; Tužinský, 2004; Viville et al., 1993).

We statistically compared the interception data (%) calculated from each measurement at individual localities in the stand in each evaluated growing season (Fig. 4). A statistical evaluation of the results is given in Table 3. Based on the completed Student's paired t-test and the nonparametric Wilcoxon paired test, a statistically significant difference was not confirmed in all growing seasons between the canopy gap and the dripping zone at the crown periphery. However, when comparing the central crown zone near the stem with these two localities, we were able to see a significant difference (bold values in Table 3) in all cases.

Relationship between interception loss in individual zones of stand measurement and gross precipitation

The expressed linear regression of the calculated values of the interception loss (mm) on the amount of gross precipitation at the measured localities in the stand (GAP, CROWN, STEM) are shown in Figs. 5, 6 and 7. Above the graphs are the linear regression equation, the coefficient of determination (R^2), Pearson's correlation coefficient (R) and p-value, informing us

Table 2. Precipitation total and interception (mm, %) in the growing seasons of 2018–2020.

Position of rain gauges	Growing season		
	2018	**2019**	**2020**
Canopy gap	Throughfall [mm]		
	610.1	493.5	777.2
	Interception [mm, %]		
	163.7 21.2	120.5 19.6	246.4 24.1
Dripping zone at the crown periphery	Throughfall [mm]		
	709.7	477.6	867.3
	Interception [mm, %]		
	64.1 8.3	136.4 22.2	156.3 15.3
Central crown zone near the stem	Throughfall [mm]		
	378.6	313.1	555.8
	Interception [mm, %]		
	395.2 51.1	300.9 49.0	467.8 45.7
Open area	Gross precipitation [mm]		
	773.8	614.0	1023.6

Table 3. Statistical characteristics of interception (%).

	Count	Average	Standard deviation	Coeff. of variation	Minimum	Maximum	Range	Shapiro–Wilk p-value
GAP 2018	12	19.4	10.21	52.61	4.4	40.0	35.6	**0.8752**
CROWN 2018	12	22.4	20.43	91.29	–17.9	53.7	71.6	**0.7529**
STEM 2018	12	58.6	15.60	26.64	36.1	87.8	51.7	**0.8792**
GAP 2019	11	18.8	15.22	80.97	–7.0	39.3	46.3	**0.6239**
CROWN 2019	11	30.8	22.17	71.89	–17.3	64.3	81.6	**0.7255**
STEM 2019	11	57.6	18.78	32.61	37.1	81.7	44.6	0.0352
GAP 2020	12	19.0	13.20	69.33	–13.3	32.3	45.6	0.0292
CROWN 2020	12	15.9	23.86	150.20	–42.9	56.7	99.6	**0.1668**
STEM 2020	12	50.7	16.54	32.63	30.5	93.3	62.8	0.0450

p* - result of Shapiro–Wilk test (bold value means, that the data come from normal distributions)

Locality	p-value	Locality	p-value	Locality	p-value
GAP 18 vs. CROWN 18*	0.6978	GAP 19 vs. CROWN 19*	0.1562	GAP 20 vs. CROWN 20**	0.2721
GAP 18 vs. STEM 18*	**0.0001**	GAP 19 vs. STEM 19**	**0.0033**	GAP 20 vs. STEM 20**	**0.0022**
CROWN 18 vs. STEM 18*	**0.0000**	CROWN 19 vs. STEM19**	**0.0044**	CROWN 20 vs. STEM 20**	**0.0022**

*Student´s paired test, ** Wilcoxon paired test (bold values define statistically significant differences $p \leq 0.05$)

whether a statistically significant difference was confirmed between the correlation of interception loss and gross precipitation. Bold values represent a statistically significant difference. The Pearson's correlation coefficient was most significant in the central crown zone near the stem, indicating a relatively strong relationship between the variables, followed by the canopy gap, indicating a moderately strong relationship between the variables as well. The least significant of the three was the dripping zone at the crown periphery, indicating a relatively weak relationship between the variables. The R-squared statistic (coefficient of determination) indicated that the fitted model explained 88.8% of the variability in interception loss in the central crown zone near the stem, 87.6% of the variability in interception loss in the canopy gap and 1.2% of the variability in interception loss in the dripping zone at the crown periphery out of the gross precipitation. A statistically significant difference in correlation was confirmed in the canopy gap and in the central crown zone near the stem. It follows that in the central crown zone near the stem, interception losses were most affected by the gross precipitation, because this space in the stand intercepts the largest amount of precipitation. The canopy gap and its interception losses are also significantly affected by the gross precipitation, but to a lesser extent. Although this space has no active surface above it to retain precipitation, it is mainly exposed to the wind. The higher the wind speed, the more the direction of rainfall deviates from the vertical direction, while the surrounding trees can act as a rain shadow. The vegetation may lead to 'precipitation shading' of the site in certain direction, but if the wind speed exceeds a certain limit, when it is able to carry the captured precipitation in the crowns, these may exceed the gross precipitation values (20 June, 4 July 2019 and 3 August 2020 (Fig. 3)). The gross precipitation total in the dripping zone at the crown periphery has the smallest effect on the interception loss, because in this area the variability of the interception loss is the highest and it is influenced by the effect of occult precipitation. In the dripping zone at the crown periphery, such a correlation was not statistically confirmed. Similar results at the same studied site during the growing seasons of 2007–2011 were reported by Oreňák et al. (2013), where the Pearson's correlation coefficient of interception loss was most significant in the central crown zone near the stem, followed by the canopy gap and least important in the dripping

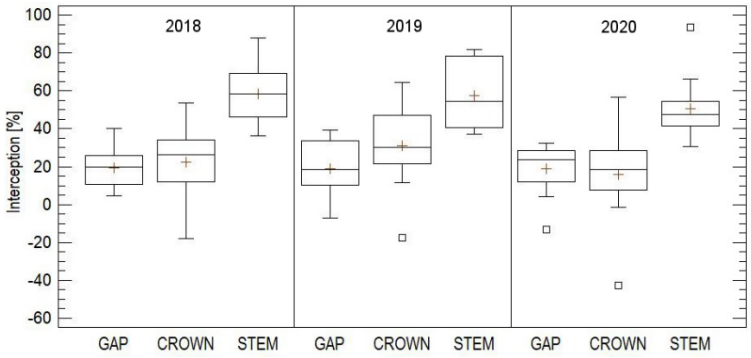

Fig. 4. Box-whisker plots (maximum-minimum; lower and upper quartiles; median; the crosses show the arithmetic mean, the squares show the outliers) of interception (%) for the growing seasons of 2018–2020.

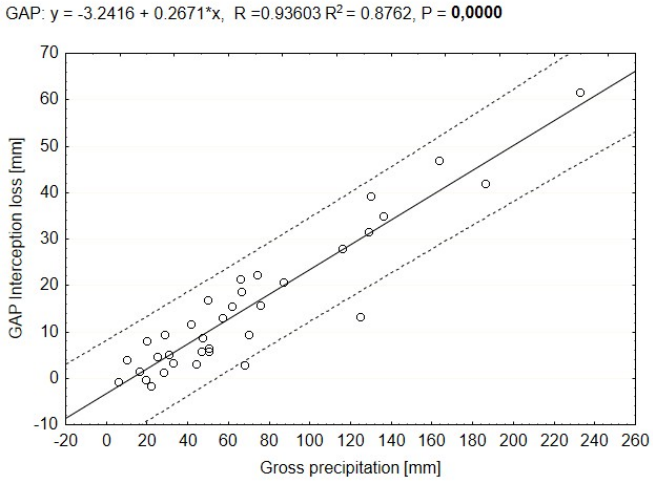

Fig. 5. Linear regression between canopy gap (GAP) interception loss (mm) and gross precipitation (2018–2020). The solid line represents the regression line; the dashed lines are the upper and lower 95% prediction intervals of the regression.

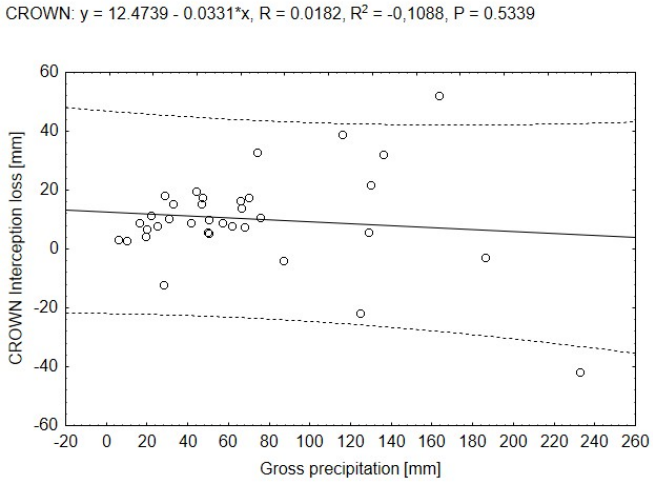

Fig. 6. Linear regression between the dripping zone at the crown periphery (CROWN) interception loss (mm) and gross precipitation (2018–2020). The solid line represents the regression line; the dashed lines are the upper and lower 95% prediction intervals of the regression.

zone at the crown periphery. Droughts, insects and fungi already contribute to the decline of spruce forests (Sierota et al., 2019). Given that interception is partially a function of forest structure and physiological characteristics of host trees (Bladon

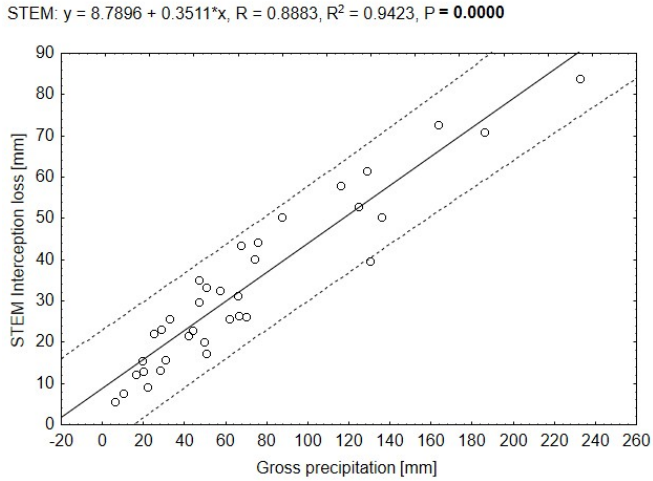

Fig. 7. Linear regression between central crown zone near the stem (STEM) interception loss (mm) and gross precipitation (2018–2020). The solid line represents the regression line; the dashed lines are the upper and lower 95% prediction intervals of the regression.

et al., 2019; Kaiser et al., 2013). Additionally, the topographic structure mediates the redistribution of water and the spatial patterns of forest vegetation, giving rise to temporal complexity in the ecological processes associated with vegetation.

CONCLUSION

Understanding how trees interact with interception processes is important for the development of effective strategies and tools for sustainable resource management in the future. Large parts of the Tatra Mts. have already been hit by significant ecosystem disturbances, including spruce bark beetle outbreaks. Our study aimed to evaluate the influence of mountain spruce forest on the distribution of throughfall in the growing seasons of 2018–2020 and provided a unique opportunity to analyze rainfall interception in an unaffected forest. And although the study design was constrained by rough terrain and challenges regarding periodical monitoring, the analysis of synoptic types points to the differences in meteorological conditions of occurrence of precipitation in the observed study plot. We recorded amounts of precipitation in the growing seasons in descending order as follows: 2020 > 2018 > 2019. Most of the precipitation totals in each period were recorded in cyclonic situations. Furthermore, based on the results of our measurements we can state that the distribution of precipitation differs within the stand structure in the sub-canopy space.

Our research can be used to develop a more mechanistic understanding of the feedbacks between hydrology and ecological processes. The lowest amount of throughfall in each evaluated period was recorded in the central crown zone near the stem, indicating that interception here was highest. The lowest values of interception were seen in the dripping zone at crown periphery, with the exception of during the growing season of 2019, when we recorded the lowest interception in the canopy gap. The mosaic of land-cover change that has affected the rest of the Tatra Mts. can alter ecosystem response and hydrology will be among the first affected ecosystem services. Interception of individual localities differed in each growing season in the cases of the canopy gap and the central crown near the stem, the dripping zone at the crown periphery and the central crown zone near the stem. Canopy gap and the central crown zone near the stem affected also the interception loss between the gross precipitation. This phenomenon owed to the presence of occult precipitation, which compensated for interception losses and enriched the stand with rainwater. The total interception of the stand reached 26.8% (2018), 30.3% (2019) and 28.3% (2020) of the gross precipitation total. In the future, we expect significant changes in the hydrological cycle in the Tatra Mts., mainly due to repeated wind storms, bark beetle outbreaks and subsequent sanitary measurements. Our study provides a basis for future comparison and changes in affected forests with baseline conditions described in the above-presented study.

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