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Influence of forest dieback on the overland flow and isotopic composition of precipitation

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Small mountain catchments in the highest part of Slovakia are undergoing significant forest changes related to windfalls and bark beetle infestations and resulting forest dieback, wood removal at some places and subsequent natural regeneration or reforestation. Natural forest changes started after 2010 also in the Jalovecký Creek catchment (The Western Mountains, area 22.2 km^2, mean altitude 1500 m a.s.l.). Coniferous forest dominated by the Norway spruce, that used to cover 44% of catchment area consequently dries, the trees defoliate, break after some time and the natural regeneration starts. These changes affect also the hydrological cycle, e.g. interception, snow cover, water infiltration to the soil and runoff formation. We present the first results of the overland flow measurements in the alive and dead forest in summer season 2021 (June to September) and compare the isotopes of oxygen and hydrogen in precipitation and soil water. The results show that the overland flow in the forest is not uncommon, although it constitutes only several per cent of the rain. About a half of 55 rainfall events registered in the open area resulted in the overland flow in the forest (21–30 events at different sites). The overland flow represented on average 4% to 7% of the open area rainfall, but maxima for individual events exceeded 10%. Throughfall in the alive forest was isotopically heavier than the open area rainfall and dead forest throughfall. Isotopic composition of the soil water was distinctly different from precipitation until the mid-July, documenting the influence of the snowmelt water.

KEY WORDS: runoff generation, changing forest, stable isotopes

Introduction

The highest mountain ranges in Slovakia, i.e. the Tatra Mountains and the Low Tatra Mountains were in the previous decades covered by dense forests. These forest were always affected by natural disturbances (windfalls, bark beetles) and human activities (forest management, mountain resorts development). However, compared to the past, the last decade brought visible deforestation at much greater areas, often initiated by windfalls and bark beetle infestations. Forest changes occur also in the Jalovecký Creek catchment that is studied since the end of the 1980' as representative for the hydrological cycle of the highest Slovak mountains. Because the catchment is part of the protected area of the Tatra National Park, its forests have been little affected by human activities during our research period. Forests, dominated by Norway spruce (*Picea abies*) used to cover 44% of the catchment while additional 31% of the catchment was covered by the dwarf pine (*Pinus mugo*), e.g. Holko and Kostka (2006). Although intensive past human activities that ended several decades ago, decreased the natural forest line almost in the entire catchment, most of the forest was recently classified as natural (Celer, 2015). However, the majority of the forest was old (over 100 years); the largest forest area was in the age class 121 to 140 years (Celer, 2015). Therefore, Celer (2015) noted that due to its age, forest breakdown and regeneration can be expected in the near future. In fact, this process started or was intensified by several windfalls and bark beetle outbreaks already before Celer's evaluation, e.g. in 2012 (Bartík et al., 2016).

Forest dieback and regeneration span over the period of many years. Defoliation after the death of the trees appears relatively quickly. The ongoing defoliation can be accompanied by the growth of lichens on trees branches and a rapid development of the forest floor vegetation. Finally, the branches and trunks break and their decomposition starts. Simultaneously, the regeneration continues by growth of pioneering species that use the chance of having more light and nutrients and less competition from the trees when the gaps and large openings form in the previously continuous mature forest.

Recent large-scale forest disturbances in Europe were evaluated e.g. by Mezei et al., 2014; 2017; Seidl et al., 2011. Senf and Seidl (2021) reported that 17% of Europe's forest area was disturbed by anthropogenic and/or natural causes between 1986 and 2016. They also concluded that although the trends in disturbance size were highly variable, disturbance frequency consistently increased and its severity decreased. Hydrological consequences of changes in forest structure can include e.g. changes in snow accumulation and melt (Bartík et al, 2019), soil moisture, hydrological connectivity and runoff generation. They were often analysed before in studies related to the effects of forest management (deforestation, afforestation). Natural forest dieback, e.g. due to bark beetle infestation takes over longer time than the dieback caused by climatic factors such as windfalls, extreme temperatures or drought. The objective of this study was to investigate the overland flow formation in a forest undergoing the natural dieback/regeneration processes and the effects of the various stages of forest dieback on the isotopic composition of precipitation.

Material and methods

Precipitation amount and isotopic composition, overland flow, soil moisture and isotopic composition of soil water were measured in the open area, alive and dead Norway spruce (*Picea abies*) forest stands in summer 2021 (June to September) in the Jalovecký Creek catchment. The site is located at the forest line (altitude 1450 m a.s.l.). Forest dieback started there in summer 2012 as a result of the bark beetle infestation (*Ips typographus*). It continued in 2016 after a large windfall that occurred in May 2014 and destroyed about 50 hectares of the forest within the distance of about 1 km from the site and a warm and dry weather in 2015 and 2016. An increased dieback at the site is observed since 2017. Our measurements were conducted in the remaining small alive forest stand that is about 130 years old and in the dead forest that died in 2012 in which the regeneration has already started. Precipitation was measured by the tipping bucket rain gauges with automatic registration of the time of each tip corresponding to precipitation depth of 0.2 mm. One tipping bucket rain gauge was installed in the forest gap, two other were installed in the dead forest. Additional data (precipitation from a weighing gauge, radiation, air temperature and humidity, soil moisture at depths 5 cm, 10 cm and 20 cm) were measured every 10 minutes at the nearby (400 m) meteorological station located in the open area at altitude 1500 m a.s.l. (Fig. 1). Monthly precipitation and air temperature in the study period compared to their long-term values measured at the meteorological station (Fig. 2) indicate that June 2021 was comparatively dry and warm while August 2021 was wet and cooler. Precipitation in August 2021 and air temperature in July 2021 were the highest on record.

The overland flow was measured at runoff plots with the area of 1 m^2 (length 2 m, width 0.5 m) by deluometers developed by foresters for the overland flow and erosion research (Midriak, 1986). A deluometer is a covered tin flume the outflow from which can be collected in a vessel. We have measured the outflow from deluometers by tipping bucket rain gauges (Fig. 3). Three deluometers were installed in both the alive and dead forest. Soil moisture of the upper 10 cm of the soil was measured every 15 minutes close to each runoff plot.

Cumulative precipitation samples for the analysis of stable isotopes of oxygen and hydrogen were collected manually once per week from three standard rain gauges (orifice area 500 cm^2) located in forest gap, alive and dead forest. Four suction cup soil lysimeters (two in both the alive and the dead forest) were installed to provide weekly samples of the soil water collected at the depth of 20 cm. However, the usable data were obtained only from two soil lysimeters in the dead forest and one soil lysimeter in the alive forest. One soil lysimeter in the dead forest provided samples covering almost the entire study period (18 June to 1 October) while other

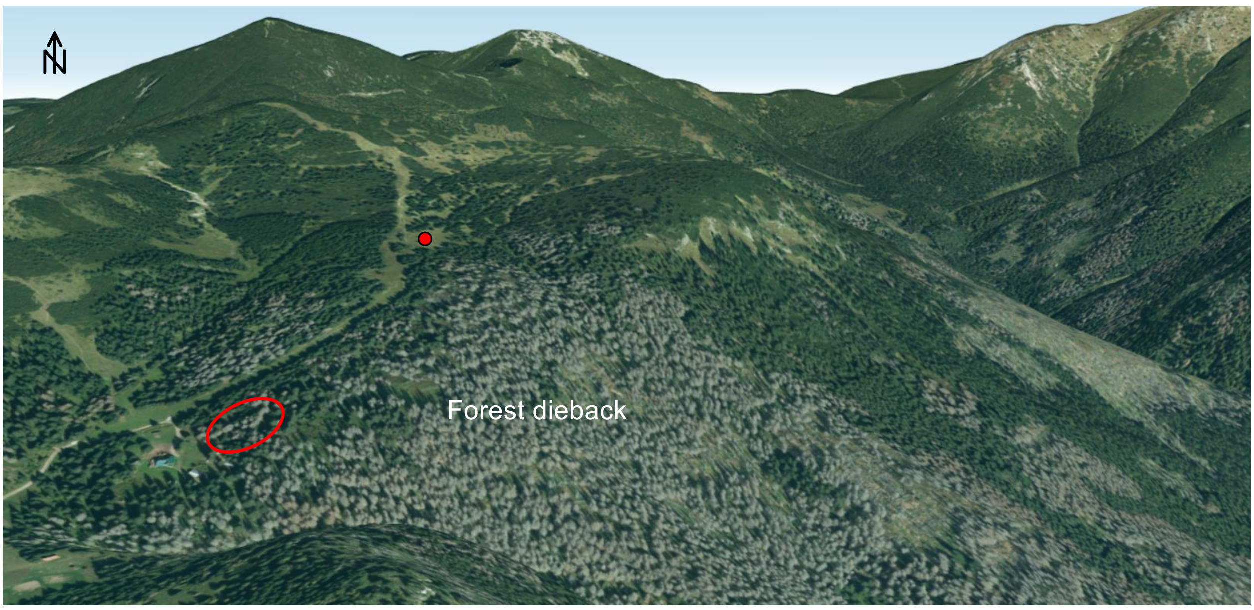

Fig. 1. Part of the Jalovecký Creek catchment showing the study area (the red ellipse), meteorological station (the red dot) and the area affected by forest dieback in 2018 (https://zbgis.skgeodesy.sk).

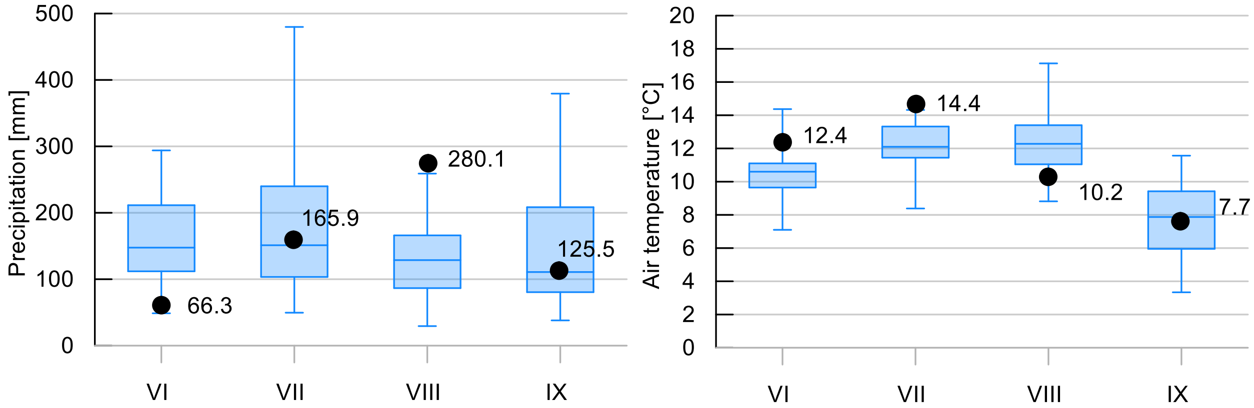

Fig. 2. Monthly precipitation and air temperature in the study period (June to September 2021) denoted by the black dots and numbers and their long-term variability (1989–2020) at the meteorological station close to the study site; the whiskers in boxplots show minimum and maximum, the boxes show upper and lower quartiles and medians.

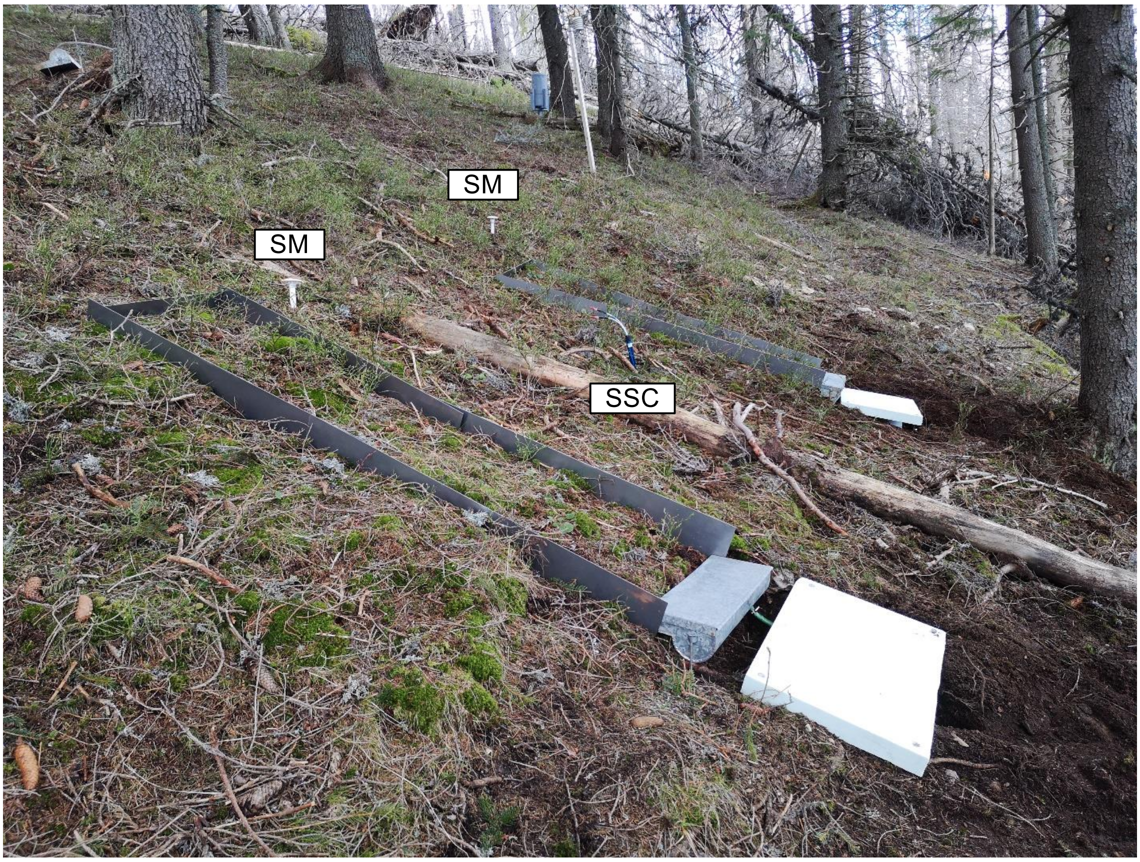

Fig. 3. Runoff plots with deluometers, soil moisture probes (SM) and a suction cup soil lysimeter (SSC) in the alive forest; the tipping bucket gauges measuring the overland flow were protected from the rain by the polystyrene covers.

two lysimeters collected enough water for the isotopic analyses only from July and August (in the dead forest) or at the end of August and in September (in the alive forest). Water samples were analysed ourselves by the Picarro 2130 laser analyzer according to a protocol presented in Holko (2015), The results are expressed in δ-values related to the international reference VSMOW2. Analytical accuracy was better than ±0.2‰ for $\delta^{18}O$ and ±1.0‰ for $\delta^{2}H$. Deuterium excess d (d= $\delta^{2}H$-8x $\delta^{18}O$) was used to check if the sampled water was not evaporated.

The obtained data allowed comparison of precipitation amount and its isotopic composition among the sites, amount and timing of the overland flow, its relation to the soil moisture and rainfall characteristics (total amount, intensity, maxima) and the relationships between the isotopic composition of precipitation at different sites in the forest and in the soil water. The precipitation-overland flow data analysis was conducted for rainfall events. The events were determined from hourly precipitation data whereby a break after the last hour with rain or the occurrence of overland flow not longer than 5 hours was allowed to attribute the following rainfall to the same event.

Results and discussion

Measured data are shown in Fig. 4. Precipitation and soil moisture document the occurrence of two wet periods at the beginning and end of August and a drier period between the end of June and mid-July. The soil moisture data indicate that soil profile could have been saturated at the beginning and end of August, i.e. favourable conditions for the overland flow generation occurred. Five episodes of higher overland flow in the forest were observed. Except the above mentioned wet periods they occurred also after greater rainfalls in the middle and at the end of July and in the middle of September. 55 rainfall events were identified in the study period while the overland flow at different plots was registered for 21 to 30 of them. The data did not indicate a clear threshold, i.e. the minimum rainfall amount that generated the overland flow. However, rainfall events in the open area exceeding 4 mm always produced an overland flow in the forest. Event precipitation in the dead forest was on average 82% and 74% of that in the forest gap (Fig. 5). Precipitation in the dead forest was sometimes higher than that in the forest gap (in 3 and 7 events out of 29 events for which the was the overland flow registered). Similar results were reported for the site in the warm periods of the years 2013, 2014 and 2018–2020 by Bartík et al. (2016) and Jančo (2020).

Although the overland flow occurrence in the forest was common, it represented on average only a few per cents of the open area precipitation (Fig. 5). It was greater at one plot in the alive forest where it represented on average about 7% of the forest gap precipitation while at other plots (in the dead as well as alive forest) it represented on average 4% to 5% of precipitation. The variability of the overland flow amount during individual events was quite great and ranged from less than 1% to more than 10% (Fig. 5). Jančo (2020) reported similar seasonal values of the overland flow amount at the study site for June to October 2017–2019; the overland flow at different plots varied in his study between less than 1% to more than 7% (the data on individual events were not available).

Total overland flow for individual events correlated very well with precipitation in the forest gap; the coefficients of determination of linear regressions ranged from 0.85 to 0.96. Therefore, it was possible to derive the coefficients relating the overland flow and the forest gap precipitation (Table 1) that can serve as the starting values to be examined by further research.

We have analysed 10-min data for selected eight events with greater overland flow. Maximum 10-min precipitation during about a half of events occurred within the first 30 minutes of the rainfall. Other events had longer rainfall durations and the maxima occurred later (about two hours after rainfall beginning or later). Although the number of the analysed events is small, the data indicate that the overland flow as well as its maximum occurred mostly within the first 30 minutes of the rain at all sites and during all events. There was not a big difference between the dead and alive forest in this characteristic. Maximum 10-min overland flow rate was best correlated with maximum rainfall amount (correlation coefficients for different sites varied from 0.71 to 0.99) and it mostly occurred in the same time interval or 10-20 minutes later.

Stable isotopes of oxygen and hydrogen in water samples serve as tracers that can indicate different origin of water. Fig, 4 shows that $\delta^{18}O$ of precipitation in the forest gap during the study period was relatively stable with the drop at the turn of August and September caused by the change in the air masses origin which is common in the study area at the end of summer. The isotopic composition of throughfall can differ from that of the open area rainfall although the observed differences in the Jalovecký Creek catchment comparing the open area rainfall and throughfall in the alive forest were rather small in the past (Holko et al., 2011). The differences between the forest gap, dead and alive forest rainfalls in summer 2021 are shown in Table 2. Throughfall in the alive and dead forest represented on average 56% and 79% of the forest gap rainfall. The differences in isotopic composition of precipitation were greater than in the past years. Precipitation in the forest gap had always the lowest concentrations of heavy isotopes while precipitation in the alive forest was mostly isotopically heavier than in the dead forest, presumably as a result of greater interception in the alive forest. Great differences

Table 1. Coefficients (C) of equations correlating the overland flow (OF) in the forest and forest gap precipitation during an event (P); OF = P x C; R^2 is coefficient of determination, n is the number of events used to determine C

Site	C	n	R^2
Dead forest 1	0.0581	30	0.921
Dead forest 2	0.0625	21	0.820
Dead forest 3	0.0519	22	0.960
Alive forest 1	0.0968	21	0.902
Alive forest 1	0.0588	25	0.908

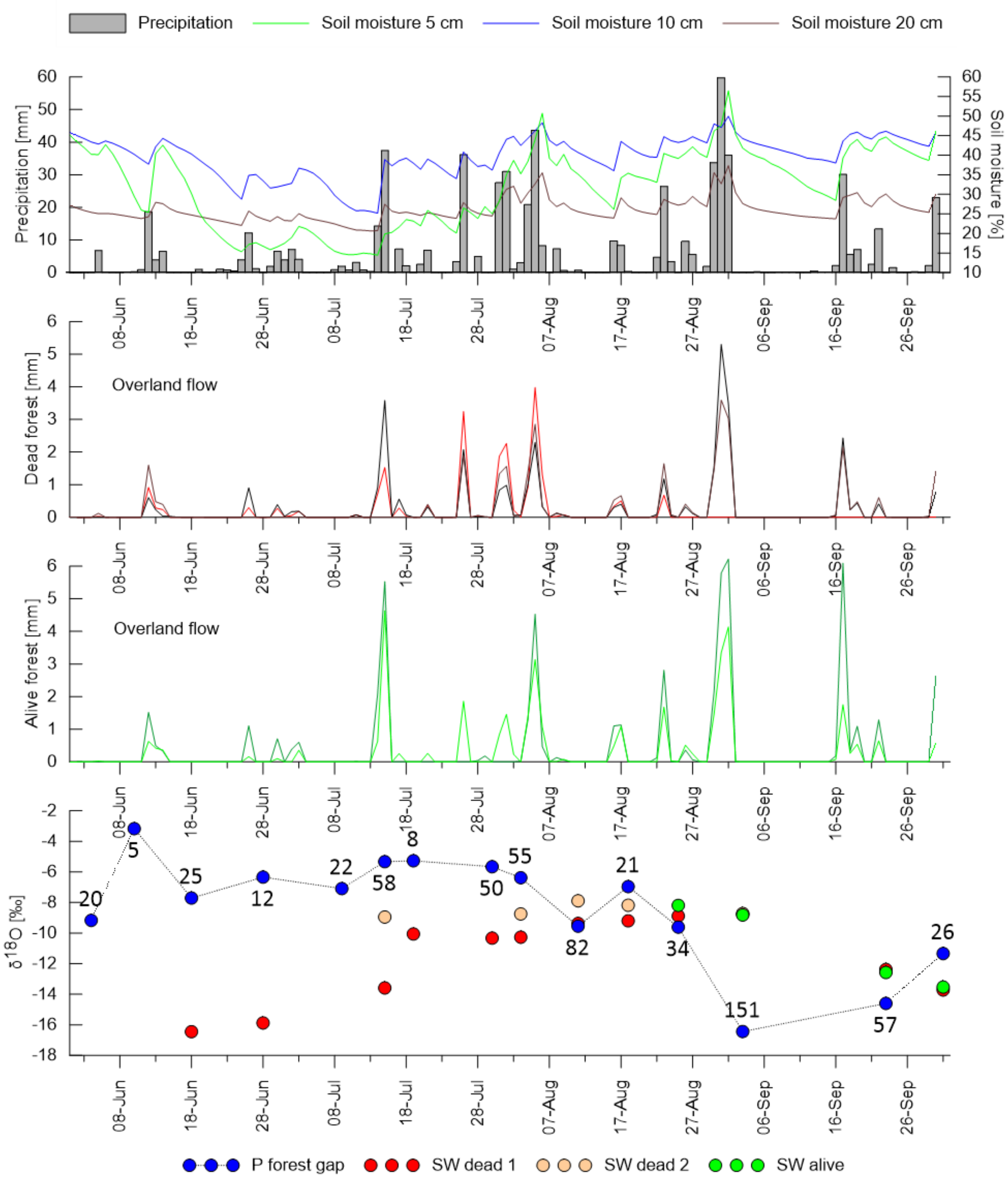

Fig. 4. Daily precipitation totals and average soil moisture at different depths at the meteorological station, daily overland flow totals in the dead and alive forest and isotopic composition of precipitation (P) in the forest gap and of the soil water (SW) in the dead and alive forest; the numbers in the lowermost panel show weekly precipitation amounts [mm] rounded to integer numbers.

in isotopic composition of precipitation were observed in the last sample collected on 1st October. Almost all precipitation collected on that day fell on September 30 as a long lasting rain (duration of about 13 hours) with smaller intensity (average 0.3 mm/10 min) falling at high relative humidity of the air (100%). Greater contribution of fog in the alive and dead forest could thus be the reason of the great difference in the isotopic composition of throughfall.

The isotopic composition of soil water was very different from that of precipitation until August (the bottom panel in Fig. 4). Isotopically light water was observed in the dead forest until the mid-July. On the basis of our previous measurements (Holko et al., 2013) we conclude that soil until the mid-July contained a significant amount of the snowmelt water that has δ^{18}O values similar to those, presented for the soil water until the mid-July in Fig. 4. The assumption about greater influence of snowmelt in the dead forest is supported by findings of Bartík et al. (2019) who reported a significant increase in the amount of water stored in the dead forest compared to the alive forest. The soil water became isotopically similar to precipitation in August while the isotopically very light precipitation from the end of August was reflected in the isotopic composition of the soil water with the time delay of at least one week.

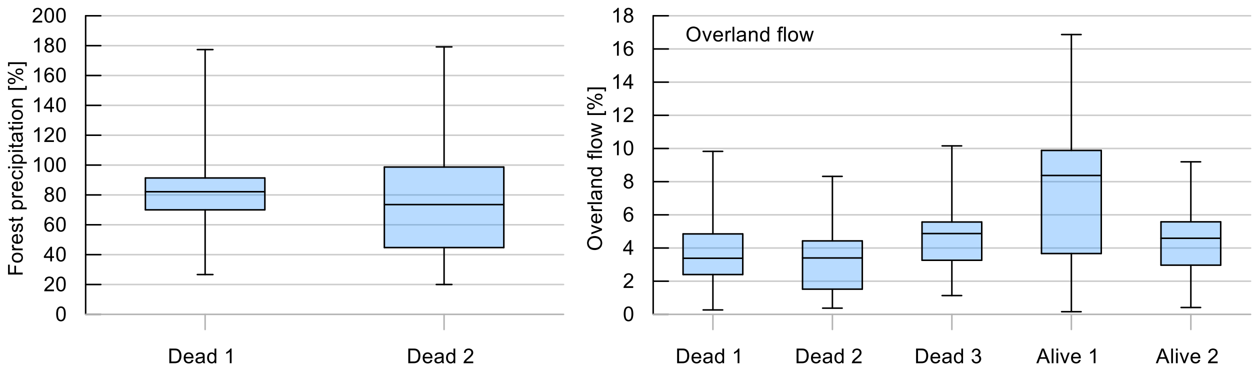

Fig. 5. Left – event throughfall in the dead forest (Dead 1, Dead 2) as a percentage of precipitation in the forest gap for the rainfall events during which the overland flow was observed (data from the tipping bucket rain gauges); right – overland flow in the dead and alive forest during the events over the entire study period (as a percentage of precipitation in the forest gap); the whiskers show minimum and maximum, the boxes show the upper and lower quartiles and medians.

Table 2. Precipitation amounts and isotopic composition of weekly precipitation in the forest gap, alive and dead forest in summer 2021; d is the deuterium excess; the red values represent evaporated samples (presumably due to small rainfall amounts and longer storage in the rain gauge)

Sampling date	Forest gap				Alive forest				Dead forest			
	P [mm]	δ^{18}O [‰]	δ^{2}H [‰]	d [‰]	P [mm]	δ^{18}O [‰]	δ^{2}H [‰]	d [‰]	P [mm]	δ^{18}O [‰]	δ^{2}H [‰]	d [‰]
4-Jun	20.4	-9.2	-60	13.1	5.8	-8.7	-56	13.3	10.6	-9.5	-63	13.4
10-Jun	5.0	-3.2	-16	9.6	1.0	-0.5	-3	1.4	3.0	-1.9	-10	5.1
18-Jun	25.4	-7.7	-50	12.4	15.6	-6.8	-44	11.2	19.2	-7.5	-48	12.0
28-Jun	12.4	-6.3	-39	11.8	3.4	-6.2	-36	13.1	7.9	-6.1	-38	11.5
9-Jul	22.4	-7.1	-47	10.1	3.6	-4.5	-33	3.7	14.0	-6.6	-43	9.5
15-Jul	58.2	-5.3	-27	15.7	49.2	-5.3	-26	16.5	56.8	-5.3	-26	16.4
19-Jul	8.0	-5.3	-32	10.5	4.4	-4.5	-25	11.2	5.5	-4.8	-28	11.0
30-Jul	50.4	-5.7	-32	13.7	25.2	-5.4	-28	16.0	45.2	-5.7	-30	15.3
3-Aug	55.2	-6.4	-37	14.2	30.4	-6.1	-35	13.9	37.0	-6.2	-35	14.5
11-Aug	81.6	-9.6	-63	13.4	61.2	-9.2	-60	14.1	88.2	-9.7	-64	13.5
18-Aug	20.8	-7.0	-41	15.0	9.2	-6.5	-37	15.6	14.6	-6.6	-39	14.3
25-Aug	33.6	-9.6	-63	13.6	25.6	-9.0	-58	14.5	26.4	-8.8	-57	14.1
3-Sep	150.6	-16.4	-117	14.6	165.6	-15.8	-112	14.5	182.4	-15.9	-113	14.5
23-Sep	57.2	-14.6	-106	10.8	40.4	-13.5	-97	10.5	52.0	-14.5	-105	11.6
1-Oct	26.0	-11.3	-80	10.6	15.6	-8.7	-57	12.6	20.4	-9.7	-66	11.3

Conclusion

The first results of the overland flow and isotopic measurements in the changing forest of the Jalovecký Creek catchment indicate that proposed experimental setup can provide useful data on the influence of forest changes on hydrological cycle. Future research can be accompanied by measurements of vegetation characteristics such as the leaf area index. Sampling of the snowmelt water before the summer period and of the overland flow could help in better identification of the soil water sources during the season and contribution of rain and soil water to the overland flow.

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