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Interception and soil water relation in Norway spruce stands of different age during the contrasting vegetation seasons of 2017 and 2018

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Abstract: Interception, soil moisture and soil water potential were observed in four Norway spruce stands of different age in two subsequent vegetation seasons 2017 and 2018. Vegetation season 2018 can be characterized as being abnormally hot and dry with only 66% of precipitation in comparison with normal conditions. The interception of spruce increased with the stand age and its dimensions, ranging between 16 and 48% in 2017 and in the majority of stands even increasing in 2018. The soil moisture significantly decreased during the vegetation season 2018, with soil water potential close to the permanent wilting point (–1.5 MPa) for a substantial part of the monitored period. Differences between individual stands were observed in terms of the soil water potential (SWP) development which does not follow the interception patterns suggesting that the stand transpiration is a driving factor responsible for the soil water budget. In all stands, with the exception of the oldest one, the SWP of the upper soil horizon was less than 1.5 MPa for more than 80 days. In such extreme conditions the drought would negatively influence any Norway spruce stand regardless of its age or structure.

Keywords: water balance; precipitation; throughfall; soil moisture; drought episodes

Norway spruce (*Picea abies* (Linnaeus) H. Karsten) is the most common tree species in the Czech Republic with the total share around 50% of forest composition (Ministry of Agriculture of the Czech Republic 2017). As a highly productive species it is common in all the countries of the Central Europe (Gebhardt et al. 2014). Spruce extension in this area includes not only the highlands or the mountain regions, but also lower altitudes, where it can be highly productive, while, at the same time, quite sensitive to such environmental stressors as dry periods, windthrows or pest attacks. In lower altitudes several cases of Norway spruce decline were observed during the last decades, often with drought considered as being a triggering factor (Holuša, Liška 2002; Šrámek et al. 2008). Drought episodes can decrease tree vitality and resistance to other stress factors (Seidl et al. 2016; Holuša et al. 2018) and in extreme condition they can lead even to the mortality of trees (Braun et al. 2015) as it was observed in 2003 in France and Germany (Granier et al. 2007) and in 2015 in Central Europe (Šrámek, Neudertová Hellebrandová 2016). Whereas in mountain areas drought periods are reflected mainly in reduced discharge of forested catchment areas without any strong influence on spruce vitality (Černohous et al. 2018), in lower-altitude regions they can cause significant deterioration of non-native Norway spruce stands. Due to the anticipated shift of climatic condition, such kind of extreme meteorological conditions can repeat more frequently, which is currently con-

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sidered as one of the most challenging problems for sustainable forestry (Temperli et al. 2012; Tumajer et al. 2017).

This article is focused on the evaluation of meteorological and soil water data from the Norway spruce stands of different age in the area of Central Bohemian hillside from years 2017 and 2018. The region has not been directly affected by the spruce decline so far, but during extremely dry year 2018 many cases of bark beetle (*Ips typographus* (Linnaeus, 1758)) infestation, increased defoliation and mortality of individual trees were observed. Data from the Želivka research station can serve as a model condition for many spruce forests in lower altitudes.

MATERIAL AND METHODS

Site description. The Želivka study site is situated in a Central Bohemian hillside (49°40'N, 15°14') at an altitude of 420 m a.s.l. The hydrological parameters in small forested catchment area of Pekelský potok, a tributary to the Káraný water dam, have been measured there since 1970's (Lochman et al. 2005). The catchment area is largely (~90%) forested by Norway spruce which is growing here fairly outside its extension area – original forests were composed from sessile oak and white fir at wetter sites and with sessile oak and European beech at dry sites. In 1994 a plot of Intensive monitoring of forest ecosystems within the ICP Forests programme was established in the catchment area. In 2016 other three plots covering different age of Norway spruce stands with measurements of throughfall and soil moisture were established to monitor the effect of the anticipated drought stress on this species (Table 1).

Meteorological and soil moisture measurements. The automatic meteorological station (WMO standard) has been working in an open area near the monitored plots (~1,200 m) since 2001. Data from this station were used for the potential evapotranspiration (PET) calculation and also for the calculation of 10-year mean values for temperature and precipitation. Precipitation on an open plot in years 2017 and 2018 was measured in forest clearing which meets the requirement for an open plot (diameter of clearing > 4 heights of neighbouring trees) and is much closer to monitored forest stands (~300 m). In individual forest stands the throughfall amount was measured using the Proamic Pro gutter type of the rain gauge (1,600 cm^2) with the Minikin ERi event recorder (EMS Brno, Czech Republic) which registers actual time of each tipping. To achieve better representativeness in regard to the whole stand we used other four manually measured (on daily basis) gutters with the total sampling area of 1.2 m^2 at each plot. The total amount from the manually measured gutters was recalculated to individual rainfall events recorded by the Minikin ERi datalogger.

Soil volumetric moisture (Campbel CS616) as well as soil water potential (Delmhorst gypsum block with the range up to –1.5 MPa) were measured in three depths of the soil profile (10, 30 and 50 cm) at each plot with a recording interval of 30 min.

Calculation and statistical evaluation. Potential evapotranspiration was calculated by means of the Penman-Monteith method (Waring, Running 2007) using the 10-min mean data from the meteorological station.

Statistical analysis was performed in R statistical software (Version 3.5.1, 2017). Independent samples t-test was used to assess differences in relation between the precipitation amount in individual rainfall events and interception in 2017 and 2018. Paired-samples t-test was used for evaluation of differences of soil moisture on individual stands between 2017 a 2018.

Table 1. Stand characteristic of research plots

	Age (yr)	Mean height (m)	Mean DBH (cm)	Basal area (m^2·ha^{-1})
ZE 01	9	8.9	8.7	21.4
ZE 02	48	18.3	19.7	41.95
ZE 03	72	32.0	31.1	61.7
ZE 04 (ICP Forests plot)	116	32.4	34.7	51.3

RESULTS

Meteorological characteristic of years 2017 and 2018

As the meteorological station does not cover any climatic normal period (1961–1990 or 1981–2010) we can compare individual years with the ten-year period 2007–2016 only. We also concentrate on the vegetation period (April–September). Looking at the mean temperature during vegetation season,

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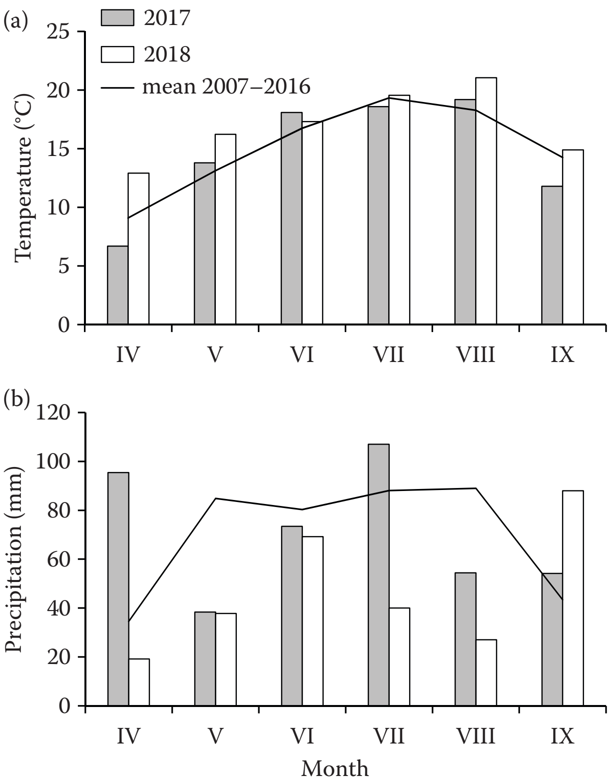

Fig. 1. Monthly temperatures (a) and precipitation (b) in 2017 and 2018 in comparison with the ten-year mean 2007–2016

year 2017 with 14.7°C was slightly below the ten-year mean (15.1°C), while, on the other hand, year 2018 with 17.0°C was strongly above this value. The biggest differences were found in April and September (Fig. 1). Mean sum of precipitation during the vegetation season in a ten-year period of 2007 to 2016 was 420.2 mm, which is close to the sum in 2017 – 422.8 mm. Precipitation amount is more variable than temperature. In 2017, April and July were strongly above the ten-year mean, with lower values recorded in May and August. On the other hand, precipitation was very low in 2018 and fairly below the ten-year mean for the entire vegetation period with the exception of September (Fig. 1). The total amount of precipitation during the vegetation period 2018 reached 281.2 mm only, which is 66% of the ten-year average.

Cumulative comparison of precipitation with the PET in 2017 and 2018 is presented in Fig. 2. Due to joint influence of both higher temperature and lower precipitation in 2018, the difference between PET and precipitation is nearly two times higher than in previous year.

Interception in Norway spruce stands

Precipitation measured on forest clearing – near to the monitored stands – was consistent with the meteorological station recording of the vegetation season amounts of 411.2 mm in 2017 and 291.2 mm in 2018. Both measurements show significant proximity with confidence interval ($R^2 > 0.92$) slope approaching 1 (1.01–1.02) and small increment (0.03 to 0.05) in 2017 and 2018 respectively.

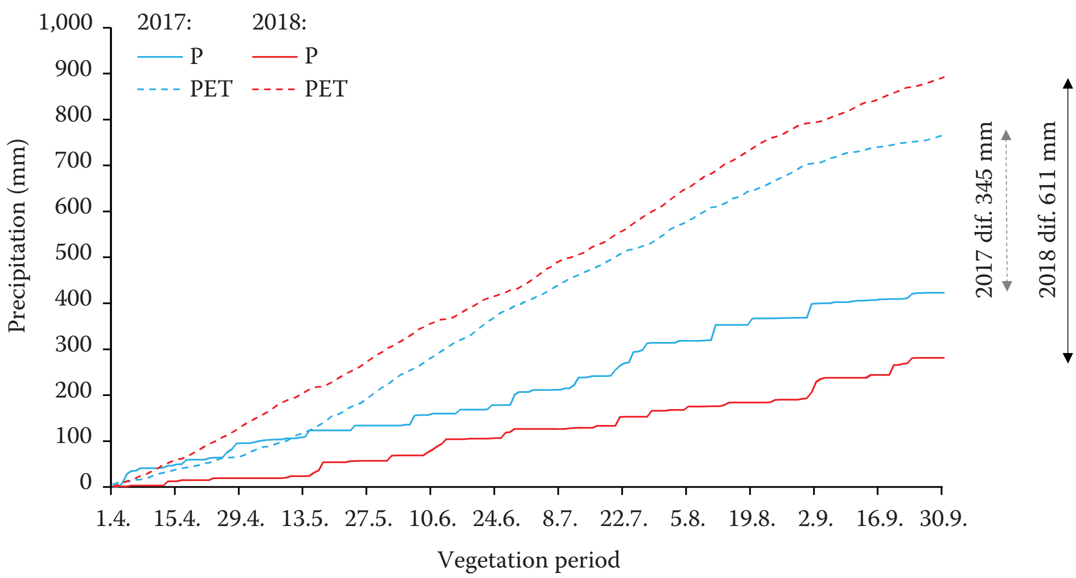

Fig. 2. Cumulative development of precipitation (P) and potential evapotranspiration (PET) during the vegetation periods 2017 and 2018; differences (dif.) of PET-P in individual years are displayed in the right part of the figure

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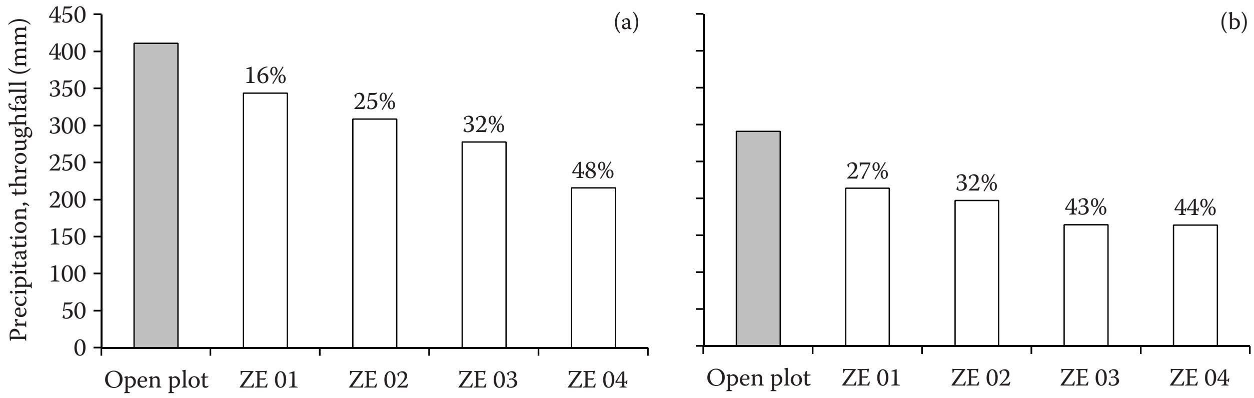

Fig. 3. Precipitation (open plot) and throughfall (forest stands: ZE 01–04) during the vegetation periods (April–September) 2017 (a) and 2018 (b);
Amount of precipitation or throughfall is given in bars, numbers indicate the interception rate at individual stands

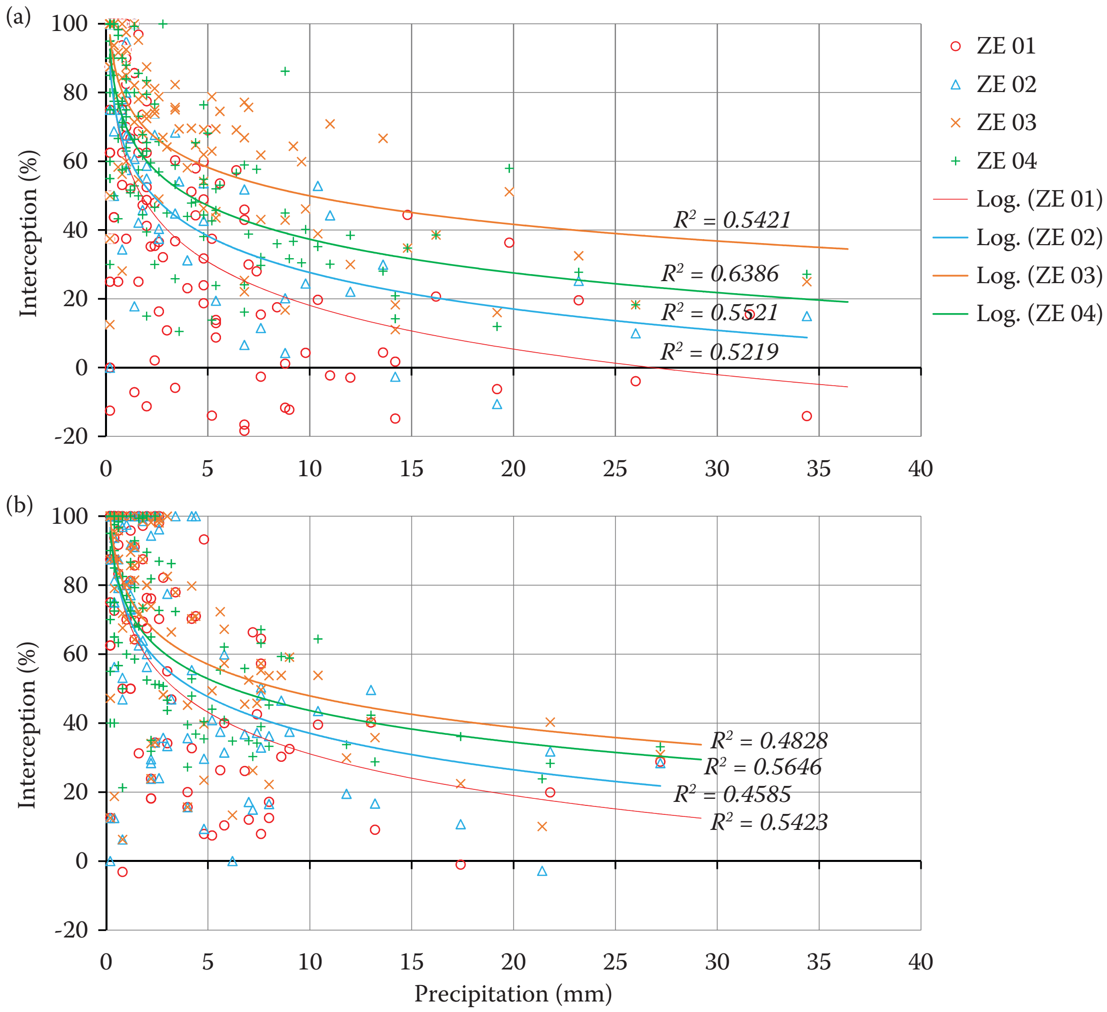

Fig. 4. Relation of precipitation of individual rain events and interception in 2017 (a) and 2018 (b) at individual plots

Precipitation throughfall in Norway spruce stands decreases generally with their age and height of trees (Fig. 3). In dry year 2018, however, the share of interception is considerably higher in younger stands than in "normal" year 2017. Interception reaches 27% in the thickets ZE 01, 32% in the young stand ZE 02 and 43% in the premature stand ZE 03 in 2018 which are values about 10% higher than in previous

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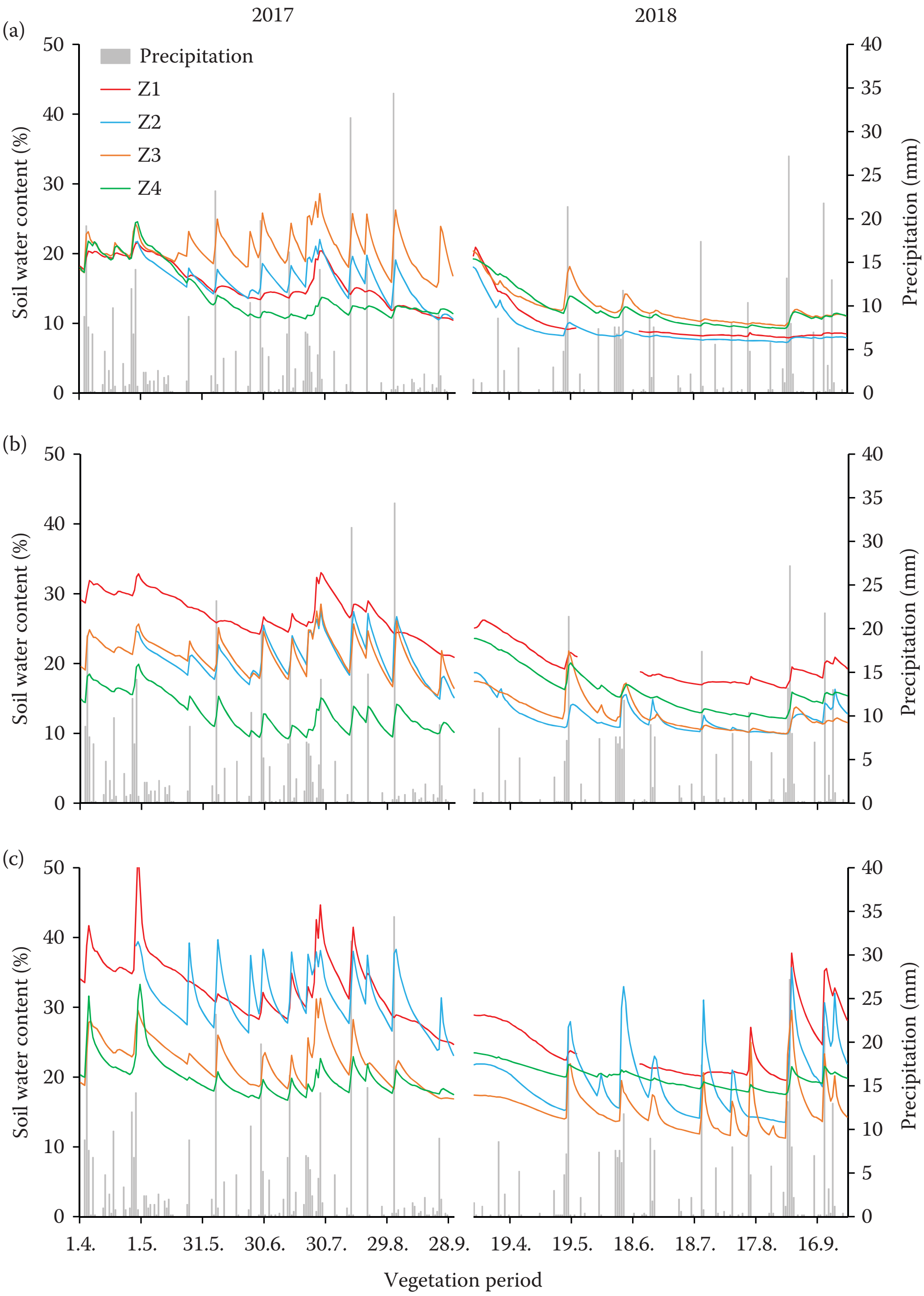

Fig. 5. Volumetric soil water content at individual plots in soil depth of 10 cm (a), 30 cm (b) and 50 cm (c) during the vegetation periods 2017 and 2018

years (Fig. 3). On the contrary, in the mature spruce stand ZE 04 interception was slightly lower in 2018 (44%) than in 2017 (47%). The relation between the precipitation amount in individual rainfall events and interception is presented in Fig. 4. There is significant difference of this relation in 2017 and 2018 at 5% level of significance for stands ZE 01, ZE 02 and ZE 03 (*P* (ZE 01) = 0.000, *P* (ZE 02) = 0.000, *P* (ZE 03) = 0.000, *P* (ZE 04) = 0.081). In 2017, the "total" interception was observed mostly in association with rain events below 1.5 mm; in one individual case of up to 2.7 mm. In 2018 it has occurred

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Table 2. Mean monthly soil moisture content (%) during the vegetation seasons 2017 and 2018

	Soil depth (cm)	2017						2018					
		Apr	May	June	July	Aug	Sept	Apr	May	June	July	Aug	Sept
ZE 01	10	20	18	14	16	15	12	15	10	9	8	8	8
	30	31	29	26	27	28	23	24	20	18	17	17	19
	50	37	36	30	33	34	27	28	24	21	21	21	30
ZE 02	10	21	17	15	18	16	13	12	9	8	8	8	8
	30	24	21	20	23	22	19	15	12	12	11	10	13
	50	39	31	31	33	31	29	20	19	21	17	15	24
ZE 03	10	21	20	21	23	21	19	16	14	12	11	10	11
	30	23	22	20	22	21	19	16	15	13	11	10	12
	50	25	24	21	23	22	19	17	16	15	13	13	18
ZE 04	10	21	18	12	12	12	12	17	13	11	10	10	11
	30	17	15	11	11	12	11	22	18	16	14	13	15
	50	23	22	18	19	19	19	22	21	20	19	18	20

commonly in case of rain events below 2.4 mm, in some cases of up to 4.4 mm. While with rainfall amount of 25 mm the interception of the spruce thickets was close to zero in 2017, the next year it was around 17% in the same case.

Soil moisture and water potential

Development of soil moisture in 2017 and 2018 has been substantially different, although some patterns are similar in both years – soil moisture in general increases with the soil depth, i.e. in 10 cm depth it is higher in older stands whereas in deeper soil it is higher in the thickets and young spruce stand (Fig. 5). In majority of the plots, a gradual decrease of soil moisture during the vegetation season was observed, occasionally interrupted by stronger rainfall events. In 2018, however, the precipitation amount was not sufficient to supply soil water stock, which led to extremely low water content (~10%) in upper soil horizons of all spruce plots from June to mid-September. In general soil moisture during the whole vegetation period was lower by 31 to 43% in 2018 in comparison with 2017 on ZE 01–ZE 03 plots. Differences of soil moisture between 2017 and 2018 are significant at 5% level (P (ZE 01) = 0.000, P (ZE 02) = 0.000, P (ZE 03) = 0.000). The mature stand ZE 04, on the other hand, did not manifest such significant difference between these two years (P (ZE 04) = 0.64) (Table 2).

Even greater distinction between the evaluated vegetation seasons is represented by soil water potential (SWP) (Fig. 6). The value of –1.5 MPa which is generally considered as the permanent wilting point, was recorded for only 26 days in the upper 10 cm layer of soil at the ZE 02 plot in 2017 (Table 3). On the other hand, such a low value prevailed in the upper mineral soil in younger ZE 01 and ZE 02 stands in 2018. The SWP in all soil horizons and at all plots was significantly more insufficient for water supply than in 2017.

DISCUSSION

Year 2018 with mean temperature 9.6°C and precipitation of 517 mm was extremely hot and dry comparing the climatic normal for the Czech Republic (Tolasz et al. 2019). In accordance with the Czech Hydrometeorological Institute the mean temperature of the vegetation season (April–September) was higher by 1.7 to 4.8°C (http://portal.chmi.cz/historicka-data/pocasi/uzemni-teploty#) and the total precipitation was by 166 mm (28%) lower (http://portal.chmi.cz/historicka-data/pocasi/uzemni-srazky#) in comparison with the climatic normal value (1981–2010). Our comparison of years 2017 and 2018 with the ten-year mean can be inaccurate in the sense of developing climate. It is probable that the ten-year period 2007–2016 is slightly warmer than climatic normal. Unlike our statement, the temperature of 2017 was evaluated as being higher than is the climatic normal for the Czech Republic by Crhová et al. (2018). Sum of precipitation, however, was evaluated as normal – similarly to our comparison with ten-year mean value.

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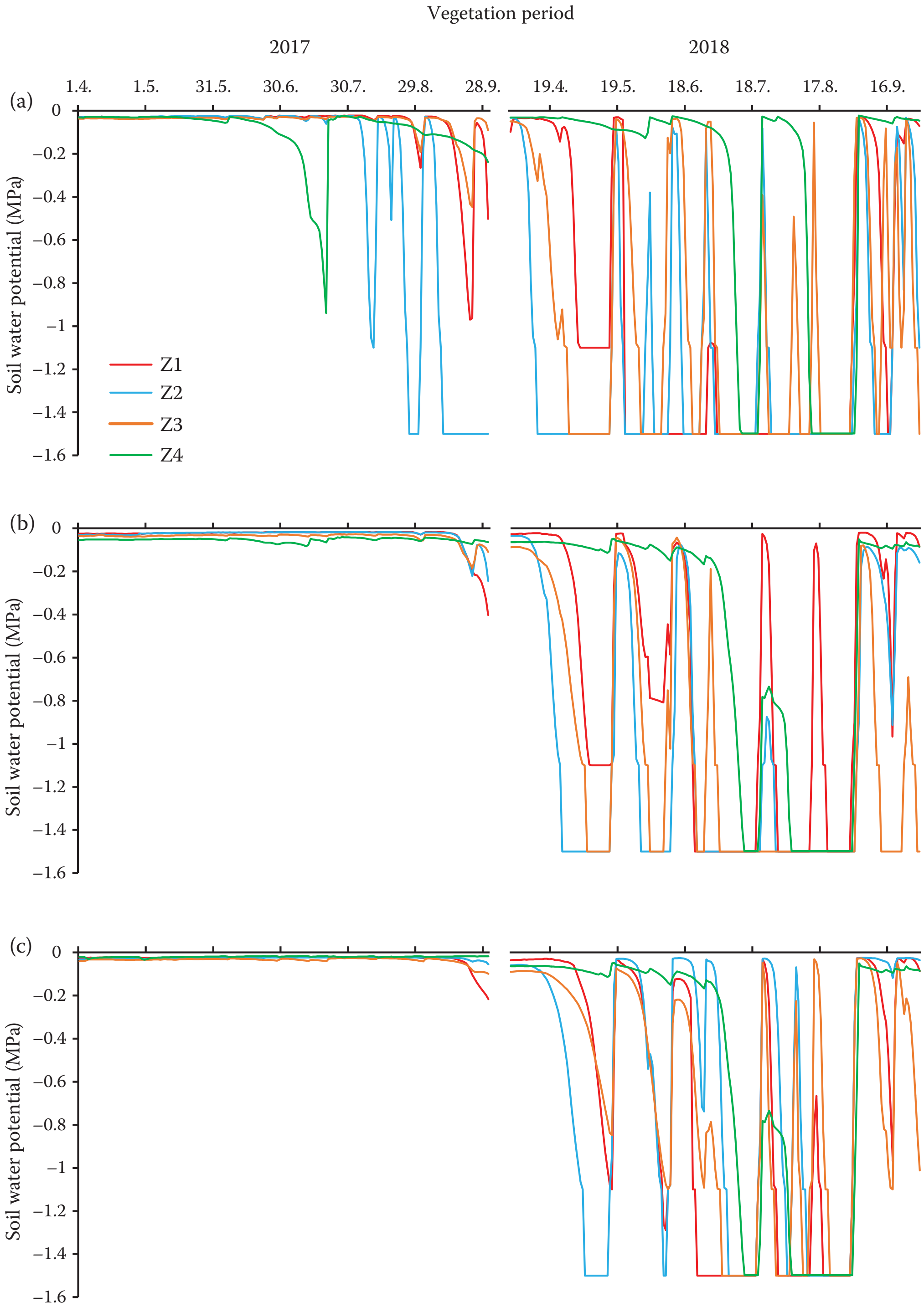

Fig. 6. Soil water potential at individual plots in soil depth of 10 cm (a), 30 cm (b) and 50 cm (c) during the vegetation periods 2017 and 2018

Measurement of interception by canopy showed reduction of rainfall amount by 16 to 48% in 2017. The interception increases with the age and height of the stand in accordance with findings by Grelle et al. (1997) or Barbier et al. (2009). It is quite high but taking in mind the site characteristic with low altitude, high mean temperature and relatively low precipitation, it is in relation with data reported by other authors. Minďáš et al. (2018) report interception between 20.5 and 35.5% in mountain Norway spruce in Slovakia, while Dohnal et al. (2014) refers to an average interception rate of 34.5% in

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Table 3. Number of days with soil water potential at the level of permanent wilting point (–1.5 MPa)

	Soil depth (cm)	2017	2018
ZE 01	10	0	99
	30	0	54
	50	0	55
ZE 02	10	26	121
	30	0	101
	50	0	48
ZE 03	10	0	83
	30	0	95
	50	0	36
ZE 04	10	0	29
	30	0	35
	50	0	35

mountain spruce in Czech Republic. In general, interception for coniferous forests is estimated from 25% to more than 50% (Krečmer 1968; Rutter et al. 1975; Gash et al. 1980; Johnson 1990; Gebhardt et al. 2014). The relative interception increased significantly during 2018 in three of our plots – ZE 01, ZE 02 and ZE 03 – which can be caused by higher temperature and thereby a higher water pressure deficit (Teklehaimanot, Jarvis 1991; Staelens et al. 2008; van Dijk et al. 2015) during vegetation season. Analysis of individual rainfall events also suggest that there was higher capacity of water retention in forest canopy in 2018 (up to 5 mm) in comparison with 2017 (~2 mm). The "wetting up" capacity of the forest canopy has been reported in values between 1.2 and 4.8 mm by different authors (Herbst et al. 2008; Dohnal et al. 2014; Minďáš et al. 2018) and it is influenced by the canopy roughness as well as by the relative air humidity before and evaporation during the rainfall event (Keim, Link 2018). In the case of abnormally hot and dry vegetation season it can be higher than in the event of usual meteorological conditions. The interception of the mature spruce stands ZE 04, on the other hand, was lower in 2018 in comparison with the previous vegetation season. As the distance between plots ZE04, ZE01 and ZE02 is less than 100 m in quite flat terrain, the real difference in rainfall events and their intensity is not probable. We cannot offer exact explanation for this distinction from other stands but we suppose that the increased defoliation – lowering the canopy closure and roughness – can play a role. Older stands and trees with greater size are more susceptible to increased defoliation as a reaction to environmental stresses including drought (Seidling 2007; Ozolincius et al. 2009; Rötzer et al. 2017); the vitality and stress tolerance of mature stands can be decreased by previous unfavourable condition as the drought period in 2015 (Šrámek et al. 2016).

Development of soil water content was significantly different between vegetation seasons 2017 and 2018. In comparison with other plots, the thickets ZE 01 showed the lowest water content in upper mineral soil (–10 cm) and the highest in deeper soil layers (30 and 50 cm). It can be explained by higher evaporation from the soil surface and lower uptake of water from deeper soil by trees of smaller dimensions (Rötzer et al. 2017). The only plot with higher soil water content during the vegetation season 2018 in the lower mineral soil layers (30 and 50 cm) was the mature stand ZE 04. This result cannot be explained solely by the lower interception rate discussed above, as the total stand precipitation was lower in 2018 than in previous year. The only other explanation is lowered water consumption by the stand, which can also be related to its lowered vitality. Changes in soil water potential between two evaluated vegetation seasons were even more pronounced. In 2017 the commonly used value of permanent wilting point (–1.5 MPa) was observed only in the young stand ZE 02 in the top soil (depth of 10 cm) during the second half of the vegetation season. In 2018 the situation was completely different with 35–121 days when the SWP was close or under the permanent wilting point. The situation was more critical in upper soil layers where the major part of the Norway spruce root system is located – so the strong limitation of spruce transpiration during the vegetation season is probable (Schwärzel et al. 2009). The lowest SWP measured in the young stand ZE 02 suggest that it is more influenced by stand transpiration or evaporation, than by the interception itself – at least when we assume identical drainage in individual stands. Differences of the SWP between vegetation seasons 2017 and 2018 were more pronounced than differences between individual stands during the dry vegetation season. Based on this finding we can conclude that forest management procedures to reduce drought stress – e.g. by reducing canopy area by thinning (Gebhardt et al. 2014; Vose et al. 2016) – can be successful only to a certain extent.

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CONSLUSIONS

The year 2018 can be evaluated as extremely hot and dry in comparison with the previous ten-year period at the Želivka research station. We have confirmed increasing interception with the age and height of Norway spruce stands in general. In dry condition of the vegetation season 2018 precipitation of the stand even increased with the exception of the mature plot of Norway spruce. This effect can be probably explained by increased defoliation of the older stand. The soil moisture significantly decreased during the vegetation season 2018 with soil water potential close to the permanent wilting point (–1.5 MPa) for a substantial part of the monitored period. There were differences between individual stands in the SWP development which does not follow the interception pattern suggesting that the stand transpiration is a responsible driving factor. In all stands, with the exception of the oldest one, the SWP of the upper soil horizon was more than 1.5 MPa for more than 80 days. In such extreme conditions the drought would negatively influence any Norway spruce regardless of its age or structure. For the forest practice, however, it will be extremely important how the stands will react to stress periods in the close future. While temporary decrease of increment will be acceptable, any sharp decrease in vitality and extensive mortality due to secondary stress factors can lead to vast disintegration of Norway spruce forests in the region.

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