THE EFFECT OF DROUGHT ON STEM VOLUME CHANGES OF NORWAY SPRUCE*

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The relationship between stem volume changes of Norway spruce and water availability has been studied during the growing season from April to October 2009 in a forest in central Czech Republic. The results proved that lack of soil water during short period has a high impact on daily stem volume changes. We analyzed the variability of daily stem diameter of Norway spruce by comparing daily maximum, minimum, its difference and average diameter and with environmental variables related to weather conditions and soil water content. We found out that the daily maximum, minimum and its difference were closest related to daily average water vapor deficits (VPD) and precipitation. However, the degree of correlation between stem diameter changes and soil water availability was low, there is still a high dependence on the amount of precipitation.

water deficit; stem increment changes; soil moisture; dendrometers

INTRODUCTION

Norway spruce (*Picea abies* L.) is economically important, but relatively drought-sensitive tree species that suffers from increasing drought intensities and frequencies, which are predicted to occur in parts of central Europe under future climate change (Gaul, Hertel, 2008). Therefore, drought, combined with increasing temperature, may decrease the vitality of the species. Soil water potential and soil moisture are informative water stress indicators, since they indicate how much soil water is available for trees. The soil water content regulates growth indirectly by controlling the mineralization and transport rates of different nutrients. Different studies from around the world have shown that water stress can limit forest productivity (Kljun, 2006). To analyze the relationship between soil water status and tree growth, the measurements of variation in the diameter of tree stems were used. According to Sevanto et al. (2001) tree diameter measurements provide a rapid response and it is considered to be a high resolution tool to detect changes in water tension inside the xylem. Stem diameter variation gives information on soil water uptake by trees. Stem diameter fluctuates daily because of transpiration-induced tension changes in the stem sap (Irvine, Grace, 1997; Perämäki et al., 2001).

In this study we measured diurnal xylem variation simultaneously with soil moisture and soil water potential of 18 spruce trees and analyzed the relationship between these three characteristics.

The benefit of diameter variation measurements consists in a non-destructive and direct tree-level measurement. The fluctuation follows the pattern of transpiration and the daily amplitude reflects the balance between transpiration rate and water uptake from soil (Perämäki et al., 2001). Sevanto et al. (2001) showed that drought results in overall decreasing trend in stem diameter, whereas increase in free water in the soil (e.g. after rainfall) makes the stem swell. Tree stem diameter varies diurnally as a result of transpiration induced tension in the sap wood (Irvine, Grace, 1997). The diameter is highest just before sunrise and lowest in the early afternoon when transpiration rates are high. Even the small variations in transpiration rates (and thus water tension) due to changes in cloud cover are observable in the xylem diameter. The daily amplitude of the variation is determined by the daily maximum transpiration rate, soil water availability (Perämäki et al., 2001), and the dimensions and properties of the stem (Sevanto et al., 2003; Perämäki et al., 2005). The higher the transpiration rate the higher the water tension and larger the amplitude. Absence of transpiration or no resistance of water flow from the soil through the stem results in zero amplitude.

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MATERIAL AND METHODS

Study site and experimental design

Tree diameter variations, soil water potential and soil moisture were measured on 18 Norway spruce trees (*Picea abies*) located in the six experimental plots (P1, P2, P3, P4, P5, P6) in the Brdy Mts, Central Bohemia (49°40′45.242″N; 13°56′13.408″E). The measurements were carried out during vegetation season in the year 2009. The plots were set up in August 2008. All plots are located in 80-year-old Norway spruce forest at 650 m a.s.l. with average annual precipitation 780 mm and average annual temperature 6.3°C. To monitor weather condition, meteorological stations were placed at the study site. In order to investigate the impact of manipulated water regime on the annual increment, two of the research plots (P3 and P4) were selected for a throughfall exclusion treatment. Two wooden roof structures (2.5 m high) were covered with translucent plastic panels to simulate periods of enhanced drought. To assess the importance of the stand wall, two of the research plots were placed inside the forest stand (P1, P2) and the others (P4, P5) at the edge of the stand. In this study we tested whether the soil water content expressed by soil moisture and soil water potential has a direct impact on annual stem increment. Design of experimental research plots can be seen in the following figure (Fig. 1).

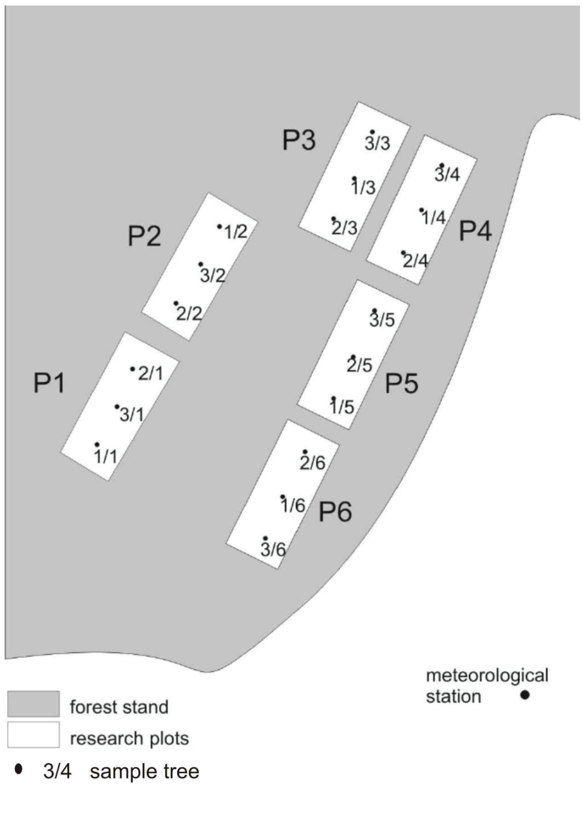

Fig. 1. Design of experimental research plots

Stem diameter variation

Stem diameter variations were measured on 18 Norway spruce trees located in the six experimental plots. To measure the daily diameter variation, we used the dendrometer increment sensor DRL 26 (EMS Brno Ltd.) with 1 μm accuracy and 1 hour record interval. In order to express, which trees indicate the lowest stem diameter variation, we calculated the daily maximum and minimum difference in all growing season. Using the Kruskal-Wallis ANOVA non-parametric test we compare the difference of maximum and minimum stem diameter variation values for each tree in three locations (stand wall, inner stand, manipulated water regime). Stem diameter variation values of trees from plots P3 a P4 were compared with the soil water potential and soil moisture data of all vegetation season 2009 (April to October). To describe daily stem increment changes, a graph of daily diameter variation in interval of two days is presented in the following figure (Fig. 2). The start of daily diameter variation changes is triggered by an increase of vapor pressure deficit, which indicates the shortage of water in the atmosphere to be saturated. Sudden increase of daily diameter variation in the first day at 1 p.m. is due to stomata closure in order to stop further transport of scarce water. In the afternoon the water transport is renewed.

Approach of stem diameter variation was also used for the whole vegetation season, where the values of minimum and maximum diameter were used to calculate the annual stem diameter difference.

Water regime assessment

Soil moisture and soil water potential were measured in 25 cm soil profile of each tree root system in all six plots. To measure the soil moisture we used the soil moisture sensor EC H_2O (Decagon Devices Inc.) with accuracy 0.04 $m^3 \times m^{-3}$ and 1 hour record interval. Soil moisture sensors were calibrated using gravimetric methods. To measure the soil water potential the gypsum block GB 2 (Delmhorst Instrument) was used with measuring range –0.1 to –15 bar and 1 hour record interval. To analyze the soil water content data we calculated the daily mean, minimum and maximum values during the vegetation season. Values of soil water potential data were transferred into MPa units based on assumption where 1 MPa is 10 bars. Kruskal-Wallis ANOVA test was used to compare soil water potential and soil water content data in three locations (stand edge, stand, manipulated water regime).

To study the daily stem diameter variation dependency on soil water content, we compared the differences of maximum and minimum stem increment values of each tree with mean soil water potential and soil moisture values using Spearman correlation coefficient.

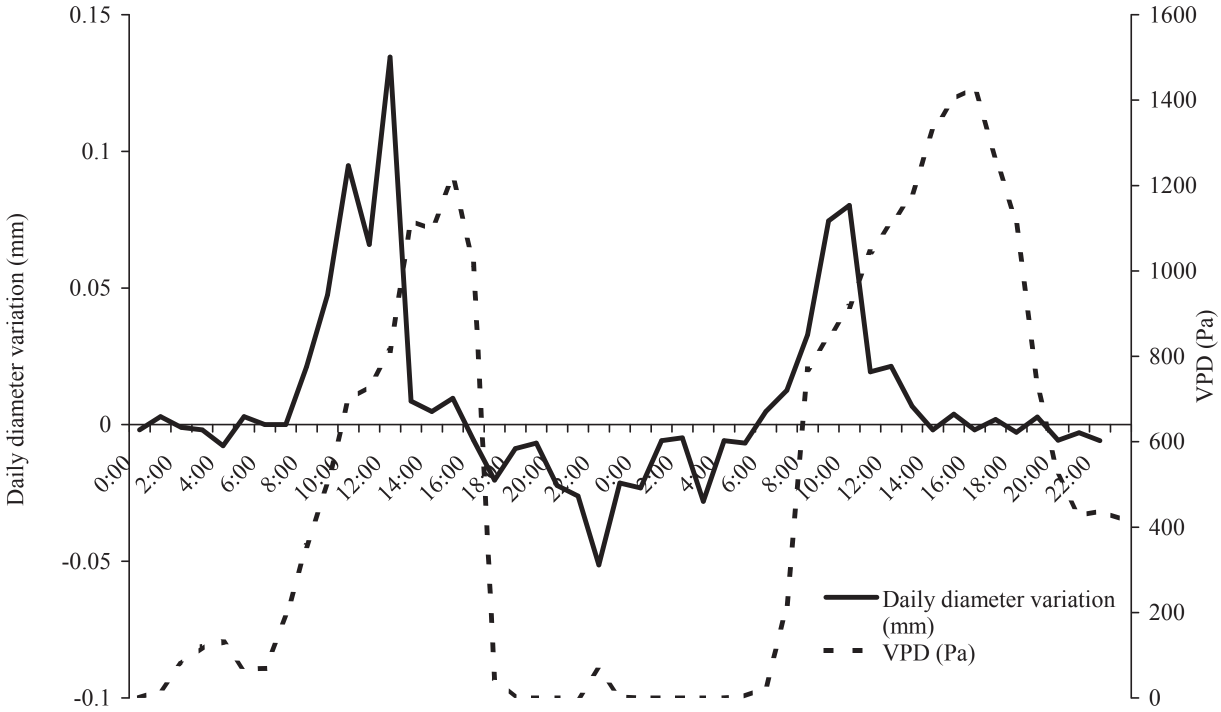

Fig. 2. Daily stem diameter variation compared to daily variation of vapor pressure deficit (VPD)

RESULTS AND DISCUSSION

The experimental plots were designed and set up in August 2008. We analyzed the weather data of the year 2009 (Table 1) and measured the DBH (diameter at breast height) of each tree (Table 2). The warmest month was August and the driest September. During these two months the trees in plot P3 and P4 suffered from severe drought. The overall sum of precipitation in 2009 vegetation season was 684 mm and average temperature 7.2°C.

Stem diameter variation

The DBH values were used to determine whether there is a strong influence of tree dimension on the annual stem diameter difference (difference of minimum and maximum stem diameter values). We used the linear regression non-parametric method (Spearman coefficient). The statistic correlation between DBH values and annual stem diameter difference per each plot was not statistically significant $r^2 = 0.1643$. Thus, we can say that the influence of DBH of each tree is minimal.

Table 1. Meteorological data expressed as mean values in hydrological year 2009

	Mean air temperature (°C)	Precipitation sum (mm)	Mean air humidity (%)	Mean maximum radiation ($W \times m^{-2}$)
November 08	2.80	30.40	97.73	268.55
December 08	-1.16	55.60	98.11	139.40
January 09	-4.84	12.20	98.47	189.02
February 09	-2.59	51.40	96.89	274.16
March 09	1.62	64.20	92.98	436.80
April 09	10.93	53.40	71.96	681.24
May 09	12.29	107.00	81.06	716.33
June 09	13.26	95.20	83.96	720.45
July 09	16.57	89.00	81.82	797.96
August 09	17.38	49.60	76.48	769.21
September 09	13.75	24.20	84.60	567.58
October 09	6.20	51.80	93.51	408.54

Table 2. Description of the experimental plots with DBH values for each tree

	P1	P2	P3	P4	P5	P6
Type of treatment	stand		manipulated water regime		stand edge	
Tree determination	1/1	1/2	1/3	1/4	1/5	1/6
	2/1	2/2	2/3	2/4	2/5	2/6
	3/1	3/2	3/3	3/4	3/5	3/6
DBH (mm)	389	392	312	374	437	381
	466	475	394	503	419	327
	365	355	451	458	452	452

DBH – diameter at breast height

Table 3. Annual stem diameter difference values [mm] of stem increment in vegetation season 2009 in all six plot

Experimental plots / trees											
P1				1/1			2/1			3/1	
Max	min	difference	18.023	2.127	15.896	15.296	1.954	13.342	17.535	3.108	14.427
P2				1/2			2/2			3/2	
Max	min	difference	18.475	4.733	13.742	11.182	1.975	9.207	12.566	1.385	11.181
P3				1/3			2/3			3/3	
Max	min	difference	2.123	0.407	1.716	11.631	8.449	3.182	6.655	4.902	1.753
P4				1/4			2/4			3/4	
Max	min	difference	8.112	5.261	2.851	5.344	3.828	1.516	1.069	0.538	0.531
P5				1/5			2/5			3/5	
Max	min	difference	23.098	0.371	22.727	24.765	0.233	24.532	28.839	5.171	23.667
P6				1/6			2/6			3/6	
Max	min	difference	15.270	0.311	14.959	17,680	6.367	11.313	31.630	0.812	30.818

Based on the Kruskall-Wallis non-parametric test (H = 13.35) we have proved the differences between individual treatments (Fig. 3). There is a significant difference between annual stem diameter difference of trees in plots with manipulated water regime (P3 and P4) compared to values in 'stand edge' plot ($P = 0.009$, $\alpha = 0.05$). The annual stem diameter difference between plots with manipulated water regime and 'stand' plots were not statistically significant even though the p-value was also low ($P = 0.079$, $\alpha = 0.05$).

Trees located in stand edge were exposed to high differences of sun radiation and soil water content. That is why the standard deviation of stand edge was the highest from all three treatments. Trees under manipulated water regime had the lowest annual stem diameter difference (1.92 mm per year) due to limited sources of water. Tree number 3/4 suffered from the highest lack of water with mean soil water potential reaching – 0.805 MPa. The annual stem diameter difference of the tree 3/4 was 0.531 mm, which is the lowest value of all stressed trees. Annual stem diameter difference values for other trees through all vegetation season (April to October) are presented in the following table (Table 3).

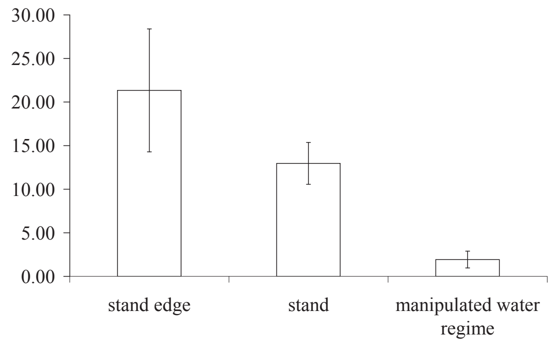

Fig. 3. Annual stem diameter difference values based on different treatment application using non-parametric Kruskal-Wallis test

Annual stem diameter difference is closely correlated with soil water availability. Increase of soil water content after long period of drought triggers stem volume change. Thus, the stem is absorbing water into the sapwood and increasing its volume. If the tracheids are blocked by cavitations no water can be absorbed and the tree is suffering from irreversible damage (Tyree, Sperry, 1989).

We have compared daily stem diameter differences with occurrence of precipitation. From the following two graphs (Figs 4 and 5) it can be seen that the highest peaks of daily stem diameter differences appear during rain event. Figure 4 demonstrates daily stem diameter differences of trees in two plots P5 and P4 during three weeks in May. On the 8^{th} and 17^{th} May

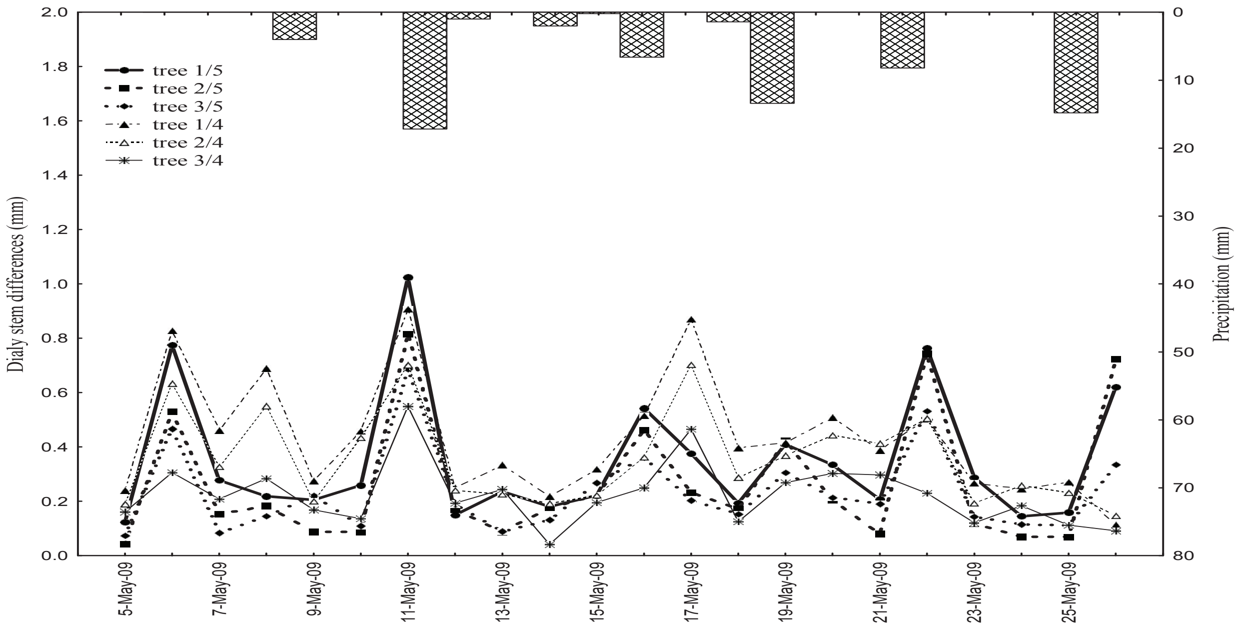

Fig. 4. Daily stem difference of trees in plots P4 and P5 compared with precipitation (May 2009)

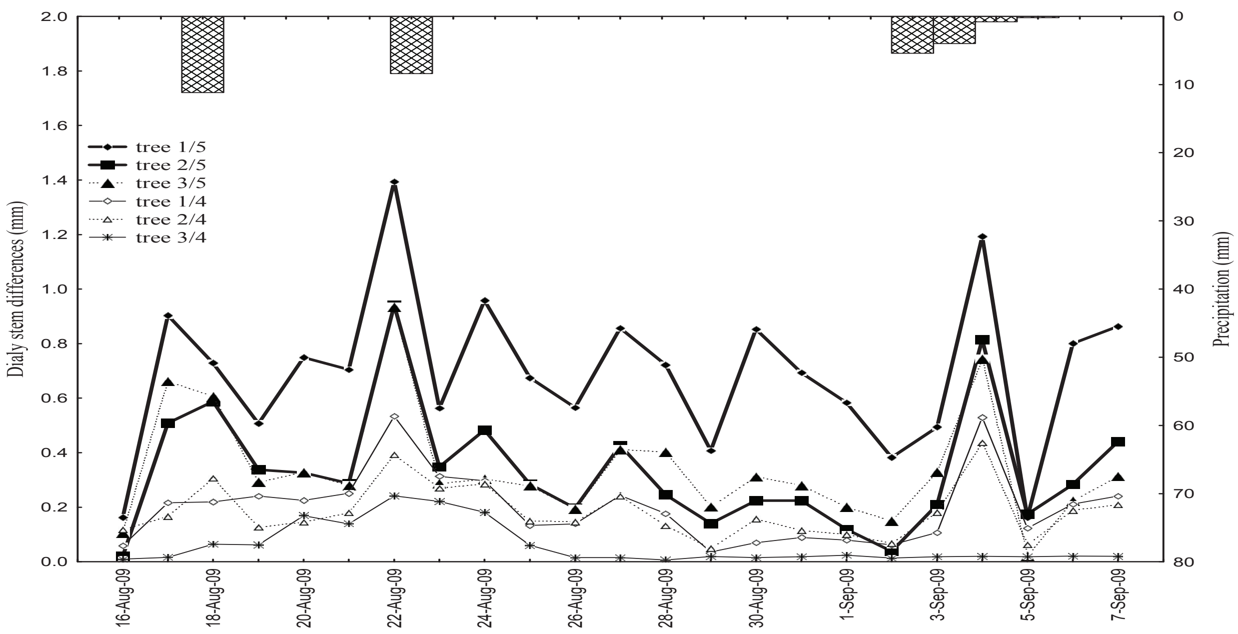

Fig. 5. Daily stem difference of trees in plots P4 and P5 compared with precipitation (August 2009)

stressed trees (P4) performed higher stem differences than P5. This means that trees in plot P5 do not need to absorb more water compared to P4 in these days.

Figure 5 shows the stem diameter difference in three weeks in August. There is a significant difference between the stem increment difference in plots P4 and P5. This could mean that the sapwood tracheids are damaged by long lasting drought. The cavitation could appear during long lasting drought mainly in high radiation peaks when the stomata are still open but there is no available water in the lower stem sapwood and soil. On 18th August plot P4 was watered with 3 m^3 of water. After watering the plots received additional precipitation of 12 mm, which was not expected. The soil was highly water-saturated and for 3 days (19th–21st August) there was no high stem diameter difference. On 22nd August after another precipitation event trees were absorbing more water to refill stem water storage. Tree in stressed plots P4 indicate lower stem diameter difference (0.5 mm for tree 1/4) on 22nd August compared with the trees in plot P5. That means that stressed trees do not have high amount of soil water available as trees in P5. From Figure 5 the lowest stem diameter difference of tree (3/4) is also evident that means that this tree is suffering from the lowest amount of soil water available.

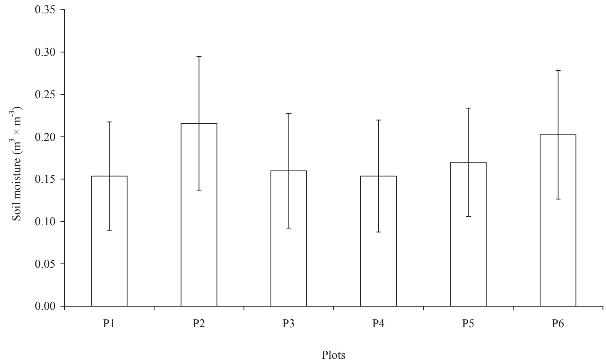

Fig. 6. Mean soil moisture values [m3 × m-3] in experimental plots

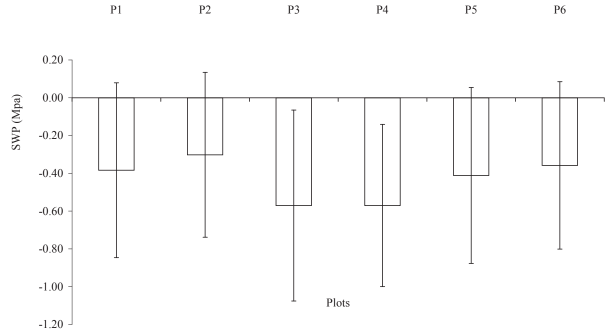

Fig. 8. Mean soil potential values [m3 × m-3] in experimental plots
SWP – soil water potential

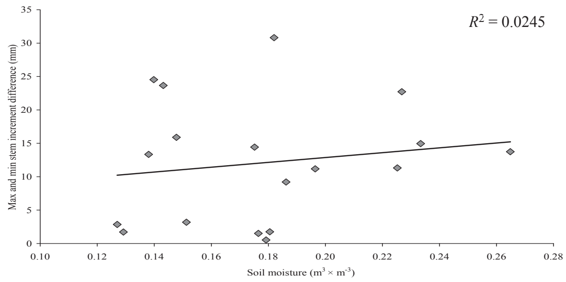

Fig. 7. Correlation between soil moisture values and annual stem diameter difference

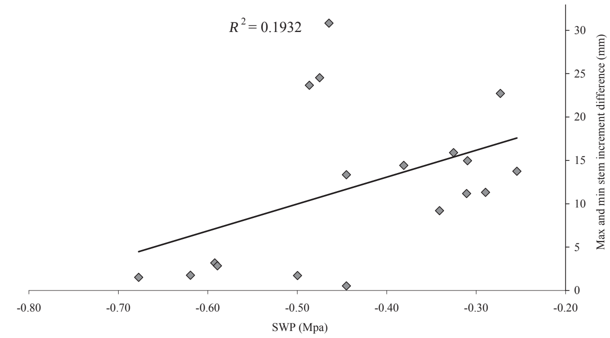

Fig. 9. Correlation between soil potential values and annual stem diameter difference
SWP – soil water potential

Water regime assessment

We have analyzed mean soil moisture data and soil water potential. Soil moisture data had to be first calibrated. Based on gravimetrical measurements it was found out that soil moisture water sensor EC H_2O measures 20% below the actual soil water content. Thus, the values of soil moisture were modified based on the 0.2 m^3 × m^{-3} soil water content difference.

Based on the results of water regime assessment, we have found out that the plots with manipulated water regime (P3 and P4) reached values of from –0.5 MPa to –0.8 MPa. Plot P4 has the lowest amount of available soil water compared to P3. The highest water potential values appeared with plots in the stand (P1 and P2). Trees in these plots suffer from minimal drought stress during the season. Higher values of soil water potential were reached on plots P6 and P5 (stand edge). This founding is connected with the plot placement and unstable moisture and annual stem diameter difference is not high (Fig. 7 and 9). The reason is the influence of tree different treatments. Thus correlation analyses should be performed in uniform data groups.

Generally speaking, soil moisture does not vary as soil potential. Values of soil moisture for plots P3 and P4 varied from 0.24 to 0.29 m^3 × m^{-3} soil water content. For a summary see graph above (Fig. 6 and 8).

Plant water use and response to varying soil water availability may have their basis in alternating the hydraulic conductance from soil to canopy (Sperry et al., 2002). The main changes in hydraulic conductivity from the soil through the plant to the atmosphere result from:
(i) changes in conductivity between bulk soil and the root as a function of soil water content (Newman, 1969),
(ii) stomatal regulation of water loss (i.e. change in the force inducing tension), and
(iii) embolisation of conduits in the sap wood (Tyree, Sperry, 1989).

The daily stem maximum diameter is to measure to what extent the plant is able to refill the stem during stomatal closure (i.e. how close to equilibrium with soil water potential the plant can get) (Sevanto et al., 2006). Since August 2008 we have observed decrease of foliage cover of stressed trees. Ability of spruce to adapt to drought condition is broad. As data of stem diameter variation for 2010 have already been available we can say that tree 3/4 has recovered from two months long lasting drought (–1.5 MPa) and in the year 2010 indicated the highest stem diameter variation.

It is known that drought stress increases levels of minerals, soluble N and soluble sugars in plant foliage, inner bark, and sapwood, because most plats lower their osmotic potential during drought by accumulating osmolytes (Mattson, Haack, 1987). As this project is also focussed on the Norway spruce susceptibility to bark beetle infestation, we are interested in drought and its effect on Norway spruce resistance. Thus monitoring of stem diameter variation measured by automatic dendrometers can give us information about ecophysiology of each tree.

CONCLUSION

Annual stem increment values of trees in stand edge (P5, P6) and stand (P1, P2) were not statistically different. Values of stem increment in manipulated water regime were statistically different from plots in stand and at the edge of the stand. We have managed to create mean drought represented by soil water potential –0.8 MPa by insolating fine roots and constructing rain water shelter. Drought stress trees have suffered from induced drought by decreasing its growth. The mean annual increment for plots with manipulated water regime was 1.92 mm compared with 12.97 mm in plots in the forest stand and 21.33 mm in plots at the edge of the forest stand. Trees in plots with manipulated water regime indicated higher stem volume changes at the beginning of drought treatment. At the end of the treatment (September 2009) they have performed minor stem volume changes due to lack of soil water.

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REFERENCES

GAUL, D. – HERTEL, D.: Effects of experimental drought on the fine root system of mature Norway spruce. Forest Ecology and Management, *256*, 2008: 1151–1159.

IRVINE, J. – GRACE, J.: Continuous measurements of water tensions in the xylem of trees based on the elastic properties of wood. Planta, *202*, 1997: 455–461.

KLJUN, N.: Response of net ecosystem productivity of three boreal forest stands to drought. Ecosystems, *9*, 2006: 1128–1144.

MATTSON, W.J. – HAACK, R.A.: The role of drought in outbreaks of plant-eating insects. BioScience, *37*, 1987: 110–118.

NEWMAN, E.I.: Resistance to water flow in soil and plant. I. Soil resistance in relation to amounts of root: theoretical estimates. Journal of Applied Ecology, *6*, 1969: 1–12.

PERÄMÄKI, M. – NIKINMAA, E. – SEVANTO, S. – ILVESNIEMI, H. – SIIVOLA, E. – HARI, P. – VESALA, T.: Tree stem diameter variations and transpiration in Scots pine: an analysis using a dynamic sap flow model. Tree Physiology, *21*, 2001: 889–897.

PERÄMÄKI, M. – VESALA, T. – NIKINMAA, E.: Modeling the dynamics of pressure propagation and diameter variation in tree sapwood. Tree Physiology, *25*, 2005: 1091–1099.

SEVANTO, S. – MIKKELSEN, T.N. – PILEGAARD, K. – VESALA, T.: Comparison of tree stem diameter variations in beech (*Fagus sylvatica* L.) in Soroe Denmark and in Scots pine (*Pinus sylvestris* L.) in Hyytiälä, Finland. Boreal Environment Research, *4*, 2003: 457–464.

SEVANTO, S. – SUNI, T. – PUMPANEN, J. – GRÖNHOLM, T. – KOLARI, P. – NIKINMAA, E. – MARI, P. – VESALA, T.: Wintertime photosynthesis and water uptake in a boreal forest. Tree Physiology, *26*, 2006: 749–757.

SEVANTO, S. – VESALA, T. – PERÄMÄKI, M. – NIKINMAA, E.: Xylem diameter changes as an indicator of stand-level evapo-transpiration. Boreal Environment Research, *6*, 2001: 45–52.

SPERRY, J.S. – HACKE, U.G. – OREN, R. – COMSTOCK, J.P.: Water deficits and hydraulic limits of leaf water supply. Plant, Cell & Environment, *25*, 2002: 251–263.

TYREE, M.T. – SPERRY, J.S.: Vulnerability of xylem to cavitation and embolism. Annual Review of Plant Physiology, *40*, 1989: 19–38.

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Vliv sucha na objemové změny kmene smrku ztepilého (*Picea abies* L.)

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Během vegetační sezóny duben až říjen 2009 byl v oblasti Brdské vrchoviny studován vliv sucha na objemové změny kmene smrku ztepilého. Cílem výzkumu bylo potvrdit významný vliv nedostatku vody na průběh objemových změn kmene. Denní variabilita objemových změn byla vyjádřena pomocí minimálních a maximálních hodnot rozpínaní běle, které byly měřeny pomocí automatického dendrometru. Hodnoty byly porovnány s dostupným množstvím půdní vody. Byla zjištěna závislost mezi denní amplitudy objemových změn kmene, tlakem nasycení vodních par ve vzduchu a množstvím srážek. I když hodnoty výběrového korelačního koeficientu r^2 mezi soubory hodnot půdní vlhkosti (půdního potenciálu) a denní amplitudou objemové změny kmene jsou nízké, k největším změnám objemu kmene docházelo vždy při srážkovém úhrnu. V tomto období docházelo k doplnění vody v běli a k větším objemovým změnám. Takto výrazné změny svědčí o významném využívání vodních rezerv a o mnohem nižším vodním potenciálu v xylému suchem stresovaný jedinců. Rovněž celkový přírůst během sledované periody byl u stromů stresovaných devětkrát nižší než u stromů nestresovaný.

vláhový deficit; změny přírůstu kmene; půdní vlhkost; dendrometr

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