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The influence of drought on the water uptake by Scots pines (*Pinus sylvestris* L.) at different positions in the tree stand

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Abstract. Periodically occurring drought is typical for the climate of Poland. In habitats supplied exclusively with rain water, tree stands are frequently exposed to the negative effects of water deficit in the soil. The aim of this study was to examine the water uptake and consumption of two individual Scots pine trees under drought conditions. The trees were located at different positions within the stand and at the time of study were over 150 years old. Soil moisture, availability of soil water and the quantity of water uptake by the individual trees were examined by measuring the water velocity inside the trunks (Thermal Dissipation Probe method).

Two periods of intense drought occurred in the summer 2006 only a few days apart. Before the drought, pine No. 1 (dominant) took up 66.7 dm^3 water per day and pine No. 2 (co-dominant) took up 52.3 dm^3 per day. The observed responses of the examined pines to the first period of drought were similar: the low soil water content resulted in a suppression of water uptake in both trees. After the end of the drought period however, the recovery responses of the two trees were different. Pine No. 1 resumed water uptake at values similar to those before the drought. Pine No. 2 on the other hand did not resume water uptake. We conclude that in case of this second tree the vegetative season possibly ended already at the end of June.

Keywords: Scots pine, soil moisture, pF curve, water uptake, sap flow, TDP, drought

1. Introduction

Poland's climate is characterised by periodic weather-related droughts, which disrupt the water balance of a given area, resulting in soil droughts that affect vegetation growth, including that of the forest. For example, 41 weather-related droughts were reported in Poland for the period 1951–1990, of which the longest lasted 13 months (Kowalczyk et al., 1995), whereas in Białowieża, an average of four periods of no rain were reported annually from 1950 to 2003 (Boczoń 2006).

The occurrence of soil droughts affects the growth of trees and their health status. In Europe, an increasing frequency of summer droughts may lead to a decline in the health of trees, and the incidence of long-term soil water deficits can cause hydraulic and physiological effects in subsequent years (Innes 1993). In Poland, nearly 75% of all forests is found in either dry or fresh habitats, in which the only source of water is precipitation. The main species of the tree stands in these habitats is Scots pine (*Pinus sylvestris* L.). Although this species occurs in a wide range of habitat conditions and is considered to be resistant to various environmental conditions, these stands are in fact susceptible to the adverse effects of drought in the soil.

The aim of this study was to determine the amount of water uptake and consumption of individual Scots pine trees aged over 150 years at different positions in the tree stand under conditions of drought-affected soils.

2. Methodology

The study site was established in the Sękocin Forest in a fresh coniferous forest habitat, with rusty soils and a deep ground water table. The study included the identification of the elements of water flow between the soil–plant–atmosphere continuum. Measurements were made of soil moisture, water flow in the tree trunks and weather conditions. The study was conducted in 2006–2007.

Soil moisture was measured using the apparatus manufactured by Easy Test, based on original solutions deve-

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loped at the Institute of Agrophysics of the Polish Academy of Sciences in Lublin. Volumetric soil moisture was determined based on the reflectometry technique (time domain reflectometry, TDR). The principle of measuring soil moisture using the TDR method consists of determining the dielectric constant of the soil that is subjected to an electrical field with a frequency of 10^9 Hz. Under such conditions, the soil acts as an insulator, whose dielectric constant is conditioned by moisture, as water is a conductor of electrical impulses. It is calculated using the following formula:

$$\varepsilon = \left(\frac{c}{v}\right)^2$$

where
ε is the dielectrical constant,
v is the velocity of the propagation of electromagnetic waves in the soil,
c is the speed of light in vacuum.

Volumetric soil moisture is determined using the following formula (Malicki et al. 1996):

$$\theta_{TDR} = \frac{\sqrt{\varepsilon} - 0.819 - 0.168 \cdot \rho - 0.159 \cdot \rho^2}{7.17 + 1.18 \cdot \rho}$$

where
θ_{TDR} is the volumetric soil moisture,
ρ is the soil density.

The method used, based on the reflectometric measurement of soil moisture, is highly compatible with the direct measurement of soil moisture by the gravimetric method (Malicki et al., 1998).

The measurements at the study site were made automatically at the depths of 10–20, 40–50 and 70–80 cm at 1 hour intervals.

Water uptake was measured using the thermal dissipation probe method developed by Granier (1985). The sensor consists of a pair of needle-like probes. They are placed in the trunk towards the centre of the tree, one above the other vertically at a distance of 40 mm. The upper probe includes heat sensors and a heater, whilst the lower has heat sensors. The sensors record the radiation of the heat in the wood that is generated by the heater. The rate of water flow (V) is determined from the relationship

$$V = 0.0119 \cdot K^{1.231}\ (cm \cdot s^{-1})$$

where K is calculated with the formula:

$$K = \frac{(dTM - dT)}{dT}$$

in which
dT – the difference in temperature between the upper and lower probe of the sensor,
dTM – value of dT, when no water is flowing in the trunk.

Sensors manufactured by Dynamax were used in the study, as they work together with the DataHog 2 data collection device from SKYE. The sensors were placed in trees at the DBH. Measurements were made automatically with a 30-minute interval.

Calculating the tree's water uptake ($cm^3 \cdot s^{-1}$) requires the measurement of the trunk's cross-sectional area through which water is conducted. Pine trees transport water through the entire width of the sapwood, so the cross-sectional area of the sapwood must be measured. The amount of water flow is the product of the measured flow rate ($cm \cdot s^{-1}$) and the cross-sectional area of the sapwood (cm^2).

Measurements of two Scots pine trees were taken, whose characteristics are presented in Table 1. Pine tree no. 1 towers above the others in the stand and has a highly developed crown, which classifies it as a dominant one of the largest in the stand. Pine no. 2, although it is only slightly shorter than pine no. 1, has a much smaller crown. Although it could be considered a codominant, its direct proximity to the pine no. 1 caused that the thickness and height of pine no. 2 are much smaller (Table 1).

The determination of drough was based on soil moisture and soil water retention (pF curve) measured in the laboratory – for each depth measurement. To determine the pF curve, laboratory equipment from the Ejikelkamp company was used. In a pressure range of 0–0.1 bar, sand apparatus was used, and from 0.2 to 15 bars, pressure chambers (Soil Moisture Ltd. of Santa Bar-bara, USA) were used. Soil drought occurred when the soil moisture was lower than pF = 3.7, which is below the limit value of the early wilting point for plants.

To determine the meteorological conditions that cause the occurrence of soil drought, the method used by Kowalczyk and others (1995) was applied, that is, the outflow of moisture was determined as the result of water balance, calculated as the difference between precipitation and evapotranspiration, where monthly evapotranspiration was calculated using the Ivanov formula (Bac 1968):

$$EP = 0.00144\ (25 + T)^2 (100 - f)$$

where
EP is the monthly evapotranspiration potential (mm),
T is the average ambient air temperature (°C),
f is the average monthly relative humidity of the air (%).

The meteorological data from the Warszawa-Okęcie weather station were used for the calculations.

3. Results

The soil water retention curves showed that at specific depths, the moisture limit values below the early wilting

Table 1. Biometric characteristics of the Scots pine trees studied

Parameters	Pine no. 1	Pine no. 2
Age	about 160 years	about 160 years
Height	27.3 m	25.6 m
DBH	69.1 cm	44.6 cm
Bark thickness	3.2 cm	2.1 cm
Width of sapwood at DBH	11.3 cm	5.2 cm
Cross sectional area at DBH	3087.6 cm^2	1294.6 cm^2
Sapwood area at DBH	1175.3 cm^2	587.7 cm^2

point were 0.048 $cm^3 \cdot cm^{-3}$ at a depth of 10–20 cm; 0.036 $cm^3 \cdot cm^{-3}$ at a depth of 40–50 cm; 0.030 $cm^3 \cdot cm^{-3}$ at a depth of 70–80 cm (Table 2). The condition of soil drought, where soil moisture is lower than the values presented above, was met in the summer of 2006 (Fig. 1). In the periods of July 2–10 and July 23 to August 2, soil moisture was below the limit value for the early wilting point at all measured depths.

The occurrence of soil drought was the result of low rainfall from the beginning of the year until July 2006, where only 180.3 mm of precipitation was recorded.
As a result of the low rainfall, only in the winter months of January and February, there was a slightly greater inflow of moisture than outflow – a total of 40 mm. Successive months brought an ever greater moisture deficit, which reached 210 mm in July. From March to July, moisture outflows were about 446 mm higher than inflows (Fig. 2). In 2006, the water balance showed a moisture deficit amounting to 319 mm. Following the criteria adopted by Kowalczyk and others (1995), we can conclude that there was a very intense drought in 2006.

Table 2. Soil moisture (cm^3 cm^{-3}) at points of the pF curve at three soil depths of the study plot

pF-curve point	Depth [cm]		
	10–20	40–50	70–80
0.001	0.462	0.448	0.419
0.4	0.458	0.445	0.416
1.0	0.445	0.421	0.385
1.5	0.377	0.381	0.346
2.0	0.277	0.240	0.222
2.7	0.072	0.053	0.041
3.0	0.056	0.042	0.034
3.7	0.048	0.036	0.030
4.2	0.040	0.033	0.027

In the period from 1 June to 15 August 2006, pine no. 1 experienced a rapid reduction in water uptake because of drought soil conditions on July 2. Water uptake was interrupted from 4 July until 3 August, except for the period of July 12–15, when water uptake was resumed for a few days (Fig. 3). The daily amount of water uptake was similar in the period before soil drought and the period after it (up to 66.7 dm^3 before the drought and up to 59.8 dm^3 after the period of drought). Monthly water uptake after the period of drought was more than 950 dm^3 in August and September (Fig. 4). The reduction in monthly consumption in October was associated with the end of the growing season.

Pine no. 2 had a daily water uptake of 52.3 dm^3 before the drought. It stopped absorbing water already on 24 June 2006 as a result of the water deficit in the soil (Fig. 3). Although there was a small amount of water uptake on 12–13 July and 4, 6, 11 August, the interruption of water uptake can be regarded as permanent for this tree in that growing season. In the months of the drought, total water consumption reached only 2 dm^3 in July and 21 dm^3 in August. The tree no longer absorbed water in successive months (Fig. 4).

4. Discussion

When an unlimited amount of water is available in the soil, as is the case in wet habitats, the variability of water uptake by a tree depends mainly on weather factors (Boczoń 2004). Disturbances in the process of water uptake may be caused by other factors, for example, by folivores that reduce the number of leaves and area of tree transpiration or by pathogens that attack tree roots, leading to the reduction in the number of roots capable of absorbing water. In wetland habitiats, the high amount of water itself is a factor limiting absorption ability. Excess water causes a lack of

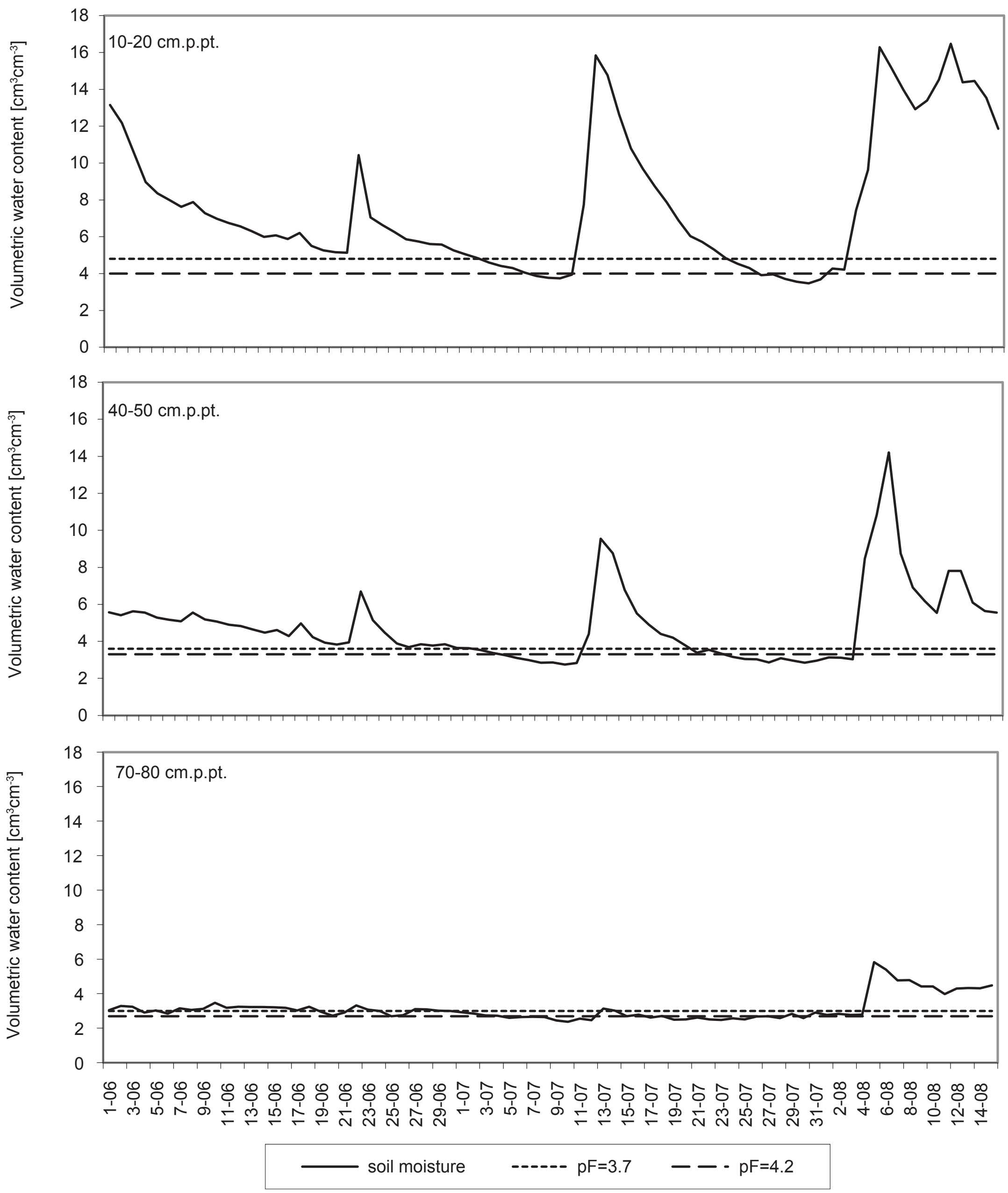

Figure 1. Soil moisture at depths of 10–20, 40–50 and 70–80 cm at the study plot with limit values at the early wilting point (pF = 3.7) and the permanent wilting point (pF = 4.2)

oxygen available to the roots, which affects their ability to function correctly, resulting in a decreased ability of trees to take up water, thereby reducing growth. In the case of dry and fresh habitats, periodic water shortages occur in the soil, which limits or completely inhibits water uptake by trees.

On the basis of water absorption measurements taken in the Sękocin Forest, different responses of the pines to soil drought can be observed. In the summer of 2006, weather conditions caused two periods of soil drought within a few days of each other. The studied pines reacted similarly to the first period of soil drought; in both the cases, they stopped absorbing water. However, after this drought was over, the trees reacted differently. Pine no. 1 resumed water uptake, and daily consumption values were similar to those before

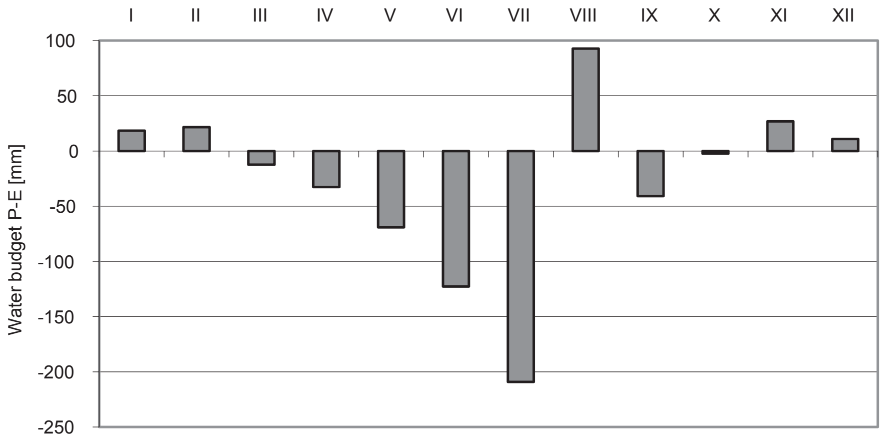

Figure 2. Monthly water balance (P-PET) in 2006 at the Warszawa-Okęcie weather station

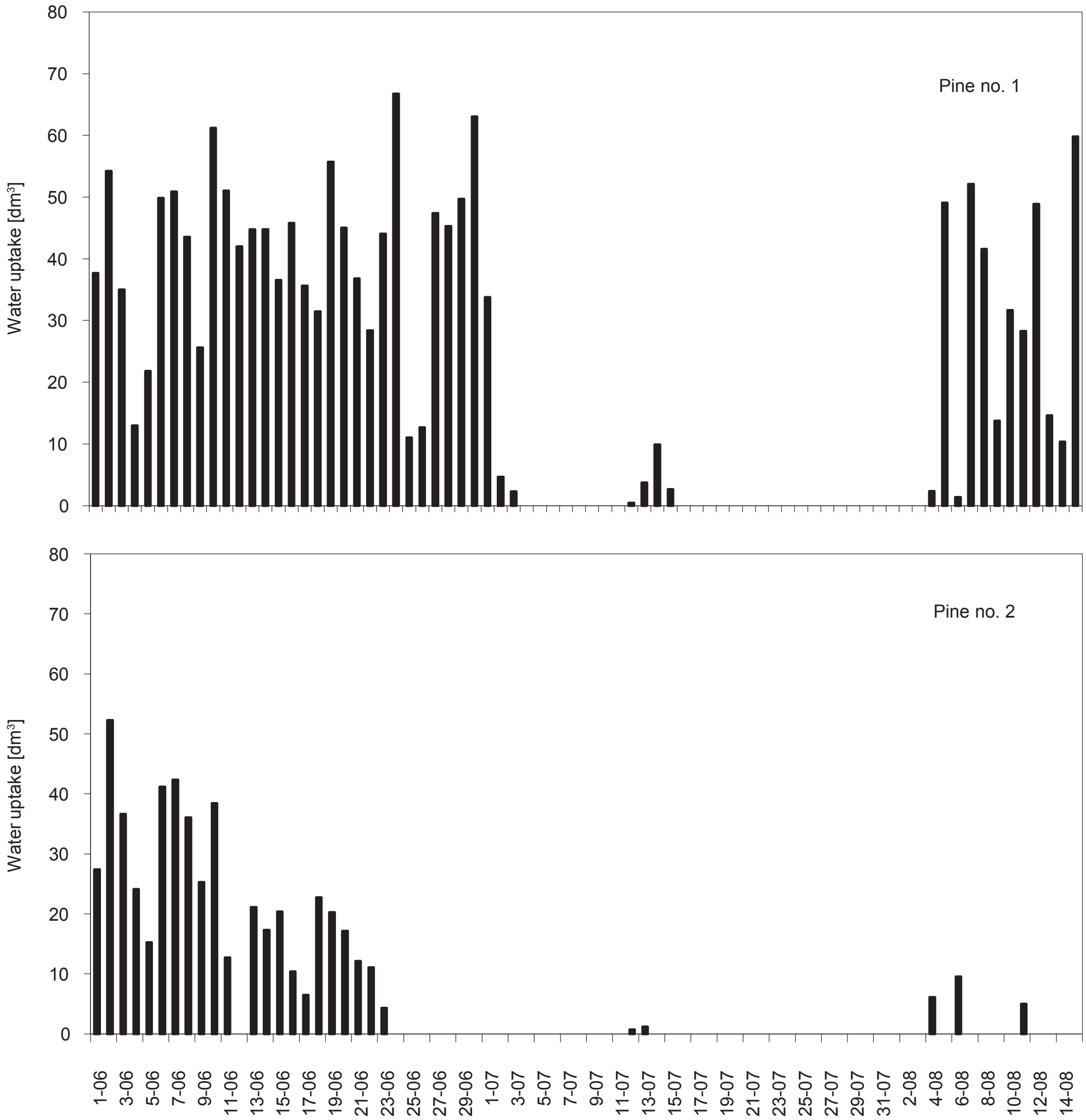

Figure 3. Daily water uptake by pine trees from 1 June to 15 August 2006

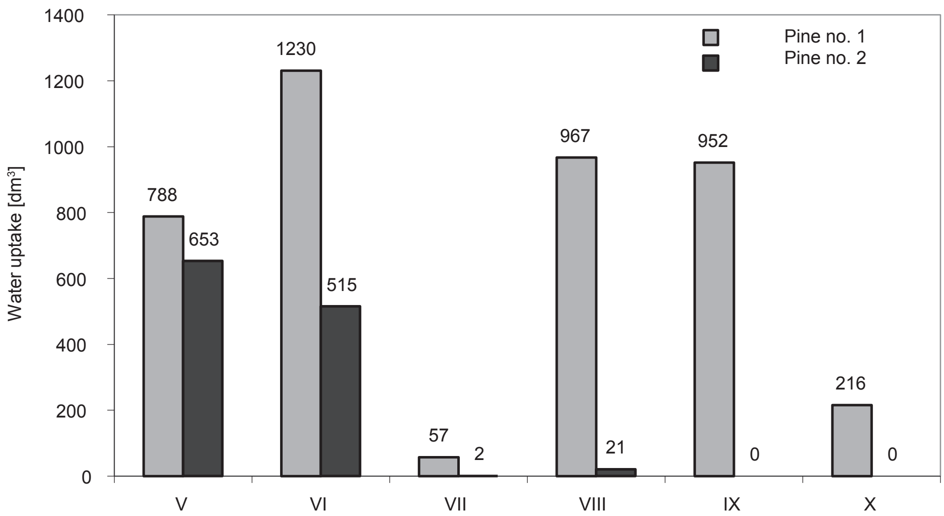

Figure 4. Monthly water uptake by pine trees from May to October 2006

the soil drought. Pine no. 2 did not resume water uptake. In the case of this tree, one can say that its growing season for that year concluded at the end of June. The diverse response of these trees to soil drought was conditioned by several factors. Pine no. 1, as the largest tree in the stand and extensively developed, was in a much better position to absorb water. Such trees have a higher water uptake than those in the lower layers of the stand. The largest and towering trees in the stand have the best growing conditions, and therefore, when there is good water availability, they are able to reach the largest size and develop the greatest leaf surface area. Their maximum water absorption surpasses the amount of water taken up by the trees in the canopy layer, and the amount of water taken up by the stand's understory layer has no practical significance for the stand's total water absorption. There is a clear interdependence between the size of trees, the surface area of the leaves and the amount of absorbed (transpired) water. Other authors have also noted this dependence. Strelcova (1998) performed measurements in a mature fir-spruce-beech stand, where under conditions of unlimited water availability in the soil, beeches in the upper layer of the canopy transpired 370 litres of water per day, whilst at the same time, beeches in the lower canopy layer transpired only 83 litres. In contrast, a single tree in the highest canopy layer transpired more than 14,500 litres of water throughout the growing season, whilst a tree in the lower canopy layer transpired just less than 3,300 litres. Similar studies were carried out in a 220-year-old stand of *Abies amabilis* fir (Martin et al., 2001). These studies clearly show that the social position of trees affects both their size and, hence, the amount of produced volume of timber, as well as on the amount of water uptake. Trees towering over the canopy absorbed a daily maximum of 281 dm^3 of water and trees in the canopy layer absorbed 101 dm^3, whilst understory trees absorbed 9 dm^3. The better growing conditions of the trees in the uppermost stand layer are due to the more favourable micro-meteorological conditions for photosynthesis and transpiration, particularly greater access to light, and consequently, a higher temperature and lower relative humidity. The intensity of transpiration decreases about 20% in large trees with dense crowns when the shadows of surrounding trees fall on their crowns (Čermak 1995).

The occurrence of drought in the first months of the growing season has particularly strong impact on the growth of trees. Limiting the availability of water causes the weaker growth of pine needles and smaller increases in trunk size (Irvine et al., 1998). This affects the increase in trunk thickness in the next year, as the shortened needles impact the effectiveness of photosynthesis and transpiration, and lower annual growth results in a reduced effectiveness of water absorption. Intense soil drought reduces the transpiration of pine stands, both in the year of its occurrence (Cienciala et al., 1998) as well as in the following year, regardless of the favourable weather and water conditions which may occur (Clausnitzer et al. 2011).

5. Conclusions

Sandy soils, in which pine stands are mainly found, retain small amounts of water. Rapid changes in soil moisture result in a clear reaction of pines to the smaller amount of available water. Soil drought occurring in the growing season interrupts the process of water uptake by pines.

The reaction of trees to the deficit of water in the soil depends on their position in the tree stand. Dominant trees tolerate drought better than trees from the general level of canopy, which, in the case of recurring adverse conditions, are not able to renew the process of water uptake after a period of drought and end their vegetation period earlier.

Conflict of interest

The authors declare no potential conflicts of interest.

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Author’s contribution

A.B. – conceptualisation of the article, literature review, data analysis, preparation of the manuscript and corrections of the text; M.W. – field work and corrections.

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