

Spatial and temporal variation of drought impact on black locust (*Robinia pseudoacacia* L.) water status and growth

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Stimulated by the rising demand for bioenergy, forestry practices for energy production are of increasing importance worldwide. Black locust (*Robinia pseudoacacia* L.) is a suitable tree species for biomass production in short-rotation plantations in East Germany, especially on marginal land where insufficient water and nutrients are a limiting factor for tree growth. Our study aims to clarify the spatial and temporal variability of the black locust growth through the analysis of the plant water status, and to evaluate the effect of adverse edaphic conditions on growth performances, amplified by periods of summer drought. The study was carried out at two sites presenting comparable climatic but different edaphic conditions: (i) fertile agricultural soil; and (ii) heterogeneous unstructured soil from a reclaimed post-mining area. During the vegetation period, the growth rate decreased in both sites following the plant water status in terms of pre-dawn leaf water potential. Particularly in the post-mining area, due to the adverse edaphic conditions, below the critical pre-dawn water potential value of -0.5 MPa, the stem growth was drastically reduced during a period of summer drought. However, the trees could cope with the extreme soil and weather conditions in the post-mining site without perishing.

Keywords: Agroforestry, Drought Stress, Soil Water Availability, Soil Heterogeneity, Reclamation

Introduction

The interest in short-rotation coppice systems rose over the last decades, aiming to improve the sustainability of the second generation bioenergy crops. Besides their positive ecological functions, fast-growing trees like poplars and willows can be harvested and used for bioenergy production (Weih 2004). Among the more common tree species used in northern Europe for bioenergy production, black locust (*Robinia pseudoacacia* L.) is planted with remarkable success for reclamation in lignite opencast mining areas in Brandenburg (NE Germany – Grünwald et al. 2009, Böhm et al. 2011). Here, due to the ongoing mining activities, the groundwater table is low-

red, and therefore plant growth depends mostly on the amount of rainfall. In those areas characterized by unfavorable edaphic conditions (Hüttl & Weber 2001), the soil is mostly an unstructured clayed-sandy material, extremely heterogeneous and poor in organic materials and nutrients. As a result (Bungart et al. 2000), a decrease in productivity is to be expected, due to the scarcity of nutrients. Furthermore, the soil water availability during summer is more prone to water deficit than in agricultural soils under the same climatic conditions. Since water and nutrient availability are the main limiting factors for primary production, there is a need to evaluate the drought impact on the black locust growth

performance, taking into account the response of the plant to different edaphic conditions. There are several research works carried out at field scale, describing the black locust biomass production and its relation to water constraint (Bongarten et al. 1992). The link between the black locust growth and the soil water availability has been recently clarified by Mantovani et al. (2014a, 2014b), however only in a controlled lysimeter experiment. Therefore, in our work we aimed at evaluating the impact of summer drought periods and nutrient paucity on black locust growth performance in the field, linking the plant water status to the radial increment of the trunk during the vegetation period. The spatial and temporal variability in leaf water potential and its implications for tree growth was taken into account. More specifically we carried out a critical comparison between black locust growth performance under water limitation in two sites with different edaphic but comparable climatic conditions.

Material and method

Study sites

The study area is located in southern Brandenburg, Germany, about 150 km southeast of Berlin and is characterized by an average annual precipitation of 556 mm and a mean annual temperature of 9.3 °C (1951-2003, nearest climatic station Cottbus, Deutscher Wetterdienst).

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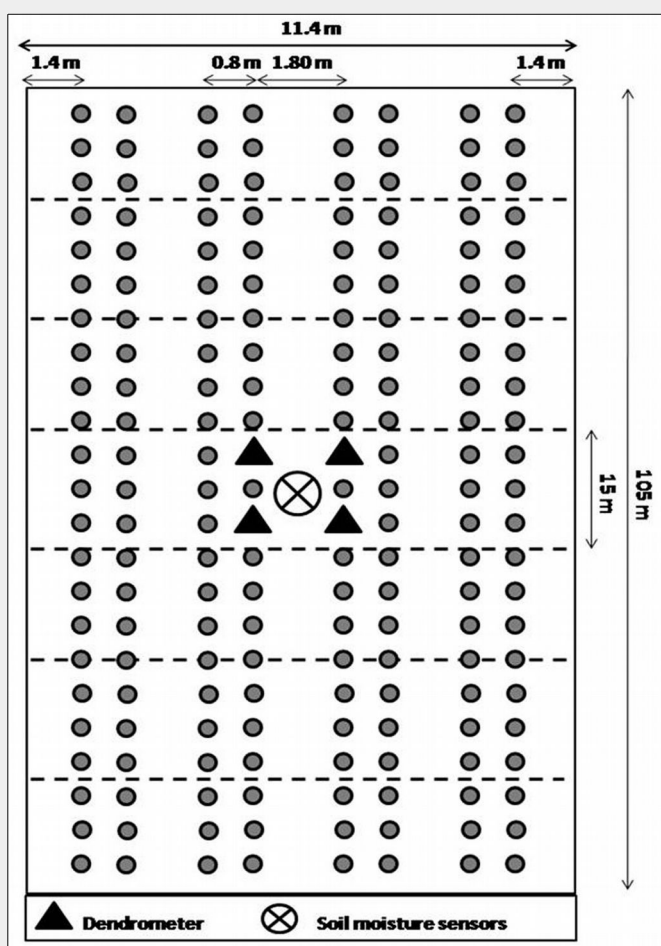
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Fig. 1 - Schematic diagram of the tree plantation in Forst and Welzow-Süd. The figures are not in scale and the circles in the figure are only representative of the tree rows, not of the single trees.



selected trees was evaluated with dendrometers (DDL, Ecomatik, Dachau, Germany) at breast height at both sites. The selected trees were located in the center of the tree rows (in the subplots W4 and F4 – see Fig. 1). The plant water status of 56 selected trees was evaluated periodically, measuring the pre-dawn leaf water potential (Ψ_{pd}) of three leaves per tree, using the Scholander pressure chamber (Plant Water Status Console 3000, Soilmoisture Inc., Santa Barbara, CA, USA). The pre-dawn leaf water potential was measured starting two hours before sunrise. The trees were georeferenced by using a differential GPS system (Trimble R8 GNSS /R6 /5800, Dayton, Ohio, USA). The spatial information, together with the Ψ_{pd} values, was integrated into a Geographic Information System (ARCGIS Spatial Analyst software, ESRI, Redland, CA, USA) and used to create a dynamic map.

Statistical analysis

A non-parametric analysis Mann-Whitney U-Test ($\alpha < 0.05$) was performed to compare the two sites in terms of: (i) bulk density; (ii) saturated hydraulic conductivity; (iii) mean cumulative daily diameter increment, measured in the subplots F4 and W4; (iv) mean Ψ_{pd} recorded during the same day in different subplots within the same site. The non-parametric Spearman's ρ correlation ($\alpha < 0.01$) was applied to link the mean weekly growth rates to the Ψ_{pd} . The analyses were carried out using the IBM SPSS® version 21 (SPSS Inc. Chicago, IL, USA). For the geospatial analysis the ARCGIS Spatial Analyst software (ESRI) was used. Spatial and temporal variations of the Ψ_{pd} were evaluated by interpolating the Ψ_{pd} values obtained in the different subplots during the vegetation period with the inverse distance weighted interpolation method (IDW).

Results

Climatic conditions

The mean daily air temperature and the vapor pressure deficit (VPD) at both study sites are shown in Fig. 2. In Welzow-Süd 30% and in Forst 25% of the measured days had a mean daily temperature lying between 20 and 25 °C. The VPD instead showed more variation between the two sites, with 33% and 16% of the days above 5 hPa Pa⁻¹ for Welzow-Süd and Forst, respectively (Fig. 2b). The global radiation at both sites was comparable, with values higher than 200 Wm⁻² for approximately 60% of the days (Fig. 3a). During the vegetation period the total rainfall in Welzow-Süd amounted to 238 mm, while in Forst 301 mm were recorded (Fig. 3b), the daily amount for each sites is shown in Fig. 4.

Hydraulic conditions and soil moisture

The mean bulk density of the Gleysol in Forst was 1.6 g cm⁻³ and the K_s values measured at 5, 20, and 40 cm depth were 59,

For the experiment two different sites were chosen: (i) Forst (51° 47' 24" N, 14° 37' 57" E), a fertile agricultural field characterized by sandy loam soil (Gleysol – FAO 2006). While located close to the river Neiße, the annual variation of the groundwater table lies between 1.0 and 2.2 m below the soil surface. (ii) Welzow-Süd (51° 37' 23" N, 14° 19' 34" E), a reclaimed post-mining site with a groundwater table lower than 100 m below the soil surface due to the ongoing mining activity. The soil here is heterogeneous and consists mainly of sands and clayed-sands in an initial stage (Regosol – FAO 2006), therefore it is still unstructured (Krümmelbein et al. 2012). The total organic carbon (TOC) measured in Forst (10.1 g kg⁻¹) was higher than in Welzow-Süd (2.9 g kg⁻¹), while the total nitrogen (TN) values amounted to 0.9 g kg⁻¹ in both sites.

Black locust bare-root seedlings were planted in Forst in the spring of 2010 and in Welzow-Süd in the spring of 2007. The plants were established in form of an agroforestry system as a short-rotation coppice for bioenergy production. The design of the agroforestry system at both sites was comparable. The tree hedgerows consisted of four double rows. Along the row the trees were planted every 0.85 m. The tree distance within and between the double rows was 0.8 m and 1.8 m, respectively. Crop alleys in between the hedgerows had

a width of 24 m. One plot of 11.4 × 105 m was selected at each site (Fig. 1), and split in 7 subplots of 11.4 × 15 m.

Air temperature, relative humidity and precipitation values were measured using weather stations and stored on data loggers (Delta-T devices Ltd., Cambridge, UK) in 10 min intervals.

Hydrological soil characteristics

The saturated hydraulic conductivity (K_s) was determined in undisturbed soil cores (100 cm) sampled at both sites at 5, 20, and 40 cm depths in six replicates. We chose the permanent head method using a lab permeameter (Eijkelkamp, Giesbeek, Netherlands). After measuring the K_s , the bulk density of the same cores was determined by oven-drying at 105 °C until constant weight of cores was reached.

Plant growth and plant water status

For each subplot four fully developed trees were selected. The monthly tree growth was recorded by measuring the diameter at breast height (DBH) with a polyethylene caliper. At the beginning of the experiment, in the spring of 2012 the mean DBH was 18.4 ± 4 mm in Forst and 35.4 ± 8 mm in Welzow-Süd, which suggest that, despite the adverse edaphic conditions, tree growth can be considered relatively normal also in the latter site. In addition, the daily growth rate of the four

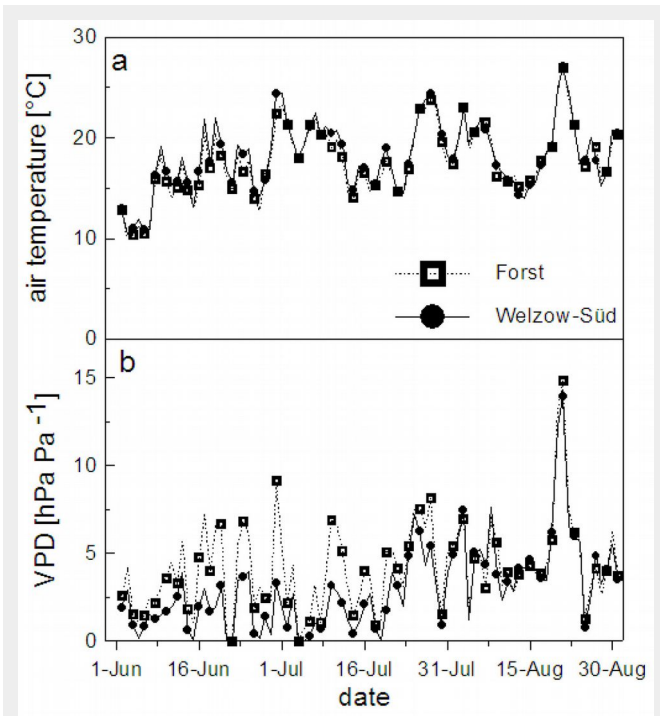


Fig. 2 - Daily mean air temperature (a) and daily mean vapor pressure deficit (b) measured at Forst and Welzow-Süd during the vegetation period (from June 1st to August 30th, 2012).

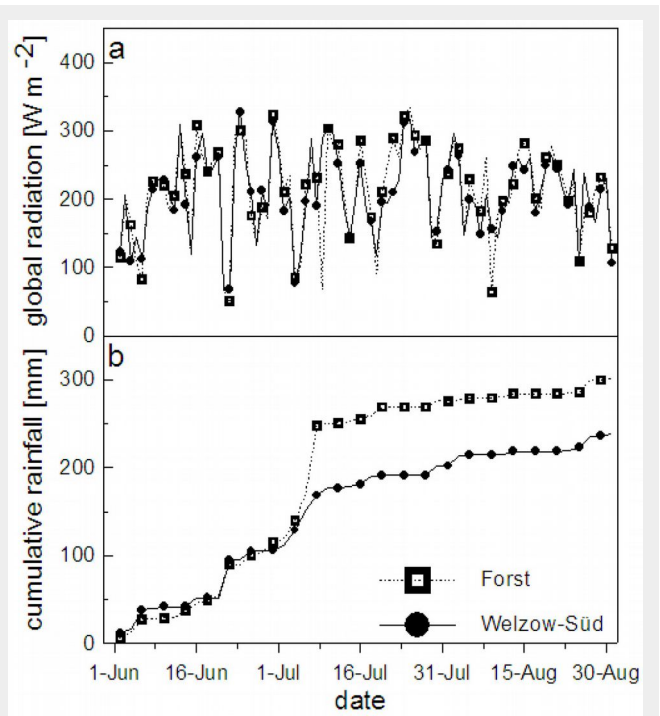


Fig. 3 - Daily mean global radiation (a) and cumulative rainfall (b) measured at Forst and Welzow-Süd during the vegetation period (from June 1st to August 30th, 2012).

17, and 27 cm day⁻¹ respectively. Although the structureless Regosol sampled in Welzow-Süd presented a comparable bulk density (1.7 g cm⁻³), the *K_s* was significantly higher, varying between values of 559 (*p* = 0.032), 223 (*p* = 0.036) and 73 (*p* = 0.42) cm day⁻¹, measured at 5, 20, and 40 cm depth respectively.

Daily diameter increment

The dendrometers installed in the subplots F4 and W4 recorded the daily diameter growth and we found no significant difference (*p* = 0.067) between the sites until July 25, 2012 (Fig. 5). The difference only became significant (*p* = 0.038) towards the end of the experiment when in Welzow-

Süd the plant diameter increased only 52% of the plants established in Forst.

Weekly growth and plant water status

The plant water status (Ψ_{pd}) in the subplots F4 and W4 became more negative in the final stages of the experiment (Fig. 6). In August both sites faced a summer drought period, which affected the tree growth. The correlation between the weekly diameter increment rate and the Ψ_{pd} was significant (*p* = 0.689) only in Welzow-Süd, and their relation was better described by a logarithmic function ($Y = -0.13 \cdot \log(X) + 0.09$, $r^2 = 0.60$) with a drastic decrease of the diametric increment following the Ψ_{pd} reduction (Fig. 7b).

Spatial variation of pre-dawn water potential

Until July 25, 2015 for all the subplots measured at both sites the mean Ψ_{pd} values were > -0.5 MPa. At the Forst site, the mean Ψ_{pd} values decreased for all subplots until the mean minimum of -0.81 MPa was reached on August 24, and no significant differences between the subplots were found. Conversely, starting from August 14 the mean Ψ_{pd} decreased drastically at the Welzow-Süd site, reaching the minimum mean values of -1.56 MPa on August 24. Here, the differences between the subplots in terms of Ψ_{pd} became significant (*p* = 0.028), ranging from -2.06 MPa in subplot W4 to -0.96 MPa in subplot W6. The soil

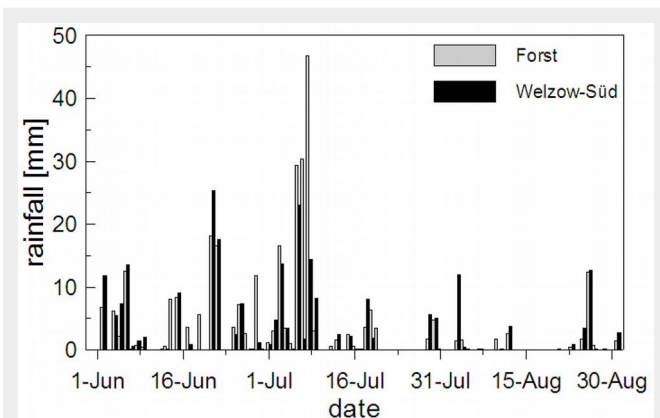


Fig. 4 - Daily rainfall amount at Forst (a) and Welzow-Süd (b) recorded during the vegetation period (from June 1st to August 30th 2012).

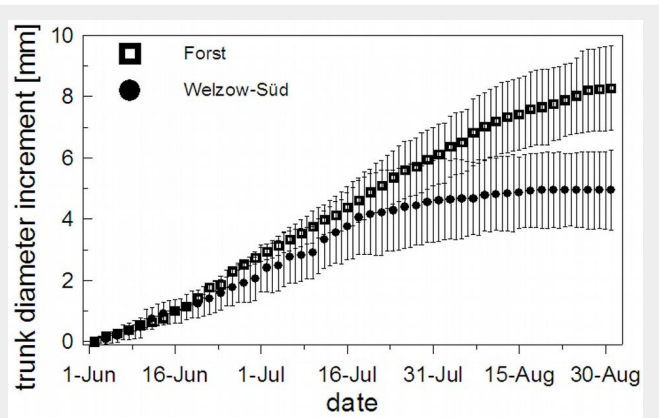


Fig. 5 - Mean and standard deviation of the trunk diameter increment measured in the F4 subplot (Forst) (a) and W4 subplot (Welzow-Süd) (b) during the vegetation period (from June 1st to August 30th, 2012).

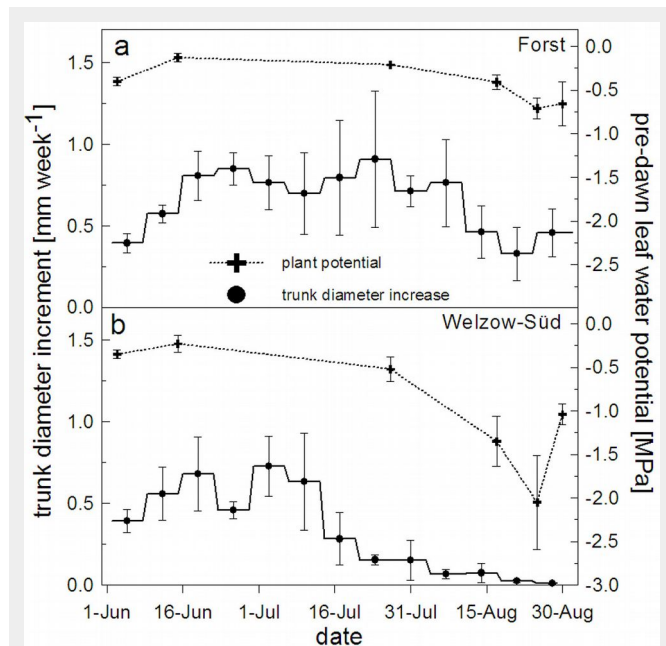


Fig. 6 - Pre-dawn leaf water potential and weekly diameter increase of trees in Forst (a) and Welzow-Süd (b) measured during the vegetation period (from June 1st to August 30th, 2012).

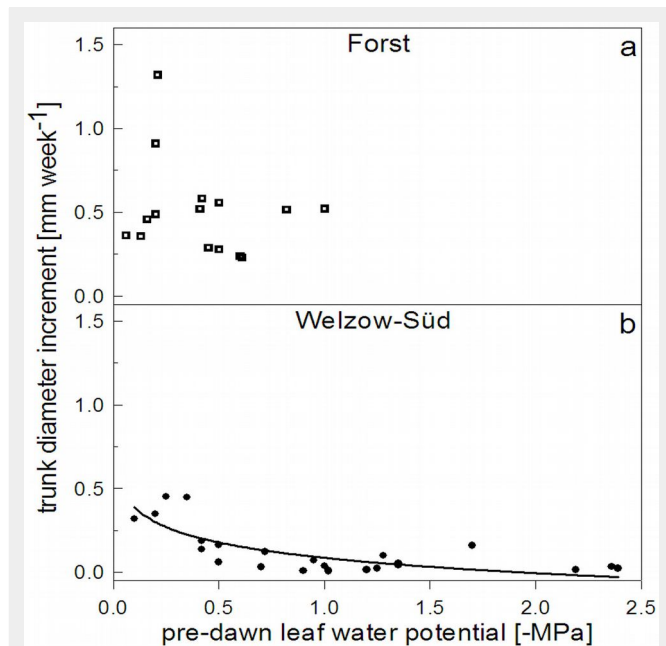


Fig. 7 - Weekly trunk diameter increase in relation to the pre-dawn leaf water potential of trees at the F4 subplot (Forst) (a) and W4 subplot (Welzow-Süd) (b) measured during the vegetation period (from June 1st to August 30th, 2012).

heterogeneity recorded at Welzow-Süd is well described by the spatial and temporal variation of the Ψ_{pd} evaluated at this site (Fig. 8).

Discussion

Besides the difference in precipitation, which led to an increased water input in Forst, the different soil characteristics such as soil texture and TOC influenced the satu-

rated hydraulic conductivity and the water holding capacity of the soil at both sites, enhancing its water storage capacity. The growth rate variation recorded at the two sites became relevant from July onwards, when the Ψ_{pd} reduction occurred in Welzow-Süd. Here the growth decrement was probably caused by the combined effects of the reduced precipitation and soil water storage, higher VPD values and low nu-

trient availability. Consequently, stomatal closure and the reduction of the leaf area under drought conditions limited the transpiration (Bréda et al. 2006, Mantovani et al. 2014a, 2014b), and enabled the trees to tolerate long-term drought conditions due to its ecophysiological and morphological adaptations (Xu et al. 2009, Veste & Kriebitzsch 2013). However, the reduction of the CO₂ uptake had drastic effects on the plant growth and consequently on the biomass production, as reported by Mantovani et al. (2014a, 2014b), where the primary production was directly proportional to the water used, independently from the drought stress frequency and duration. Instead, water constraint caused changes in the soil-root and leaf-atmosphere interfaces. Consequently, CO₂ uptake and transpiration decrease limited the tree growth, and in extreme cases the tree survival was at stake. The heterogeneity recorded in Welzow-Süd in terms of plant growth was related to the Ψ_{pd} and mirrored the heterogeneous soil property which caused the water availability variation in space and time, described by the dynamic maps in Fig. 8. During the night the water potential of a non-transpiring plant equilibrated with the wettest water potential of the soil around the root system (Ritchie & Hinckley 1975). As recorded by Veste et al. (2008), the spatial heterogeneity of soil water availability is linked with the pre-dawn water potential of trees under water limitation. In addition to water constraint, the indirect effect of the nutrient uptake reduction did occur, caused by the poor edaphic conditions at Welzow-Süd. However, since the diametric increment was higher in Forst than in Welzow-Süd at similar water poten-

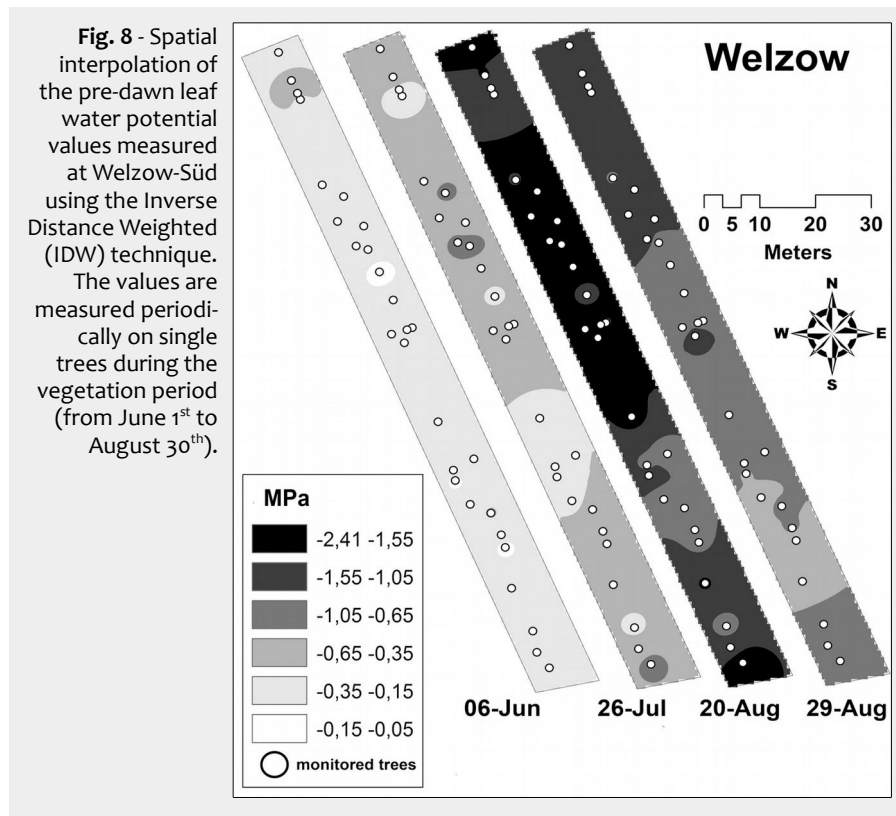


Fig. 8 - Spatial interpolation of the pre-dawn leaf water potential values measured at Welzow-Süd using the Inverse Distance Weighted (IDW) technique. The values are measured periodically on single trees during the vegetation period (from June 1st to August 30th).

tial values, other factors such as different tree ages and better soil conditions and nutrition may have contributed to increase the primary production in Forst. *Robinia pseudoacacia* is less dependent on the uptake of nutrients in comparison to other broad leaf trees because of its capability to fix biological nitrogen even under extreme edaphic conditions, as they are found in post-mining sites (Veste et al. 2013) or under drought conditions (Mantovani et al. 2013, Wurzbürger & Miniati 2014). Nevertheless, Kanzler et al. (2015) has observed for *Robinia* an increase of the growth rates after phosphate fertilization in Welzow-Süd. The fact that limited phosphate, in combination with low Molybdenum availability in the soil, has an impact on the biological nitrogen fixation was confirmed by Wurzbürger et al. (2012). Those differences in soil nutrients might partly explain the differences in the absolute growth rate between sites, while temporal and spatial differences within sites depend on the tree access to soil water.

Conclusions

The black locust growth performance is severely affected by the temporal and spatial variation of the leaf water potential, which varies according to the soil typology and water availability. Further nutrient deficiency may inhibit root expansion, causing the reduction of water uptake which indirectly influences the leaf water potential as well. If the water and nutrient uptake is limited due to critical edaphic conditions, which were site-specific in our experiment, the tree growth stops during a longer drought period. However, due to its morphological and ecophysiological adaptations *R. pseudoacacia* is able to cope with the extreme soil conditions in post-mining sites. Therefore, black locust could be an alternative species to be grown in post-mining areas, where the competition with food crops is reduced and soil protection and rehabilitation is the main goal. The spatial and temporal variation of the growth performance in such post-industrial areas can be simply quantified by using the pre-dawn leaf water potential method, evaluating at the same time the degree of soil heterogeneity in the area.

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