SOIL WATER, TEMPERATURE REGIME AND GROWTH OF YOUNG OAK STANDS GROWN IN LYSIMETERS SUBJECTED TO DROUGHT STRESS AND AIR WARMING

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Abstract

In a 3-year lysimeter experiment we investigated how young trees of *Quercus robur*, *Q. petraea* and *Q. pubescens*, growing either on acidic loamy sand or calcareous sandy loam, responded to an elevation in air temperature by 1-2°C and drought periods lasting several weeks. As intended, the water potentials were clearly lower in drought-treated soil than in the control treatment. Decreased evapotranspiration from the drought-stressed stands led to significantly higher air temperatures due to reduced transpirational chilling. The air-warming treatment had only little effect on soil water availability and evapotranspiration. The effects on water consumption by the trees were paralleled by the effects on tree growth. Drought significantly reduced shoot growth, whereas growth did not respond to air-warming. The trees allocated relatively more biomass into roots and less into shoots than trees not subjected to drought. There was no mortality in any of the treatments, demonstrating that by reducing their growth rates young oaks can resist drought stress quite well. Oaks growing on irrigated acidic soil consumed more water and produced longer shoots than on the calcareous soil, suggesting that growth was limited by an additional factor: preliminary leaf mineral analyses indicate a potential manganese deficiency in these soils.

Keywords: Climate change, soil-plant interactions, soil water regime, evapotranspiration, manganese

1. Introduction

IPCC scenarios predict a global mean annual temperature increase of approximately 2–6 °C during the 21st century, as well as a change in precipitation patterns (IPPC 2007). In central Europe, including Switzerland, the mean temperature has increased approximately by 1.5 °C since 1970: this is about 1.5 times more than in the rest of the northern hemisphere (IPPC 2007). Until 2050 the mean temperature in Switzerland is expected to increase by another 1.8 °C in winter and 2.7 °C in summer. The amount of precipitation in 2050 is predicted to be about 8% higher in winter and 17% lower in summer than at present (Frei et al. 2004).
Moreover, the number of days without any precipitation will increase, while extreme rainfall events will be more common (IPPC 2007). Consequently, dry and hot spells like that experienced in summer 2003 will be quite frequent in central Europe in future (Schär et al. 2004).

How will global warming, higher air temperatures and drought periods, affect trees in central Europe? For example, *Picea abies* and *Fagus sylvatica*, widespread and important trees in forestry, are known to be comparatively vulnerable to high temperatures and soil water deficits (Friedrichs et al. 2009). Therefore, looking ahead, forest management has to think about a shift to other, more heat and drought tolerant tree species. Oaks are known to be tolerant to drought stress as well as heat waves because of their taproots, which allows them to take up water from deep soil layers, xeromorphic leaf structure and large xylem vessels for effective water transport (Abrams 1990, Epron and Dreyer 1993, Kubiske and Abrams 1993, Canadell et al. 1996, Leuschner et al. 2001) and have been reported to grow and to be competitive in regions with low precipitation rates and comparatively high temperatures (Chiatante et al. 2006, Wohlgemuth 2006). Higher air temperatures were found to favor the growth rates of plants by extending vegetation periods, increasing nutrient turnover rates and accelerating metabolism processes (Saxe et al. 2001, Scheffer et al. 2002, Morin et al. 2010). Drought is expected to decrease aboveground growth rates (Ogaya and Penuelas 2007), whereas root growth is often increased relative to shoot growth, in particular in deeper soil layers where water in general remains available for longer periods than at the surface, while shortened shoot growth reduces transpirational water losses (Jacobs et al. 2009). The aim of this study was to investigate how the most widespread oaks in central European temperate forests, *Quercus petraea, Q. pubescens* and *Q. robur*, will react to increasing air temperatures and drought periods and if they can be considered for sylviculture in future.

Using lysimeters in open top chambers (OTC), we exposed mixed young oak stands on two different soil types to elevated air temperatures and artificial drought periods and studied the response of tree growth, soil water regime and microclimate to these treatments.

## 2. Material and Methods

**Study Site & Experimental design**

The study was part of the multidisciplinary experiment “Querco” conducted in the model ecosystem facility of the Swiss Federal Research Institute WSL, Birmensdorf, Switzerland (47° 21’54” N, 8° 27’54” E, 450 m a.s.l.). The facility consists of 16 open top chambers (OTC). The hexagonal OTC’s were 3 m in height and had a useful surface area of 6 m². Each OTC was

![Fig. 1. Mean weekly water content at a depth of 50-75 cm (n=4) and water potential at a depth of 56-68 cm in 2009 (n=8) in acidic (left) and calcareous (right) soil. Bold lines on the x-axis refer to periods when drought treated chambers were irrigated.](image-url)
subdivided into two 1.5 m deep concrete lysimeter compartments which were filled with a 0.5 m drainage gravel package consisting of 3 layers of pure quartz gravel of decreasing grain size from bottom to top. On top of this drainage layer, the lysimeters compartments were filled with either an unlayered calcareous sandy loam (pH 7.3) or a two-layered acidic loamy sand (pH 4.1), in 2005. After one year of soil settlement, 24 two-year old saplings of *Q. petraea*, *Q. pubescens* and *Q. robur* from four different proveniences each were planted in a random distribution in spring 2006 in each of the compartments and were grown with sufficient water supply and at ambient air temperature during one vegetation period (Arend et al. 2011).

From 2007 to 2009 we applied four different treatments with four replicates arrange in a Latin square: air-warming, drought, their combination and a control. The side walls of the OTCs with the air-warming treatment were kept more closed than those of the control treatment. As a result, the green-house effect of the chambers increased the air temperature during daytime by about 1-2 °C during periods of growth. Control and air-warming treated OTCs were watered with 10 mm deionised water, enriched with nutrients, every 2-3 days, whereas there was no irrigation in the drought-treated OTCs for several weeks in a row (-43% to -60% irrigation during the vegetation periods (April to October) compared to the long term mean, Fig. 1). Drought periods were interrupted by intensive irrigation, simulating heavy rainfall. In the non-growing period, the roofs of the OTCs stayed permanently open to expose all treatments to natural precipitation.

**Biomass and Growth Measurements**

Shoot growth of all trees was measured during each vegetation period from 2007 to 2009. In spring 2010, roots were harvested and maximal root length was determined. A 2D picture from each rootstock was taken from the front. Images were edited with ImageJ 1.44h (U.S. National Institutes of Health, USA) and the projected root area in five layers, each 20 cm deep, was determined with IDL 7.1 (ITT Visual Information Solutions, USA).

**Statistical Analysis**

All statistical analyses were carried out with R 2.11.1 (R: A language and environment for statistical computing, R Development Core Team, AT). Treatment and interaction effects were analysed with a three-way full factorial design (irrigation, air-warming and soil) ANOVA model and tested for a level of significance of p < 0.05 (linear mixed-effect models). The split-plot design of this experiment was considered in all statistical analyses, if needed. Measurements were...
transformed by means of Tukey's first aid transformation before analysis to fulfill models assumptions of normal distribution. Significant differences between treatments and soil types were tested with Tukey HSD.

3. Results & Discussion

**Water Regime, Evapotranspiration and Temperature Regime 2009**

As intended, drought treatment significantly lowered the soil water potentials (SWP) and soil water contents (SWC) in both soils in 2009 (Fig.1). After rewetting in July and August 2009, SWP and SWC in drought treated soils slightly increased, but still remained below those of the regularly watered control soils. Surprisingly, increased SWC values were found in the acidic soil in the air-warming treatment, while no air-warming effect was found on SWC in the calcareous soils and neither in the acidic soil in combination with the drought treatment. During periods of high demand for plant water uptake (June & August 2009), SWC and SWP were significantly lower in the acidic than in the calcareous soil in the control and air-warming treatments without additional drought stress, indicating a higher water consumption of oaks growing on acidic soil.

Drought treatment significantly reduced evapotranspiration on both acidic and calcareous soil (Fig. 2). After rewetting, evapotranspiration from drought treated plots increased and no differences between drought and regularly watered OTCs remained, indicating that the oaks recovered, completely. Air-warming had no effect on evapotranspiration, neither on acidic, nor calcareous soil. Under humid conditions, evapotranspiration from acidic soil was significantly higher than from calcareous. In contrast, no differences between the two soil types remained during drought conditions. This finding is in line with the lower SWC and SWP in the acidic soil as well as with the higher above ground biomass of oaks on well watered acidic soil (Fig. 1).

The air-warming treatment significantly increased the mean monthly daytime (8 a.m. to 6 p.m., UTC+1) air temperatures in the OTCs by about 1.2 °C in relation to the control (Fig. 3). Furthermore, also the drought treatment increased air temperatures, due to reduced transpirational chilling (Fig. 2, Fig. 3). Rewetting in July 2009 tended to reduce the monthly temperature difference between controls and drought treated soils. However, this effect was not significant. In combination, air-warming and drought treatment had an additive effect on temperatures.

**Growth parameters 2009**

Drought treatment significantly decreased shoot growth from 2007 to 2009 (Tab. 1). In contrast, there was no significant response to air-warming under both drought and humid soil conditions. Probably the air temperatures in the control treatments were already close to the optimum. There was no mortality in all treatments indicating that oaks can get through drought periods quite well by reducing their growth. This is all the more important considering that our drought treatment (-43% precipitation during the vegetation period 2009) was much more severe than predicted in climate change scenarios (-23% precipitation during summer in 2070 (Frei et al. 2004)).

On regularly watered soils, shoot growth was significantly higher on the acidic than on the calcareous soil. This finding is in line with the fact that oaks growing under natural conditions prefer acidic soil (Landolt and Bäumler 2010). Lower soil manganese availability due to the higher pH of the calcareous soil could explain this inhibition in

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<th>Soil</th>
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<th>Air-Warming</th>
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<th>Air-Warming &amp; Drought</th>
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<tr>
<td><strong>Shoot length (cm)</strong></td>
<td>179.6 ± 8.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>217.4 ± 1.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>107.8 ± 3.8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>111.5 ± 7.5&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>a</td>
<td>135.5 ± 5.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>153.9 ± 3.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>95.9 ± 4.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>102.3 ± 4.2&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>c</td>
<td>91.4 ± 3.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>88.8 ± 1.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>92.1 ± 1.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>91.9 ± 1.3&lt;sup&gt;a&lt;/sup&gt;</td>
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<td><strong>Max. root length (cm)</strong></td>
<td>88.4 ± 2.3&lt;sup&gt;a&lt;/sup&gt;</td>
<td>81.3 ± 2.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>87.9 ± 2.6&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>91.9 ± 1.3&lt;sup&gt;a&lt;/sup&gt;</td>
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Tab. 1. Mean shoot length growth 2007-2009 (cm) and mean maximal root length 2009 (cm), ± 1SE, n=8. Different letters refer to significant differences within a row, * refers to significant differences between acidic (a) and calcareous (c) soils within a treatment.
growth. Indeed, preliminary foliage analyses (2008) for the control treatment show that leaf manganese concentrations were below the deficiency threshold (35 to 100 ppm) given by Bergmann (1993) on the calcareous soil (21±4 ppm) and in the normal range on the acidic soil (1760±307 ppm). Under drought conditions, the difference in aboveground growth between the two soils became insignificant, as water here was the limiting growth factor obviously. The trees growing in regularly watered acidic soil, had higher projected root areas in the upper 40 cm than the trees in the drought treatments. Below 40 cm, however, there was no significant difference between these treatments (Fig. 4). Thus, it appears that well watered trees built up more roots in the top soil layers to absorb the regular water input, whereas drought treated trees allocated relatively more biomass in roots in lower soil layers to access deeper lying soil water during drought periods. In calcareous soil, no treatment effects on root distribution were measured except from the topsoil layer where drought treated oaks built up fewer roots than in the control treatment. Comparing root system development in the topsoil layers, projected root areas were significantly higher in the acidic than in the calcareous soil. At a depth of 20-40 cm no differences between the two soil types were found, while below 40 cm the projected root area was significantly higher in the calcareous than in acidic soil.

In contrast to the aboveground growth, the drought treatments had no significant effect on maximal root length (Tab. 1), indicating that all trees fully exploited the available rooting depth (100 cm). The soil type had an influence on the total root length in the air-warming treatment where the roots in calcareous were longer than in acidic soil.

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5. Literature

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Fig. 4. Projected root area (cm$^2$) in five different soil layers in acidic (left) and calcareous soils (right), ±1SE, n=8. Different letters refer to significant differences between the treatments within a soil layer.


