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Impacts of summer water limitation on the carbon balance of a Scots pine forest in the southern upper Rhine plain

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ABSTRACT

Regional climate models for Central Europe predict more frequent and longer-lasting periods of low precipitation and high air temperature in summer for the second half of the 21st century. Such periods of low water availability will be of major importance for photosynthetic activity, plant growth and the carbon budget of ecosystems. From 2004 to 2007, we investigated the effects of water limitation on a 45-year-old Scots pine forest in the upper Rhine plain. This region with its relatively high air temperature and low precipitation during the vegetation period already now represents the expected future precipitation and temperature conditions for large areas of Central Europe. Using the eddy covariance technique to measure net ecosystem CO_2 exchange, we found that below the permanent wilting point (i.e., 12 vol.%), net carbon uptake was controlled rather by temperature than by photosynthetically active radiation. In 2005, relatively moderate air temperature and comparatively high precipitation amounts in summer lead to optimal growth conditions and to an annual carbon sink of 600 g C m^{-2} $year^{-1}$ for this pine forest. In contrast, dry and hot conditions in July 2006 resulted in soil moisture values below the permanent wilting point, subsequent stomatal closure and a 40% reduction of the net carbon uptake, leading to an annual C sink of only 380 g C m^{-2} $year^{-1}$ for the pine stand. We thus conclude that regional-scale impacts of limited water availability on ecosystem sink capacity are no single events, but already now a re-occurring phenomenon in some regions of Central Europe.

1. Introduction

The global mean air temperature at the earth's surface increased on average by 0.6 °C during the last 100 years and is likely to increase also in future (IPCC, 2007). In addition, regional climate models for Europe also predict more frequent and longer-lasting periods of low precipitation during summer, together with increasing air temperature (Gerstengarbe et al., 2003; Schär et al., 2004). The likelihood of these trends varies between 'likely' (probability of occurrence >66%) and 'virtually certain' (probability of occurrence >99%; IPCC, 2007).

The higher air temperature is predicted not only to increase physiological processes such as photosynthesis (until the temperature optimum of these processes is not exceeded and

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water and other nutrients are not limited), but also the available energy at the earth's surface, thereby resulting in higher rates of potential evapotranspiration. Co-occurring altered precipitation patterns will likely lead to extended periods of water limitation or even drought, especially for vegetation on shallow soils with low soil water storage capacity (Gessler et al., 2004). Gross primary production of mid-European deciduous forests, modelled for the years 1960–2100 following the B2 scenario of the IPCC, is expected to rise until 2020, followed by a slowing down of the positive trend due to increased water stress, which will result in these forests to become a smaller carbon sink (Davi et al., 2006) or even carbon sources from these forests. Such a decrease in Europe could already be observed during the exceptionally hot and dry summer 2003 (Ciais et al., 2005), during which water limitation was a major driver of water and carbon fluxes (Granier et al., 2007).

The present study investigated the interactions between growing conditions (light availability, temperature and water supply) and energy and carbon fluxes of a Scots pine forest in the southern upper Rhine plain (south-western Germany) from 2004 to 2007. Comparisons of measurements (Rost and Mayer, 2006) with model outputs (Gerstengarbe et al., 2003; Schär et al., 2004) show that the southern upper Rhine plain, with its high air temperature and convective summer precipitation, represents today the future precipitation and temperature conditions that are predicted by regional climate models for other regions in Central Europe. The forest site can therefore be considered as a model for forest stands in other regions of Central Europe that are expected to experience highly variable precipitation and temperature conditions and frequent summer water limitations (Sturm et al., 1996; Wellpott et al., 2005; Schindler et al., 2006). We will refer to water limitation as intervals of time (days to weeks) when precipitation totals are below the corresponding climatological precipitation totals and soil moisture continuously decreases as a consequence. The objectives of the present study were to investigate the influence of limited water supply during the summer on the carbon balance of this forest stand, and to relate it to ecophysiological processes.

2. Materials and methods

2.1. *Experimental design*

The long-term forest meteorological experimental site Hartheim (47°56′N, 7°36′E; 201 m a.s.l.; e.g., Jaeger and Kessler, 1996; Schindler et al., 2006), operated by the Meteorological Institute of the University of Freiburg since 1974, is located within a slow-growing (mean annual growth rate approx. 0.3 m year^{-1}), even-aged Scots pine forest (*Pinus sylvestris* L.), planted in 1963. The Hartheim area is a highly uniform flood plain. Climate conditions at the Hartheim site are characterised by relatively high air temperature (annual mean air temperature for the period 1978–2001 10.3 °C) and convective summer precipitation. The mean annual total of the precipitation in the period 1978–2001 is 642 mm (Imbery, 2004). The forest extends over 10 km in the north–south direction and 1.5 km in the east–west direction. The fetch in the prevailing wind directions SSW and N is characterised by a 1:100 tower height to fetch relationship. In 2005, mean stand height (H) was approximately 14 m, mean diameter at breast height (dbh) was 0.19 m, one-sided plant area index of the Pine trees (PAI, measured by means of two LAI-2000, Li-COR Biosciences, Lincoln, NE, USA), was 1.77 m^2 m^{-2} and the stand density was 800 trees ha^{-1}. The soil is a carbonate-rich, two-layer calcaric Regosol. The upper layer consists of sandy loam with a mean depth of 0.4 m (0.15–0.8 m) and the underlying layer is alluvial gravel. Absolute mean water storage capacity of the upper layer is 80 mm, field capacity is 31.4 vol.% and the permanent wilting point is 11.7 vol.% (Hädrich, cited in Sturm et al., 1996). The herbaceous understorey vegetation is dominated by *Brachypodium pinnatum*, *Carex alba*, and *Carex*

Table 1 – Instrumentation at the long-term forest meteorological experimental site Hartheim (Meteorological Institute, University of Freiburg)

Component	Symbol	Type of instrument
Photosynthetically active radiation above the canopy	PAR	Li-190SZ (quantum sensor)/Li-COR Biosciences, Lincoln, NE, USA
Photosynthetically active radiation below the canopy	PAR_{bc}	Li-190SZ (quantum sensor, 2 levels)/Li-COR Biosciences, Lincoln, NE, USA
Short-wave radiative fluxes	K↓, K↑	CM21 (ventilated pyranometer)/Kipp&Zonen Inc., Delft, Netherlands
Long-wave radiative fluxes	L↓, L↑	CG4 (ventilated pyrgeometer)/Kipp&Zonen Inc., Delft, Netherlands
Soil heat flux	G	HFP01SC, HFP01 (heat flux plate)/Hukseflux, Delft, Netherlands
Soil temperature	T_s	PT100 (6 levels)/Heraeus Sensor Technology, Kleinostheim, Germany
Soil moisture	Θ	CS615 (TDR)/Campbell Scientific Inc., Logan, Utah, USA
Air temperature, wet bulb temperature	T_a, T_w	Aspirated psychrometers PT100 (8 levels)/Heraeus Sensor Technology, Kleinostheim, Germany
Horizontal wind velocity	U	WAA151 (cup anemometer, 8 levels)/Vaisala, Helsinki, Finland
Wind direction	dir	W200P (wind vane)/Vector Instruments, Denbighshire, UK
Wind components	u, v, w	CSAT3 (sonic anemometer)/Campbell Scientific Inc., Logan, Utah, USA
Concentrations of H_2O and CO_2	c_{H_2O}, c_{CO_2}	Li7500 (open-path IRGA)/Li-COR Biosciences, Lincoln, NE, USA
Precipitation	P	Ombrometer, pluviometer/Ott Hydrometrie, Kempten, Germany
Precipitation (throughfall)	P_t	Rain gutter with tipping bucket gauge ARG100/Campbell Scientific Inc., Logan, Utah, USA
Data acquisition		CR5000, CR23x, CR21x (datalogger)/Campbell Scientific Inc., Logan, Utah, USA