Agricultural and Forest Meteorology 151 (2011) 1023–1034

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Review

Relationships between canopy transpiration, atmospheric conditions and soil water availability—Analyses of long-term sap-flow measurements in an old Norway spruce forest at the Ore Mountains/Germany

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ARTICLE INFO

Article history:
Received 2 January 2011
Received in revised form 27 March 2011
Accepted 11 April 2011

Keywords:
Picea abies
Inter-annual variability
Extreme events
Thinning
Plant available water
Canopy precipitation

ABSTRACT

At the study site Tharandt Anchor Station in Saxony/Germany sap flow measurements are conducted in an old Norway spruce (*Picea abies* [L.] KARST.) stand. During the study period from 2001 to 2007 several events like thinning, long and short drought periods and a winter storm significantly affected the amount of canopy water use. We show that intra-annual variation of Ec is strongly related to VPD and PPFD. While there is a non-linear relationship between daily Ec and VPD, daily Ec is limited by daily integrated PPFD indicating stomatal control of Ec through photosynthesis. On a monthly or seasonal basis, reduction of Ec is not only related to high VPD and non-saturating PPFD, but also to higher frequencies of precipitation. In comparison to this, nearly 55% of canopy precipitation and 20% of available energy were used for transpiration during the growing season. Intensive seasonal soil water measurements at the site revealed that on average about 74% of soil water removal within the rooting zone can be related to tree water uptake. A good correlation was found between annual Ec and Ec_{max}, usually occurring in June or July. Further, the monthly sums of June plus July were good predictors of annual Ec. Within the study period, the extreme drought in 2003 revealed a clear threshold of soil water content by 9.5 vol% and had the most pronounced effect on annual Ec followed by a stand thinning. The winter storm "Kyrill" in January 2007 had caused loss of green needles and twigs. It is assumed that the observed reduction in Ec during spring was related to the reduced leaf biomass and potentially to root damage of bended trees. Excluding the effect of extreme drought and forest management, a mean inter-annual variation in Ec of ±15% and in Ec/VPD of ±8% remained. It is concluded that lag-effects of drought and the winter storm add lacking explanation to the inter-annual variability of canopy transpiration besides the typical variation of atmospheric conditions.

Contents

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doi:10.1016/j.agrformet.2011.04.007

1. Introduction

In the last 200 years, Norway spruce (*Picea abies* [L.] KARST.), a comparably fast growing tree species was favoured for timber production in Central Europe leading to extended monocultures. Today, its natural distribution in the boreal zone of Europe and Asia is covering an area of 6–7 Mio hectare (Leitgeb and Gärtner, 2005). In Central Europe repeated cultivation of spruce at the same sites increased soil acidification and has led to shallow-rooted trees being more susceptible to drought and, as a consequence, to bark-beetle attack. Further threats to the vitality of spruce were related to acid rain, but meanwhile slow recovering from atmospheric input is observed (Matzner et al., 2004). Today spruce monocultures become more and more instable by increasing summer temperatures and higher frequencies of soil drought. Hence, forest management has changed towards semi-natural mixed forests including deciduous tree species like European beech (*Fagus sylvatica* [L.]). Nevertheless, in mountainous areas Norway spruce will remain an important forest tree. Future site conditions may not only include increasing temperatures and higher evaporative demand but also a higher frequency of extreme events. Stand water relations are crucial for valuing site conditions, and long-term observations are necessary for a better understanding of inter- and intra-annual variability including responses to extremes or management effects. In forest stands, transpiration of trees is a dominant component of stand water balance. An approved method to study water relations from tree to stand level are sap flow measurements of trees (Čermàk and Kučera, 1987; Čermàk et al., 2004; Cienciala et al., 1992). However, in the literature of the past typically only one year of measurements is described and it remains difficult to value the range of environmental conditions at one site as well as to compare results from different sites (Table 1). Annual canopy transpiration rates determined for old-growth stands at different sites is in the same range as canopy transpiration (83–214 mm $year^{-1}$) observed in different years of this study at the Tharandt site.

A summary of older transpiration values from different forest stands is given by Molcanov (1957). For spruce, Molcanov citied daily water consumption rates of 0.6–1.1 mm d^{-1} and yearly sums between 178 and 254 mm. Meanwhile, more overviews have been presented, but they are usually based on combinations of measured and modelled data from pure or mixed stands (Patzner, 2004; Peck and Meyer, 1996). Measurements of sub-boreal mixed forests dominated by spruce are published by Cienciala et al. (1997, 1999), Lagergren et al. (2008) and Lundblad and Lindroth (2002). A systematization of transpiration rates related to stand structure was attempted by Peck and Meyer (1996). However, because of the short-term and non-consistent data sets, relationships between transpiration and stand characteristics were found to be weak. Applying the same methodological approach of sap flow measurements, significant relationships between canopy transpiration, stand age, and stand density were found in a spruce catchment (Alsheimer et al., 1998; Köstner et al., 2001). The temporal and spatial scales of transpiration studies are usually extended by modelling (Köstner et al., 1998; Lauterbach, 2000; Schwärzel et al., 2007, 2009a). For example, Hammel and Kennel (2001) simulated the water balance of several forest sites in Bavaria (Germany) with the hydrologic model BROOK90. But simulated transpiration rates mostly resulted in higher rates than measured by sap flow. This indicates that more appropriate parameterisations of forest stands are required to represent variation in site conditions and structural parameters like stand age, stand height, tree density, forest composition and the long-term range of flux rates (Cienciala et al., 1999; Köstner et al., 2001; Moore et al., 2004).

In the presented study canopy transpiration of an old-growth spruce forest was determined by sap flow measurements over seven successive years. During this period several meteorological events like extreme rainfall, soil drought and winter storm as well as silvicultural interventions like stand thinning took place. The aim of this study is to value the impact of these events on annual canopy transpiration in relation to the typical variation of climatic conditions. For this, relationships between inter-annual or intra-annual variability of flux rates and environmental conditions were examined.

2. Materials and methods

2.1. Site description

The experimental site Anchor Station Tharandt (50°57′49″N, 13°34′01″E, 385 m a.s.l.) is situated within the Tharandt Forest, a forested area of 60 km^2, 20 km SW of the city of Dresden. Since 1996 fluxes of carbon dioxide and water vapour are continuously measured by the eddy-covariance technique within the projects of CarboEurope and FLUXNET (Grünwald and Bernhofer, 2007). Sap flow measurements are recorded since 2001 at the tower site. The climatic conditions at the site can be described as sub-oceanic/sub-continental with an annual mean temperature of 7.6 °C and annual mean precipitation of 820 mm.

The soil is characterized by a frost pattern structure with loamy-skeletal podsol-brown earths (WRB: Dystric Cambisol, skeletic) and loamy podsol-brown earths (WRB: Dystric Cambisol) on rhyolite. These soils have developed from periglacial sediment consisting of debris from rhyolite and loess. Soil mapping has shown that the subsoil horizons are often compacted and characterized by mottles and related redoximorphic features. Depending on the micro relief there is a high variability of grain size, soil thickness and quality of the humus layer. This affects site conditions of individual trees growing in troughs and on humps (Nebe and Fiedler, 1985). Field capacity and wilting point in the upper 50 cm of the soil were determined to 169.5 mm and 80.5 mm, respectively. So the plant available water amounts 89 mm. More information on the soils and site conditions is given in Schwärzel et al. (2009b).

The vegetation around the flux tower (500 m radius) is dominated by Norway spruce (72%), but also Scots pine (*Pinus sylvestris* [L.], 15%), European larch (*Larix decidua* [Mill.], 10%), silver birch (*Betula pendula* [Roth], 1%) and 2% of others are found. In canopy gaps, the forest floor is covered mainly by wavy hair-grass (*Deschampsia flexuosa* [L.] Trin.).

Sap flow measurements were conducted in plots S and SE of the tower in up to 80 m distance. Because of intensive management all trees represent the same canopy layer with only 1% of suppressed trees. However, small-scale scale variability of soil conditions (micro relief) could have affected site conditions of individual trees. Also three larch trees were periodically (2004–2007) measured but not included in this evaluation. At the beginning of sap flow measurement in 2001, stand age was 110 years and mean tree height reached 28 m.