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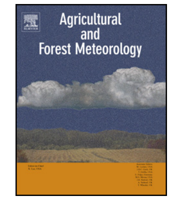

Transpiration and water use strategies of a young and a full-grown short rotation coppice differing in canopy cover and leaf area

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ABSTRACT

In order to evaluate the influence of canopy cover and leaf area on the water use of short rotation coppices (SRC), we measured evapotranspiration and transpiration of a young and a full-grown mature poplar SRC throughout one growing season, using the Bowen-ratio energy balance method and sap flux technique, respectively. The young SRC at Fuhrberg had a sparse though developing canopy reaching a maximum leaf area index (LAI) of 3.8 $m^2\,m^{-2}$ in August, while the mature SRC at Großfahner earlier reached maximum LAI at 7.4 $m^2\,m^{-2}$. Despite contrasting canopy densities, growing season total evapotranspiration (Fuhrberg: 380 mm, Großfahner: 445 mm) and transpiration ratios did not differ substantially, because understorey transpiration and soil evaporation probably compensated low tree transpiration in the first half of the growing season at LAI < 3 $m^2\,m^{-2}$. Mid-season mean daily transpiration on rainless days was 2.34 ± 0.13 mm d^{-1} at Fuhrberg and 3.16 ± 0.81 at Großfahner. The values for the full-grown SRC at Großfahner were in the middle range of reported values for poplar SRCs of comparable LAI and canopy density, and came from efficient stomatal regulation of transpiration, in which poplar clones might differ. Bulk canopy conductance (g_c), calculated by inverting the Penman–Monteith equation and related to vapor pressure deficit (D), revealed stomatal control of transpiration at the mature plantation, and according to a simple hydraulic model, was sufficient to maintain a minimum leaf water potential at high atmospheric demand. This indicated isohydric behavior and marks a conservative water use strategy, which avoids water stress by limiting transpiration rates at high D and might be typical for the investigated poplar hybrid (J-105). The young plantation exhibited a similar water use strategy, when LAI was above 3 $m^2\,m^{-2}$. Before canopy closure, the ratio of stomatal sensitivity (m) and reference conductance (g_{cref}, i.e. g_c @ $D = 1$ kPa), which are parameters of a logarithmical response curve of g_c to D, was significantly lower than the theoretical ratio for isohydric responses. This indicates poor stomatal control of water loss and reflected the contribution of understorey-transpiration and soil evaporation to total stand evapotranspiration, which might increase severely at high evaporative demand in sparse poplar stands.

1. Introduction

Short rotation coppices (SRC) with fast-growing tree species like poplar (*Populus ssp.*) and willow (*Salix ssp.*), cultivated for woody biomass production, provide a sustainable way to replace fossil fuels and mitigate greenhouse gas (GHG) emissions. Experts therefore recommend SRCs to become part of an overall strategy to achieve the minimum target of GHG emission reduction as required by the EU Renewable Energy Directive (Djomo et al., 2011). Anyhow, if area requirements for woody biomass production increase significantly, environmental impacts of large-scale cultivations have to be taken into consideration.

Extensive research on SRC water use in Sweden, England and other countries across climatic gradients revealed substantially higher evapotranspiration of SRC than conventional agricultural crops, which they might replace. Daily transpiration rates can be as high as 7–10 mm d^{-1} (Allen et al., 1999; Hall et al., 1998; Persson and Lindroth, 1994), thereby exceed crop reference evaporation and water use of deciduous forests (Roberts, 1983; Stephens et al., 2001). In some cases, excessive transpiration rates are facilitated by high stomatal conductance that is maintained even during periods of high vapor pressure deficits, imposing little restriction to

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evaporative demand (Hall et al., 1998). Where pedo-climatic conditions are favorable, these transpiration rates can be sustained over long rainless periods with the help of a deep rooting system, that enables SRCs to tap large soil volumes and available groundwater resources (Zhang et al., 1999). Rainfall interception of SRCs is also increased compared to conventional agricultural crops (Dimitriou et al., 2009), therefore negative impacts on aquifer recharge and stream flow have to be expected where short rotation forests replace conventional arable crops in a large scale (Petzold et al., 2011).

However, transpiration rates comparable to or lower than crop reference evaporation are also documented (Fischer et al., 2013; Linderson et al., 2007; Meiresonne et al., 1999; Zhang et al., 1999) and the variability in reported SRC water use rates is high. The extent of negative hydrological effects from the high water use highly depends on individual climate conditions and soil water availability (Dimitriou et al., 2009) that determine evaporative demand and water supply. Water availability often is also the main growth limiting factor for poplar and willow plantations (Jug et al., 1999; Linderson et al., 2007; Lindroth and Båth, 1999). For an economically beneficial and ecologically sustainable production of woody biomass, it is therefore crucial to carefully select adequate production sites. Moreover, if area requirements increase, additional factors have to be identified to increase the water-efficiency of short rotation coppices by management (King et al., 2013).

Aside from careful site selection, management practices seem to influence SRC water use and might hold potential to increase water-efficiency of short rotation forestry. Management schemes with longer rotation periods that allow for the development of dense canopies with high leaf area are generally suspected to use more water than plantations with shorter rotation periods, where trees are coppiced before developing a dense canopy (Busch, 2009; Persson and Lindroth, 1994; Petzold et al., 2011). However, most field studies on SRC water use were conducted in full-grown mature plantations and to our knowledge there is currently a lack of reports addressing the water use of young SRCs during an early phase of stand development, e.g. at low leaf area before canopy closure.

Another factor for SRC water use that is amenable to management seems to be the choice of plant material. Some woody species cultivated in short rotation display a wide range of physiological mechanisms to regulate transpiration in response to environmental variables. Poplars (*Populus sp.*) are generally considered to be drought-avoiding, isohydric tree species (Tardieu and Simonneau, 1998) that efficiently control transpiration by stomatal regulation in response to atmospherical and soil drought (Tardieu and Simonneau, 1998). Notwithstanding, this rather conservative, water-saving strategy may not apply to all poplar hybrids. More drought-tolerant, anisohydric water use strategies are also reported from greenhouse experiments (Ceulemans et al., 1988; Larchevêque et al., 2011), and an intraspecific variability of the water use strategy and drought-resistance of poplars is recognized (Almeida-Rodriguez et al., 2010). Anisohydric behavior is characterized by loose stomatal control of transpiration and dropping leaf water potentials under moderate drought. On the one hand, this anisohydric strategy allows for high photosynthetic activity and thus biomass production under atmospheric and soil drought, but also results in high water use and increases the risk of fatal xylem cavitations under severe drought. However, the variability in poplar water use strategy was found on potted plants and might be far from how things actually work at the field scale, and water use strategies have yet not been addressed at the canopy level in European poplar hybrids.

Within this context, we analyzed water use patterns and water use strategy of an uncoppiced young (third growing season) poplar plantation at the onset of canopy closure, and a high-density mature (sixth growing season) plantation with a dense canopy and high leaf area. With the overall aim to aid in developing adaptive, sustainable management strategies for woody biomass production systems, considering the trade-off between production and water consumption of SRCs, the first objective of this paper was to evaluate the influence of canopy cover and leaf area on SRC water use. These traits can vary with management and might thus provide means to manipulate SRC water use. The second objective was to characterize water use strategies of some widely used hybrid poplars (e.g. “J-105”, *P. nigra* × *P. maximowiczii*). The water use strategy can vary among poplar hybrids and has implications on productivity and water use of individual poplar hybrids growing under individual pedo-climatic conditions. Information on individual water use behavior of poplar hybrids would thus help to select adequate plant material for specific sites, under consideration of water management aspects.

Table 1
Stand and site characteristics of the study plots.

	Fuhrberg	Großfahner
Location	52°35′N, 9°49′E	51°30′N, 10°49′E
Elevation (m)	37	189
Mean annual temperature and rainfall (°C, mm)	8.9, 677	9.4, 549
Size (ha)	3.8	0.6
Cultivated poplar clones	“Max 1”, “Androscoggin”, “AF2”	“Japan J-105”
Distance between plants/(double) rows (m)	0.65/(0.8) 2	0.5/0.75
Actual plant density ($N\,ha^{-1}$)	12750	9454
Soil texture	Sand/loamy sand	Silt loam
PAW[a] (mm)	160	205
Groundwater level	3.8–4.5	1.8–2.7
Shoot age/stool age (years)	2/2	5/5
Stand height (m)	2.5	9.5
Maximum leaf area index ($m^2\,m^{-2}$)	3.8	7.4

[a] PAW: plant available soil water capacity (soil water storage between pF 1.8 and pF 4.2 in 0–100 cm soil depth).

To address both objectives, we used the Bowen-ratio energy balance method and sap flux techniques (Granier-type thermal dissipation probes; TDP) to estimate canopy transpiration (E_t), from which we calculated canopy conductance (g_c). To compare the water use potential of the plantations, we used the empirical description of the stomata closure reaction (i.e. the stomatal sensitivity) to increasing vapor pressure deficit (D) introduced by Oren et al. (1999). This description is based on a reference conductance at low D (g_{cref}, i.e. g_c @ 1 kPa), that facilitates comparisons of water use among plant stands and seasons. Additionally, it allows inferences on the water use strategy (isohydric or anisohydric) of the investigated plant stands, via the link to a simple hydraulic model.

2. Material and methods

2.1. Study sites

In our study, two poplar SRCs with different plant age, contrasting stand structure and leaf area were investigated. Some site and stand characteristics are listed in Table 1. Our young poplar plantation (hereafter called “Fuhrberg”) is located about 40 km northeast of Hanover in the lowland drinking water catchment “Fuhrberger Feld” (elevation: 37 m asl.). At Fuhrberg, we measured evapotranspiration during the growing season 2011 using the Bowen-ratio energy balance (BREB) method. The plantation was established 2009 from cuttings in a double row planting scheme