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Modeling stand water use response to soil water availability and groundwater level for a mature *Populus tomentosa* plantation located on the North China Plain

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ABSTRACT

To help achieve precise irrigation in *Populus tomentosa* plantations, the stand water use characteristics of a mature *P. tomentosa* plantation under well-watered drip irrigated conditions were investigated over two growing seasons (April–October) in 2010 and 2011. Crop coefficient models for predicting stand water use were constructed and tested. The quantitative responses of stand water use to groundwater level (GWL) under different irrigation conditions and soil water availability (r_θ) in different soil layers, which have not been thoroughly examined in poplar plantations, were also investigated. The stand evapotranspiration (ET_a) was dominated by soil evaporation (E_s) before late April and after the middle of September, but transpiration (T_r) became the dominating component of ET_a between late April and mid-September accounting for 77%. The mean daily T_r, E_s and ET_a for non-rainfall periods were 2.67, 1.04 and 3.71 mm d^{-1}, respectively. The relative mean absolute error of the crop coefficient models used to predict ET_a (13%) and T_r (16%) in the non-irrigated treatment (CK) during periods with no water stress were small, suggesting these models can be used to accurately predict stand water use of *P. tomentosa* under well-watered conditions. Fractional transpiration rate of *P. tomentosa* was significantly ($p < 0.0001$) correlated to r_θ of different soil layers within 0–70 cm depth, but the same relationship was not detected for r_θ below 70 cm depth. The proportion of variation in T_r explained by r_θ was highest ($R^2 = 0.630$) in the 0–30 cm layer. Tree transpiration was unconstrained when the r_θ of the 0–30 cm layer was above 0.6, but if r_θ in the surface 30 cm soil was not maintained above 0.6, there was a reduction of water uptake and transpiration in *P. tomentosa.* Significant ($p < 0.0001$) correlation was found between fractional transpiration rate and GWL in the CK treatment, and as the GWL decreased below 300 cm depth, T_r of *P. tomentosa* declined gradually. Whereas, similar phenomenon was not observed in the irrigation treatment. This study therefore indicates (1) that the shallow soil layers should be the key soil zone for irrigation water management in plantations of *P. tomentosa* and similar tree species located on sites similar to those in our study, and (2) as the GWL declines below 300 cm depth, irrigation should be applied in *P. tomentosa* plantations to maintain water uptake and tree growth.

1. Introduction

Soil water is an important growth limiting factor for poplar plantations (Hogg et al., 2013; Xi et al., 2016), so irrigation has often been implemented to greatly increase the yield of poplar production plantations (Shock et al., 2002; Voltas et al., 2006; Stanturf and van Oosten, 2014; Xi et al., 2014). However, water resources are becoming increasingly scarce in China (Piao et al., 2010; Haddeland et al., 2013). Thus, in order to conserve water resources and maximize irrigation water use efficiency when using irrigation to increase the productivity of poplar plantations, precise irrigation strategies should be adopted, i.e., to provide irrigation water in appropriate amounts at appropriate times.

To achieve precise irrigation in plantations, it is necessary to understand stand water use (evapotranspiration, transpiration, and soil evaporation) characteristics and be able to precisely predict the stand water use, as these can help to determine when to irrigate and calculate the irrigation amount. At present, a lot of studies have

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investigated stand water use characteristics of poplar plantations, but most of them only focused on single component of stand water use, such as transpiration (Petzold et al., 2011; Shen et al., 2015) or evapotranspiration (Pistocchi et al., 2009; Jassal et al., 2013; Fischer et al., 2013; Zhou et al., 2014). Although Schmidt-Walter et al. (2014) simultaneously estimated transpiration and evapotranspiration (by adding transpiration and canopy evaporation, with soil evaporation neglected) in a hybrid poplar plantation, comprehensive quantification of the different components of stand water use in poplar plantations overall remains a challenge and has not been achieved yet. This information however is the key to designing management strategies for improving water use efficiency of irrigated plants (Yunusa et al., 2004; Gong et al., 2007).

The FAO crop coefficient method is widely used for predicting crop water use, and the crop coefficients of a number of crops have been determined (Allen et al., 1998). However, for poplar trees, relevant information is relatively scarce (Gochis and Cuenca, 2000; Gazal et al., 2006; Guidi et al., 2008; Schmidt-Walter et al., 2014), and in China only Hou et al. (2010) have derived the crop coefficients for *Populus euphratica*. In addition, the seasonal variation of the crop coefficient of poplar trees has been investigated in a number of studies (Gazal et al., 2006; Hou et al., 2010; Schmidt-Walter et al., 2014), but, to our knowledge, no attempt has been made to develop its relationships with plant characteristics. Therefore, to realize precise irrigation in poplar plantations in China, it is important to obtain information on crop coefficients of widely planted poplar species, and subsequently develop a model that can be applied to predict the crop coefficients of poplar using some easily measured plant characteristics.

Understanding the quantitative response of stand water use to soil water availability is also very essential for precise irrigation, as this information could be used to determine the soil water availability threshold, below which tree water stress will occur or growth will be inhibited (Xu et al., 2011; Xi et al., 2016). At present, the effects of soil water availability on water use of poplar trees have been well investigated (Braatne et al., 1992; Petzold et al., 2011; Xi et al., 2014; Zhou et al., 2014), but the quantitative response of poplar water use to soil water availability at different layers throughout the root zone has not been thoroughly examined in stand level.

In drought or seasonal drought areas with a shallow water table, the variation of groundwater level should be considered in determining irrigation scheduling in poplar plantations (Xi et al., 2013), since poplar trees grown under this environment often rely on absorbing groundwater to avoid water stress (Gazal et al., 2006; Folch and Ferrer, 2015; Shen et al., 2014, 2015; Xiao and Huang, 2016). Thus, understanding the quantitative response of stand water use to groundwater level is also extremely critical for realizing precise irrigation management in poplar plantations located in areas with a shallow water table (Folch and Ferrer, 2015). However, to our knowledge, relevant research is also limited (but see Gazal et al., 2006; Shen et al., 2014, 2015), although the qualitative influence of groundwater level on the water use of poplar plantations has been well-researched (Zhang et al., 1999; Folch and Ferrer, 2015; Xiao and Huang, 2016). In addition, if long-term irrigation is applied to poplar plantations growing under a shallow water table conditions, whether their stand water use responses to groundwater level will change remains unknown.

Populus tomentosa, species indigenous to China, plays a key role in poplar plantations in the North China Plain (Zhang et al., 2012). However, at present, the average productivity (12 m^3 ha^{-1} yr^{-1}) of *P. tomentosa* plantations is only about a quarter of their potential productivity (>40 m^3 ha^{-1} yr^{-1}) (Zhu et al., 1995; Xi et al., 2014). Consequently, in order to increase the productivity and irrigation water use efficiency of *P. tomentosa* plantations using precise and high-efficiency irrigation strategies, this study was conducted with three objectives: (1) to reveal the potential stand water use characteristics of *P. tomentosa* under well-watered (irrigation) conditions, (2) to establish crop coefficient models for predicting the water use of *P. tomentosa* plantations, and (3) to examine the quantitative responses of stand water use to soil water availability in different soil layers under non-irrigated conditions, as well as to the groundwater level under both irrigation and non-irrigation conditions in *P. tomentosa* plantations.

2. Materials and methods

2.1. Experimental site description and experimental design

The experimental site was located in Gaotang County, Shandong Province, China (36°58′N, 116°14′E, and elevation 27 m). This area has a warm temperate monsoon climate, with mean annual rainfall, temperature and free surface evaporation of 545 mm, 13.2 °C and 1880 mm, respectively. The silty soil was developed from quaternary alluvium, and has a pH of 8.1, 41.5 mg kg^{-1} available N, 7.11 mg kg^{-1} available P, 76.8 mg kg^{-1} available K and 0.94% organic matter in the 0–40 cm soil layer.

The experiment was carried out from 2010 to 2011 in a *P. tomentosa* plantation, which was established in late March 2005 using clone B301. The trees were planted using an alternate wide- (6 m) and narrow- (2 m) row spacing scheme with intra-row spacing of 1 m (a schematic diagram of this planting scheme is shown in Xi et al., 2016), and the stand density was 2500 trees ha^{-1}. A subsurface drip irrigation (SDI) system was installed in the plantation in April 2008, and irrigation commenced from April 2010 onwards. Three drip laterals were installed at 20 cm depth for each tree belt (two rows of trees) with one placed in the middle of the narrow row zone and two placed in the wide row zone and 60 cm distant from the tree line. The lateral had 2 L h^{-1} drippers at a spacing of 50 cm from each other.

This study was a sub-experiment of our SDI experiment conducted in 2010 and 2011, details of which can be referred to Xi et al. (2014). The SDI experiment included three soil water potential (SWP) treatments, under which the trees were irrigated when the average SWP at 20 cm depth and 10 cm distant from a drip emitter reached −25 (T25), −50 and −75 kPa, respectively. A control non-irrigation treatment (CK) was also included. In this study, only the T25 and CK treatments were used. During the experimental period, the irrigation of T25 was implemented from early April to early August, with irrigation amounts of 336 and 323 mm in 2010 and 2011 respectively. This irrigation scheduling combined with the onset of the rainy season and the high groundwater level after July resulted in good surface soil water status (average SWP at 20 cm depth were −14 and −20 kPa in 2010 and 2011, respectively) in the T25 treatment throughout the growing season (Fig. 1), indicating that trees in this treatment were under well-watered conditions. Thus, the T25 treatment was used to investigate the stand water use characteristics of *P. tomentosa*, and to establish and parameterize crop coefficient models for predicting stand water use under well-watered conditions. The stand water use data for the CK treatment during a period of no water stress were used to validate the established crop coefficient models. Then, water use data of the CK treatment under both no water stress and water stress periods were used to examine the quantitative responses of stand water use to soil water availability, and data from both the T25 and CK treatments were used to investigate the stand water use response to groundwater level.