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# Modeling growth response to soil water availability simulated by HYDRUS for a mature triploid *Populus tomentosa* plantation located on the North China Plain

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ABSTRACT

To establish the methodological basis for developing optimal irrigation strategies for increasing the productivity of triploid *Populus tomentosa* plantations using modelling methods, the accuracy of HYDRUS models for simulating one-dimensional (HYDRUS-1D) soil water dynamics under rainfed natural conditions (NC), and two-dimensional soil water dynamics (HYDRUS (2D/3D)) under subsurface drip irrigated (SDI) conditions was evaluated using field data. The relationship between tree growth and soil water availability ($r_\theta$) at different depths, which has not been thoroughly investigated in poplar plantations, was also examined. In general, the average soil water content ($\theta$) in different soil layers predicted by both HYDRUS models and the $\theta$ within the two-dimensional domain around drippers predicted by HYDRUS (2D/3D) agreed well with the observed values. Under both treatments, the $r_\theta$ increased with depth and was most variable in the surface 30 cm soil. The amount of variation in basal area at breast height (ABH) growth explained by $r_\theta$ in various soil layers ranged widely, suggesting that soil water at different soil depths made different contributions to the variation in growth. The proportion of variation in ABH growth explained by average $r_\theta$ was highest ($R^2 = 0.709$) in the 0–30 cm layer, and decreased with increasing integrated depth of the root-zone. Tree growth was unconstrained when the $r_\theta$ of the 0–30 cm layer was above 0.7. Based on these results, it can be concluded that HYDRUS-1D and HYDRUS (2D/3D) can be used as tools to accurately simulate long-term soil water dynamics in *P. tomentosa* plantations, at least in sites with similar characteristics to ours. HYDRUS modeling can be used to assess the impacts of $r_\theta$ on productivity of mature *P. tomentosa* plantations. This study also shows that monitoring soil moisture of the surface soil provides a robust means for predicting tree growth of *P. tomentosa* plantations at sites with similar soil to ours.

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## 1. Introduction

Poplar plantations account for a large portion of the fast-growing and high-yielding plantations in China, and their area exceeds 8.5 million ha. However, their productivity ($<15\ m^3\ ha^{-1}\ yr^{-1}$) is far lower than the world average for poplars ($20–30\ m^3\ ha^{-1}\ yr^{-1}$) (Zheng, 2006), and needs to be increased urgently in order to meet demand for wood in China. Soil water can exert an important control on poplar growth (Dong et al., 2011; Hogg et al., 2013), so irrigation has been widely used to increase the productivity of poplar plantations (Shock et al., 2002; Voltas et al., 2006; Xi et al., 2014). Nevertheless, as the water resource is scarce in China, high efficiency irrigation strategies must be adopted when increasing the productivity of poplar plantations using irrigation.

Despite the importance of these systems, little research has been undertaken on high efficiency irrigation strategies in poplar plantations. These limited studies have mainly focused on developing efficient irrigation strategies by conducting field experiments to compare the impacts of different irrigation regimes on above- and below-ground growth, tree ecophysiological characteristics or

*Abbreviations:* SDI, subsurface drip irrigation; NC, rainfed natural condition; SWP, soil water potential; ABH, basal area at breast height; DBH, diameter at breast height; *E*, soil evaporation; *T*, transpiration on ground area basis; *I*, canopy rainfall intercept; LAI, leaf area index; *P*, rainfall; SA, surface area per unit length of drip tubing; RMSE, root mean square error; RMAE, relative mean absolute error.

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plantation productivity (Shock et al., 2002; Voltas et al., 2006; Xi et al., 2014). Although these field studies are useful, they require time-consuming, laborious, and expensive work, and moreover only a few irrigation strategies can be compared in one experiment. A more expedient alternative to identifying efficient irrigation strategies involves modeling the effects of various irrigation strategies on tree growth.

To predict the growth of planted trees under different irrigation strategies using modeling, it is first necessary to quantify the dynamics of soil water content within the tree root zone under different irrigation strategies. The HYDRUS model is a well-known mechanistic model for simulating variably saturated one- (HYDRUS-1D), two- and three-dimensional (HYDRUS (2D/3D)) water movement and root water uptake in soils based on finite element numerical solutions of flow equations (Šimůnek et al., 2006a,b; Phogat et al., 2013). However, to our knowledge, in poplar plantations, only Zhu and Ren (2009) used HYDRUS-1D to simulate one-dimensional soil water flow, while HYDRUS (2D/3D) has never been tested.

The second requirement for predicting growth of planted trees under different irrigation regimes is a good understanding of the quantitative effect of soil water availability on tree growth. Although research has investigated the impacts of soil water availability on the growth of poplar plantations (Hansen, 1988; Dong et al., 2011; Xi et al., 2014), only Shock et al. (2002) and Zhou (2013) have established the relationship between growth of poplar plantations and soil water availability at one or two soil depths. However, there has not been a thorough examination of the quantitative relationship between poplar plantation growth and soil water availability at different layers throughout the root zone.

Triploid *Populus tomentosa* plays a key role in fast-growing and high-yielding poplar plantations of the North China Plain (Zhang et al., 2012), but currently the average productivity ($12\,m^3\,ha^{-1}\,yr^{-1}$) (Xi et al., 2014) of triploid *P. tomentosa* plantations in this region is far lower than the potential productivity of >$40\,m^3\,ha^{-1}\,yr^{-1}$ (Zhu et al., 1995). This study was undertaken to establish a methodological basis for developing optimal irrigation strategies to increase the productivity of triploid *P. tomentosa* plantations using modelling methods. The two objectives of this research were to: (1) evaluate the accuracy of HYDRUS models with precisely measured input parameters for simulating long-term soil water dynamics in triploid *P. tomentosa* plantations under both drip irrigated and rainfed conditions, using field data, and (2) examine the relationship between tree growth and soil water availability in different soil layers in triploid *P. tomentosa* plantations.

## 2. Materials and methods

### 2.1. Experimental site description and experimental design

This research was carried out in a triploid *P. tomentosa* plantation, located in Gaotang County, Shandong Province, China (36°58′N, 116°14′E, and elevation 27 m). This plantation was planted in 2005 using an alternate wide- (6 m) and narrow- (2 m) row spacing scheme with intra-row spacing of 1 m (Fig. 1a). The site has a warm temperate monsoon climate. The mean annual rainfall, temperature and free surface evaporation at the site are 545 mm, 13.2 °C and 1880 mm, respectively. The soil is developed from quaternary alluvium, and its chemical and physical properties are shown in Table 1.

The present study was a sub-experiment of our subsurface drip irrigation (SDI) experiment conducted in 2010 and 2011, details of which can be found in Xi et al. (2014). Three drip laterals with an installation depth of 20 cm and a discharge rate of $2\,L\,h^{-1}$ were installed for each tree belt (installation pattern is shown in Fig. 1a). To achieve the objectives of the present study, we used two treatments of the SDI experiments: a rainfed control treatment in which no irrigation was applied (NC), and a treatment in which the trees were irrigated when the average soil water potential (SWP) at 20 cm depth and 10 cm distance from a dripper reached −25 kPa (T25). HYDRUS models were used to simulate the soil water dynamics in these two treatments. Parameters needed for running the HYDRUS models were obtained by field measurement—such as those for characterizing root water uptake distributions (root distribution), initial soil water conditions and boundary conditions for soil water movement (transpiration on a ground area basis ($T$, $cm\,d^{-1}$), soil evaporation ($E$, $cm\,d^{-1}$), precipitation ($P$, cm) and groundwater level (cm)).

### 2.2. Field experiment measurements

Three plots each of which included ten measurement trees were established in both treatments. Diameter at breast height (DBH) of trees in these plots was measured at monthly intervals, and the data were used to calculate basal area at breast height (ABH) for individual trees.

One set of thermal dissipation probes (TDP30, Dynamax Inc., TX, USA) was installed into the sapwood 1.3 m above the ground on the southern aspect to measure trunk sap flux ($cm\,d^{-1}$). In 2010 and 2011, sap flux of three and five trees within different DBH classes, respectively, in each treatment were measured during the whole growing season, and their sap fluxes were assumed to be the sap flux of trees within corresponding DBH classes in that specific treatment. The stand level $T$ on each treatment plot was estimated using Eq. (1) (Kumagai et al., 2005)

$$T = J_S(\frac{SA_{plot}}{A_G}) \quad (1)$$

where $J_s$ ($cm\,d^{-1}$) is the weighted mean stand sap flux; $SA_{plot}$ is the total sapwood area of a plot at 1.3 m above the ground and $A_G$ is the plot area.

There are two major sources of error in scaling up sap flux to the stand level using Eq. (1): determinations of $SA_{plot}$ and $J_s$ (Kumagai et al., 2005). To accurately estimate $SA_{plot}$, an allometric equation ($R^2 = 0.996$) describing the relationship between DBH and individual tree sapwood area ($SA_{tree}$) was developed using windthrown and felled trees (n = 67). Then $SA_{plot}$ was estimated by integrating all the calculated $SA_{tree}$ in a plot. When determining the mean stand sap flux, the variation in sap flux among different trees and throughout the sapwood should be taken into account. However, in our plantation, the individual tree transpiration rate measured using one set of thermal dissipation probes was similar to (5.6% lower) and linearly correlated ($R^2 = 0.955$) (Li et al., 2014) with that measured using a whole-tree potometer (see Knight et al., 1981), so the sap flux across the sapwood area of each tree could be assumed to be uniform. Sap flux of only a small number of trees were measured due to a shortage of probes. However, we believe that the tree-to-tree variations in sap flux, when estimating $J_s$, was greatly reduced through selecting trees from different DBH classes and using the weighted average method.

Twelve micro-lysimeters were used to measure $E$ (Boast and Robertson, 1982). Four micro-lysimeters with an internal diameter of 7.5 cm and a depth of 20 cm were installed under the canopy (Fig. 1a) of each of three sample trees, which were selected from the irrigated treatment (T25) and were within different DBH classes. Micro-lysimeters were weighed every day to estimate $E$. Soil in the micro-lysimeters was replaced every three or four days with nearby soil. The average $E$ measured by the twelve micro-lysimeters was used as the $E$ within all the plots of T25. The average $E$ measured by the six micro-lysimeters installed at 150 and 250 cm distant from the tree line was used as the $E$ for all the NC plots, as soil water

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