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Discrepancy in tree transpiration of *Salix matsudana*, *Populus simonii* under distinct soil, topography conditions in an ecological rehabilitation area on the Northern Loess Plateau

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ABSTRACT

Complex naturally carved topography and large-scale artificial landforms significantly perturb hydrologic cycles and cause heterogeneity of water availability. Afforested trees exhibit distinct growth and survival strategies on distinct habitats on the Northern Loess Plateau in China. The objective of this study was to quantify tree transpiration discrepancies of two tree species aged > 30 years on different soil and topography conditions, and to explore the interactions with the atmosphere, hydrology, soil and topography, through long-term (up to seven years) observations of sap flow, meteorological factors and soil water contents (SWC). Results showed that mean whole-tree transpiration (T) of *Salix matsudana* and *Populus simonii* in the growing season were 46.7 and 175.2 kg d^{-1}, respectively, in a dam field, and were 5.6-fold and 4.2-fold the magnitude of that on a sloping field, respectively. Daily T was positively correlated ($P < 0.001$) with meteorological factors (i.e., reference evapotranspiration, ET_0; solar radiation, R_n; vapor- pressure deficit, VPD). Daytime ET_0 explained 37% of *S. matsudana* variation in T on the sloping field, up to 77% of the variation on a dam field, and 80% of the variation in T from *P. simonii* on both fields. The T of *S. matsudana* was significantly positively correlated with SWC from topsoil to 200 cm depth, and the correlation increased (partial R up to 0.55 at 200 cm depth) as depth increased on sloping field. However, no consistent correlations between T and shallow depth SWC existed on *S. matsudana* and *P. simonii* on dam fields and *P. simonii* on sloping field. Annual rainfall soil-water recharge depth reached up to 600 cm in wet years, but only 120 cm in dry years on sloping field with aeolian sandy soil, and was 200 cm even in wet years in dam field with loessial soil. Trees on the dam field absorbed water mainly from shallow groundwater. Tree fine roots gathered in the subsurface soil on the sloping field but not in the dam field indicated a root distribution adaption to precipitation patterns and water-use strategy. Soil water deficit formed in the 0–600 cm soil layer on the *S. matsudana* sloping field in normal and dry years, and soil water was replenished during wet years. Neither species is suitable for extensive revegetation implementation in this area due to their negative impacts on water resource sustainability.

1. Introduction

Water availability is a critical and restricting ecological factor in arid and semi-arid ecosystems (Chang et al., 2006). The Loess Plateau, situated in the northwest of China, is a unique critical zone with extensive and deep loess deposits (~640,000 km^2 in area, up to > 250 m in depth) featured as the most highly erodible soils on Earth (Jin et al., 2018). These soils are in an arid and semi-arid and continental monsoon climate (Jin et al., 2018). Soils in the area are characterized by severely eroded dense gullies and hills, fragmented landscapes, sparse vegetation and fragile ecosystems. Thus, starting in the 1950s, various government strategies such as revegetation, afforestation, construction of check dams, terracing and other eco-engineering practices have been implemented to remediate soil and water losses and restore ecological balance (Chen et al., 2015). For example, the Grain for Green project was launched in 1999 and is the largest active revegetation project in China or elsewhere (Deng et al., 2014; Zhang et al., 2018b). Consequently, following a large-scale land-use conversion of barren land or cropland into grassland, shrub land or forest, vegetation cover on the Loess Plateau has nearly doubled from 31.6% to 59.6% between 1999

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Forest Ecology and Management 432 (2019) 675–685

and 2013 (Chen et al., 2015). Both sediment discharge and runoff into the Yellow River have declined dramatically. However, continued excessive runoff and discharge decline have caused concerns over river safety and water supply in the lower reaches of the river (Chen et al., 2015; Yang and Lu, 2018). The negative impact of excessive or inappropriate revegetation and afforestation efforts, and the resultant soil drying has also been raised (Zhang et al., 2018b). The Loess Plateau is now threatened by a warming and drying due to climate changes, with more frequent climatic extremes likely to occur (Zhao et al., 2017). Thus, comprehensive knowledge on hydrological traits of rehabilitated vegetation and their interactions with the environment is essential to assess their eco-hydrological effects and guide future revegetation activities, and to work on a sustainability under changing climate.

Various studies have criticized the unbalanced revegetation-water relations on the Loess Plateau at both regional scales (Wang et al., 2018a, 2017; Zhang et al., 2018b) and from field observations (Jin et al., 2018; Zhang et al., 2018a). The introduction of exotic species, deep-rooted perennial vegetation and trees have been attributed to almost 80% of the current soil desiccation on the Loess Plateau (Chen et al., 2015; Shangguan, 2007). Poplar, willow, black locust and other tree species have been widely planted during afforestation, which contributed to a rapid expansion of tree cover on the Loess Plateau to 12% by 2014 (Wang et al., 2017). These trees usually absorb relatively more water from soil than grass and shrubs to satisfy their enormous canopy transpiration demands, and trees may extract shallow groundwater through deep root system; afforested trees likely worsen water-deficit related issues in water-limited regions (Tian et al., 2017). For instance, black locust, widely planted on the Loess Plateau, drew soil water down close to wilting point in the 0 to > 500 cm soil layers within < 5 years of planting in areas where the mean annual precipitation was < 600 mm (Liang et al., 2018).

By 2012, about 113,500 check dams were built on the Loess Plateau, creating 3200 km^2 of dam fields as small “alluvial plains” which have formed from sedimentation in front of check dams (Xu et al., 2004). Complex naturally carved topography (e.g., hills, slopes, gullies, plateaus, etc.) and large-scale artificial landforms (e.g., check-dam systems, terracing, etc.) have largely perturbed local hydrologic cycles and have caused uneven spatial distribution of water availability (Ambroise, 1995; Huang et al., 2013). Soil texture, closely related to soil water retention, is also an important factor influencing soil water availability (Dodd and Lauenroth, 1997; Hultine et al., 2006). Owing to previously mentioned reasons, afforested trees across the Loess Plateau have been found to differ in growth, survival status and morphology under distinct soil and topography conditions, even with exactly the same species and planting ages. “Stunted aged tree” depicts a common phenomenon on upland hills and slopes on the Northern Loess Plateau, in which a tree far less than its normal size struggles to survive under water scarcity and soil degradation after a long planting period (Aerts, 2013; Chen et al., 2008). However, the same tree species exhibited robust and even excessive growth in a gully and check-dam system, running a risk of consuming the limited water reservoirs (Peng et al., 2015).

So far, few studies have fully inspected the interactions between tree hydrological traits and complex topography as well as soil properties on afforestation. Majority of hydrology assessments of afforestation have been derived mainly from soil moisture measurements in the soil profile (Zhang et al., 2018a). However, water budgets do not accurately reflect tree hydrological traits with soil moisture measurements made to limited soil depths as tree roots can penetrate far deeper than practical monitoring depths into thick loess deposits. Quantifying of tree transpiration through sap flow methods facilitates *in situ*, automatic and continuous estimation of whole-tree water use (Cermak et al., 2004; Wang et al., 2018b). The thermal dissipation probe (TDP) method, also called the Granier method, is one of the most commonly used sap flow technique due to its simplicity, high degree of reliability as well as relatively low costs (Lu et al., 2004).

In this study, we measured sap flow of *Salix matsudana* and *Populus simonii* over up to successive seven growing seasons, from 2011 to 2017, which included dry, normal and wet years, in a sloping field site with an aeolian sandy soil and a dam field site with a loessial soil. We monitored meteorological conditions and soil-water conditions, and surveyed the root distribution and tree morphology. The objectives of this study were to (1) quantify the water use of two common afforested tree species in a water-wind erosion crisscross region on the Loess Plateau, (2) assess the effects of environmental factors on driving tree water use, including meteorological conditions and soil-water conditions, and (3) determine the interactions between tree hydrological traits and topography and soil textures.

2. Materials and methods

2.1. Site description

The study site was located in the Liudaogou Catchment (38.78° N, 110.35° E, and 1200 m a.s.l) in Shenmu City, Shaanxi Province, China. The catchment, west adjacent to Mu Us Desert, is within the Loess Plateau, China, referred to as the “water-wind erosion crisscross region”. It is characterized by many deep gullies and undulating slopes and hills. Fluvial and aeolian landforms are subject to periodic intense rainfall and winds that cause severe soil erosion (Fan et al., 2010). This area is in the continental monsoon climate zone and has a mean annual temperature of 8.4 °C. Mean annual precipitation (MAP) is 437 mm, of which 70% falls in intense rainstorms between July and September. Mean annual grass reference evapotranspiration (ET_0) from the FAO-56 Penman-Monteith equation (Allen et al., 2006) is approximately 1200 mm.

The dominant soil types in this area are a loessial soil and an aeolian sandy soil (Table 1). The loessial soil is developed directly from Quaternary loess parent material with elementary pedogenesis and is susceptible to water erosion. The aeolian sandy soil forms from coarse sandy soil deposits due to intense wind erosion and is distributed discontinuously on the undulating slopes and hills, implicating severe soil degradation and desertification having occurred. The aeolian sandy soil generally has coarse texture, poor cohesion, intense infiltrability, and low water retention. To harness the enormous soil and water losses and intercept water erosion sediments from loessial soil in hilly and gully areas, massive check dams had been built up behind the outlets of branch gullies, and dam fields have formed over several decades of loessial soil deposition within check dam system.

We selected two sites with distinct main soil and topography conditions. The first site is a level dam field site with loessial soil in a silted-up check dam system built about five decades prior to the experiment, and the second site a sloping field site with aeolian sandy soil. We

Table 1
Soil particle composition (%), soil texture, soil bulk density (BD, g cm^{-3}), field capacity (FC, cm^3 cm^{-3}) and wilting point (WP, cm^3 cm^{-3}) of two typical soils in the study plots. Classification of soil texture is based on the USDA system (Soil Science Division Staff, 2017).

Soil names	Soil particle contents (%)			Soil texture	BD (g cm^{-3})	FC (cm^3 cm^{-3})	WP (cm^3 cm^{-3})
	Sand (0.05–2 mm)	Silt (0.002–0.05 mm)	Clay (< 0.002 mm)				
Aeolian sandy soil	92.0	6.8	1.2	Sand	1.62	0.12	0.04
Loessial soil	52.5	35.8	11.7	Sandy loam	1.49	0.25	0.07