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Fine root distributions of shelterbelt trees and their water sources in an oasis of arid northwestern China

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ABSTRACT

Shelterbelt trees play an important role in maintaining the sustainability of oases agricultural ecosystems, but the trees require a considerable amount of water for survival. The objectives of this study were to investigate the root distributions, transpiration and water sources of shelterbelt trees (Gansu Poplar; *Populus gansuensis*) in order to improve water management efficiency. Fine root and soil water distributions were investigated along three transects that passed through cropland and an adjacent shelterbelt, while sap flow measurements were conducted on six Gansu Poplar trees. Results showed that roots were mainly distributed within 5 m of both sides of an irrigation channel passing between the first and second tree rows. The maximum distance to which trees extended fine roots horizontally was about 18 m from the shelterbelt. In 2-m soil profiles, fine roots were mainly distributed in the 1.4–2.0 m and 0–0.4 m layers depending on the available water sources. A positive relationship was observed between soil water and fine root mass density. Trees grown near the cropland-shelterbelt border exploited water from cropland irrigation and irrigation channel leakage, greatly enhancing their transpiration. During the growing season of 2013, the mean total transpiration of trees grown farther away from the border (10.75 and 17.45 m) was 216.9 mm, whereas for trees grown nearer to the border (0.85 and 6.30 m) the amounts were 670.1 and 488.7 mm, respectively. If the trees were assumed to absorb the same amount of water from soil, rainfall and groundwater sources, then irrigation water sources provided 67.6% and 55.6% of the water meeting the transpiration requirements of the trees closest to the border. The results have important implications for water management in oasis agricultural areas by limiting the extension of shelterbelt tree roots into adjacent cropland in order to improve irrigation water use efficiency.

1. Introduction

Sandy desertification is one of the important environmental problems confronting the oases agricultural ecosystems in the middle reaches of the Heihe River Basin in northwestern China (Luo et al., 2005). The Heihe River Basin is situated in a desert area and is, therefore, in an inland arid region. The oasis areas support agriculture in an otherwise desert landscape. In order to protect the cropland against damage from sandstorms and dry thermal winds originating in the desert, shelterbelt trees have been planted around and within the oasis areas that cover 84,700 ha. Since the 1980's, the total area covered by these trees has increased to 18,000 ha, according to the Zhangye Water Conservation Bureau of Gansu Province (Zeng et al., 2002; Liu et al., 1997; Chang et al., 2004). The four main species of shelterbelt trees are *Populus gansuensis*, *Populus bolleana*, *Tamarix chinensis*, and *Pinus sylvestris* (Su et al., 2010). Although the shelterbelts effectively protect and improve the environment of the oasis areas, which potentially leads to their sustainability, the shelterbelt trees also require a considerable amount of water in order to survive and grow. Consequently, these trees have increased the demands on the scarce regional water resources. Water consumption in the oases amounts to 86% of the total water resources available from the Heihe River, and irrigation accounts for 96% of the water consumed (Chen et al., 2003). Therefore, it is essential to know the water consumption of, and the water sources used by, the shelterbelt trees in order to facilitate sustainable management of the limited water resources.

The fine roots (diameter <2 mm) are the main means by which

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plants absorb water and nutrients, and the spatial distribution of the fine roots in turn directly affects the amounts and distributions of the plant available water and nutrient resources. Previous studies have found that fine root distribution was closely related to rainfall, soil water, soil texture and the water table (Dawson and Pate, 1996; Wilcoxa et al., 2004; Schenk and Jackson, 2005; Zhao et al., 2010; Gang et al., 2012; Imada et al., 2013; Ferrante et al., 2014; Padilla et al., 2015). Typically, most of the fine roots of plants are concentrated in the upper soil layers and the density of the roots notably decreases with increasing soil depth (Schenk and Jackson, 2002; Schenk, 2008). Jackson et al. (1996) reported that the root systems in boreal forests and temperate grasslands were the shallowest, while those in deserts and temperate coniferous forests were the deepest. Drought can result in a redistribution of fine roots to deeper mineral soil horizons in order to access deep soil water resources as well as nutrients (Persson et al., 1995). For example, the maximum root depth under a 12-year-old jujube plantation was 10 m in the absence of irrigation in the semiarid hilly region of the Chinese Loess Plateau (Ma et al., 2013). Tree roots are also able to extend horizontally to exploit water sources; for example, into cropland that was 20 m away from the trees in an agroforestry system in southwestern Australia (Woodall and Ward, 2002). Cheng et al. (2013) reported that the distributions of the fine roots of *Caragana korshinkii* were affected by soil texture; in a sandy soil the fine root density was higher than in a silt loam soil within the upper 0.8-m soil layer, but the opposite was observed in the lower 0.8–2.8 m soil layer.

Tree water consumption can be determined by measuring sap flow. There are many factors influencing tree sap flow, including meteorological factors, soil water and groundwater. The main meteorological factors are solar radiation, air temperature and vapor pressure deficit (VPD). Shen et al. (2015) found that sap flow is positively related to solar radiation, while linear (Gazal et al., 2006) or logarithmic (Shen et al., 2015) functions can both describe relationships between sap flow and VPD under certain conditions due to a complex response of sap flow to VPD. Soil water is a critical factor affecting tree sap flow in arid areas where plants are always growing under water deficit conditions (Zhao and Liu, 2010; Naithani et al., 2012). Groundwater is another factor that influences tree sap flow where there is a relatively shallow water table. Some studies have shown that sap flow increases with decreases in the depth of the water table (Gazal et al., 2006; Ma et al., 2013).

A number of studies have focused on sap flow and its temporal and spatial variations of trees among shelterbelts in the middle reaches of the Heihe River Basin (Chang et al., 2006; Zhao et al., 2007, 2010; Yi et al., 2014). However, little is known about the fine root distributions and the sources of water used by the shelterbelt trees. The shelterbelts around and within the oasis are typical of agroforestry systems. Since the shelterbelts are affected by climate, soil texture, cropland irrigation and shallow groundwater, the root distributions and water consumption of the trees can be more complex in these areas. Therefore, it is important to gain information and to understand the patterns of root distributions and the water sources used by the shelterbelt trees in order to better manage them and to improve water resource use efficiency in the whole Heihe River Basin.

In the presented study, we investigated fine root and soil water distributions along three transects that passed through cropland and an adjacent shelterbelt. We also conducted sap flow measurements for six Gansu Poplars at different distances from the cropland-shelterbelt border. We hypothesized that soil water availability would affect the vertical and horizontal distributions of fine roots. We also hypothesized that the total water consumption of the trees at different distances from the border would be different due to the location-specific limitations of the water sources.

2. Materials and methods

2.1. Site description

The field experiment was conducted between May 1 and October 1 in 2013 at the Linze Ecological Observational and Experimental Station (39°21′N, 100°07′E), which is located in a desert-oasis ecotone in the middle reach of the Heihe River Basin of Northwest China (Fig. 1a). This area has a continental arid temperate climate with a mean annual precipitation of 116.8 mm (1965–2000), about 90% of which falls during the rainy season between June and September. The annual mean air temperature is about 7.6 °C, and the mean maximum and minimum temperatures, which occur in August and December, are 39.1 °C and −27.8 °C, respectively. The mean annual open water evaporation is about 2365 mm (Chang et al., 2006). The mean frost-free period is 165 days, and the relative humidity ranges from 7.3% to 80.9% (Ji et al., 2007). During the study period, the mean monthly temperature was 20.4 °C and the mean precipitation was 50.5 mm.

2.2. Experimental design and measurements

An 80 m × 16 m experimental plot was selected to pass through spring wheat cropland (for 22 m of its length), a shelterbelt with 9 rows of trees (for 36 m), and maize cropland (for 22 m). In this study, only the spring wheat cropland and half of the shelterbelt (i.e., 4 tree rows) adjacent to the spring wheat field were investigated. The shelterbelt trees were Gansu Poplars (*P. gansuensis*) that were planted in 1980 with row spacing ranging from 4.45 to 6.7 m. The growing season of Gansu Poplars was from May 1 to October 1 in 2013. An irrigation channel with a depth of 0.5 m and a mean width of 0.65 m had been constructed between the first and second rows (Fig. 1b), from which sub-irrigation channels transferred water to the spring wheat crop, while the maize crop was irrigated only through another main channel located outside of the study area. During the growing seasons of spring wheat (March 6 to July 10), the crops were irrigated every 7–14 days with approximately 100 mm of water on each occasion; a further irrigation (100 mm) was applied at the beginning of the winter season (November 5) after sowing the spring wheat. During the growing season of the spring wheat, the bed and sides of the irrigation channel were sealed with a thin plastic sheet to prevent water leakage for further studying the effect of irrigation channel leakage to tree transpiration. The plastic was removed after July 27. From July 27 to September 30, water was permitted to leak from the irrigation channel for a total duration of 241 h; no irrigation was conducted from September 30 to November 5. During the study period from May 1 to September 30, 2013, ten irrigations supplied a total of 960.8 mm of water to the spring wheat crop, while the amount of rainfall was 105.6 mm (Fig. 2). With regard to the crops, the irrigation schedule was designed to ensure that the crops did not suffer water stress. Actually, excessive irrigation was used to ensure excess salts were prevented from accumulating in the soil profile.

2.2.1. Soil water measurements

Three 44.56-m long transects, 4 m apart, were laid out through the spring wheat cropland (18.66 m) and the first four rows of the adjacent shelterbelt trees (25.9 m). Eight polycarbonate Trime Domain Reflectometry (Trime-TDR) access tubes (4 cm in diameter and 300 cm long) were installed in the soil along each transect to facilitate multiple determinations of water content over time and space under the cropland and shelterbelt (Fig. 1b). The distance