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Effect of rainfall pulses on plant growth and transpiration of two xerophytic shrubs in a revegetated desert area: Tengger Desert, China

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ABSTRACT

Rainfall is one of the most important abiotic factors limiting physiological processes and ecological adaptability of plants in arid regions. In this study, the leaf area index (LAI), new branch length (NBL) and sap flow scaled transpiration of *Caragana korshinskii* and *Artemisia ordosica* in response to rainfall pulses were investigated during the growing season from 2008 to 2012, and then the plant acclimation was discussed. Results indicated that rainfall intervals and depth can trigger a cascade of plant physiological and acclimation responses of *C. korshinskii* and *A. ordosica* at different time scales. The approximate water consumption of *C. korshinskii* and *A. ordosica* were 15.54 ± 2.89 mm and 3.40 ± 0.07 mm for every 1 cm of branch growth, respectively. In daily time scales, rainfall pulses of 0–5 mm would result the plant transpiration to increase by 14 ± 2%–31 ± 9%; however, when the rainfall is larger than 5 mm, daily plant transpiration was reduced by about 7 ± 1%–39 ± 2%, and restored its pre-rainfall values within 1–2 days. Rainfall intervals of 0–5 days (d) and 5–10 d have a dominant impact on the increment of LAI, NBL and transpiration of *C. korshinskii* and *A. ordosica*, which accounted for approximately 50%–80% of the total. On interannual scales, plant growth and transpiration were linearly correlated with annual rainfall. *A. ordosica* acclimated to drought by losing some or all parts of the plant, and *C. korshinskii* survived during the dry period mainly by losing its leaves and by entering dormancy and ceasing growth.

1. Introduction

Rainfall in water limited ecosystems was usually defined as a pulse resource input (Noy-Meir, 1973; Holt, 2008; Yang et al., 2008), as it was considered as the sole source of water replenishment in these areas with strong spatial and temporal heterogeneity and randomness (Rodriguez-Iturbe et al., 1999; Li et al., 2004). The pattern of global precipitation has changed (Phillips et al., 1998; Loik et al., 2004), which can trigger a cascade of biological transformations or ecosystem responses (Gutiérrez et al., 1997; Holmgren et al., 2006). Several long-term studies showed that rainfall pulses can increase the net photosynthetic rate of *Nitraria sphaerocarpa Maxim.* and *Calligonum mongolicum Turcz.* to approximately 1.65–2 times the rate of the pre-rainfall value, demonstrating the importance of the desert plants' response by improving their assimilation rate to precipitation patterns under a future climate (Liu et al., 2012). Yang et al. (2014) found that physiological characteristics except water use efficiency of *Haloxylon ammodendron* have obvious response to rainfall pulses of 6–12 mm. In some other desert ecosystems, such as in the Chihuahuan Desert (Brown et al., 1997), the Sonoran Desert (Bowers, 1997), north-central Chile and northwest Peru, herbaceous plants respond very rapidly to pulses of precipitation by germinating, growing, and producing large quantities of seed, its coverage has increased from 11–16% to 54–80% (Holmgren et al., 2006).

Various meteorological factors may interact to influence plant ecophysiological responses, such as the size, frequency, and timing of precipitation pulses, which has obvious scale dependence along the different spatial and temporal availability of water to plants (Ogle and Reynolds, 2004). Intra-annual precipitation patterns, particularly the seasonal distribution of precipitation, are widely recognized as governing functional and species diversity (Dodd et al., 1998; Schwinning et al., 2003). On daily time scales, one off precipitation intensity can have a dramatic impact on plant photosynthesis, transpiration or stomatal conductance (Zhao and Liu, 2010; Yang et al., 2014). In addition, plant species (BassiriRad et al., 1999; Cheng et al., 2006) and regional differences (Burgess, 2006; Eberbach and Burrows, 2006) also play important roles. For instance, the sap flow of *Eucalyptus crebra* increased rapidly as rainfall increased from 5 to 20 mm in eastern Australia, but did not increase under comparable conditions in southern Australia as they were sufficiently reliant on antecedent soil water (Morgan and Barton, 2008; Zeppel et al., 2008). Shrub species (*Isopogon gardneri*) rapidly increased their sap flow (by up to 5 times) after 34 mm of rainfall in southern Australia, whereas eucalyptus species (*Eucalyptus wandoo*) did not respond to the summer precipitation (Engel et al., 2005; Stewart and Burgess, 2006). Results from a

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simple ecohydrological box model showed that temporal rainfall intermittency allows for vegetation persistence at low values of annual rainfall volume, whereas it would go extinct if rainfall were constant because a minimal amount of water is in fact needed to activate biological processes such as reproduction and seed germination. If precipitation is concentrated in time, this minimum amount of soil water is intermittently exceeded and vegetation cover can persist. In case rainfall is uniformly spread, soil moisture never exceeds the threshold needed to activate plant reproduction and germination and the vegetation cover tends to disappear (Baudena et al., 2007).

Pulsed rainfall water availability would lead to the more competitive effects among neighboring plants in arid and semiarid environment as the limited water cannot support large areas of relatively homogeneous and continuously distributed higher plants communities (Chesson et al., 2004; Li et al., 2013). In addition to differing in plant growth over time, variation in precipitation in arid ecosystems is leading to plant adaptation in water use strategies, and significant interspecific differences in response will change the plant composition of desert communities (Xu et al., 2007). During pulses of bounty rainfall, the seedlings of desert plants can germinate, establish, and prepare for long droughts penetrating their roots deep into the desert soils. Plant life-forms appear to specialize in taking up water from specific soil layers at certain times of the year (Schwinning and Ehleringer, 2001). The Westoby–Bridges' pulse-reserve model (Noy-Meir, 1973) and 'threshold-delay' model (Ogle and Reynolds, 2004) addresses the response of various plant functional types (FTs) to pulses of precipitation and delays associated with plant responses. It predicts that there are 'biologically important' rainfall events that stimulate plant growth and reproduction (Pockman and Small, 2010). Although plant-water relations have been an important part of ecophysiological research, the long term influence of rainfall intervals and depth on plants under natural conditions is little understood, mainly because of the unpredictable variations of precipitation and the complexity of plants function (Xu et al., 2007). Furthermore, most studies concentrate on the conceptual models of plant water use strategies (Reynolds et al., 2004), experimental investigations on plants in revegetated desert areas that have evolved special physiological and morphological traits in the process of adapting to the frequent aridity, torridity and other environmental stresses are missing (Xu et al., 2007). Thus, understanding the responses of plant growth and transpiration to rainfall pulses is the basis for comprehending the physiological responses of desert plants and how these responses determine the acclimation of desert plants to their habitats (Zhao and Liu, 2010).

In revegetated desert areas, xerophytic shrubs, such as *Caragana korshinskii* and *Artemisia ordosica* have been widely planted at the southeastern fringe of the Tengger Desert in western China since 1956, which has been viewed as a successful model for desertification control and ecological restoration along the transport line in the arid desert region of China (Li et al., 2004). However, in recent years, due to the challenges of climate change and harsh natural environments, a series of problems have arisen, such as declining vegetation cover, poor plant growth and widespread water stress, which have led us to investigate the acclimation of the revegetated vegetation (Li et al., 2013). Previous research indicated that the adaption strategy of *Eragrostis poaeoides*, which is the dominant herb species in the sand-binding vegetation communities, was seed dormancy, which means that only part of the yearly produced seed bank germinated in the growing season, and the remainder of the seed was saved for the next growing season or longer (Zhang et al., 2004). However, *C. korshinskii* and *A. ordosica* have received less attention, mainly due to the reason that the effects of precipitation variation on plant growth and acclimation of shrub species may be complicated and extensive when compared with the above mentioned annual plants. In this study, based on a 5-year long-term monitoring and focused research in the Shapotou Desert Research and Experimental Station of Chinese Academy of Sciences. Precipitation, the leaf area index (LAI), new branch length (NBL) and transpiration of *C. korshinskii* and *A. ordosica* were measured and the plant acclimation to drought stress was investigated continuously from April 2008 to October 2012. The specific objectives of the study were: (1) determine how plant growth and transpiration respond to specific rainfall events (different rainfall depth and rainfall interval), and (2) explore the plant acclimation in a drought environment. Our goal was to provide a scientific basis for understanding the mechanisms that underlie the responses of these desert plants to global climatic change.

2. Materials and methods

2.1. Study area

The study was conducted in the soil Water Balance Experimental Fields (WBEF) of the Shapotou Desert Experimental Research Station, Chinese Academy of Sciences. The research station borders the Tengger Desert, China's fourth largest desert, located in the central part of west China (37°27′N, 104°57′E). The climate at the site is characterized by abundant sunshine and low relative humidity. The minimum average monthly relative humidity is 33% in April, and the maximum is 54.9% in August. The elevation of the area is 1330 m, and the mean annual precipitation is 188.2 mm (according to meteorological records from 1956 to 2009), falling predominantly between June and September. The mean annual temperature is 9.6 °C, and the mean monthly temperatures are −6.9 °C in January and 24.3 °C in July. The potential evapotranspiration during the growing season (May–September) is 2300 mm to 2500 mm. The windy season lasts from September to April, with average wind velocity of 2.6 m s^{-1}. The soil substrate is loose and impoverished moving sand and is classified as Typic Psammaquents, with a field capacity of 6.70% and a wilting coefficient of 0.61%, and the long-term moisture content varies between 3% and 4%. Groundwater lies 80 m below the surface and therefore cannot be used by plants (Li et al., 2004; Zhang et al., 2008).

To protect the Baotou–Lanzhou railway line from sand burial, a non-irrigation vegetation protection system was established in 1965. First, a woven willow branches or bamboo fence was first erected perpendicular to the prevailing wind direction and the moving sand dunes. After the fence, 1 m × 1 m straw-checkerboards were established as matrix for sand fixation. Then xerophytic shrubs, such as *C. korshinskii*, *A. ordosica*, *Hedysarum scoparium*, *Caragana microphylla*, *Calligonum arborescens* and *Atraphaxis bracteata* were planted at a spacing of 1 m × 2 m or 2 m × 3 m, with straw checkerboard barriers as a protective screen (Li et al., 2006). After 50 years, the planted shrub vegetation was replaced gradually by dominant shrubs, such as *C. korshinskii*, *A. ordosica* and some herbaceous plants, and the revegetated zone forms a stabilized sand-binding vegetation community (Li et al., 2004). Three 10 m × 10 m sample plots in the revegetation system were assigned to investigate the basic characteristics of the plant, such as species age, height, density, and stem diameter. The results are described as follows (Table 1):

2.2. Plant growth measurement

Six *C. korshinskii* and six *A. ordosica* shrubs were selected in each 10 m × 10 m sample plots for long-term monitoring and local observation. The values of the plant leaf area index (LAI, m^2/m^2) were measured using a LAI-2000 (Li-Cor, Lincoln, NE, USA) on the 10th and 25th of each month during the growing season (April to October) of the plants. The actual value of the LAI was the difference between measurements in the growing season and that measured before the emergence of leaves (branch area index). In each sap flow sensor-wrapped stems, ten branches were selected and then labeled for observation during our experimental period. The NBL was also measured half a month along with the LAI measurement. In each plot, the number of young plants, plant coverage and ratio of live branches to dead branches were recorded monthly during the plants growing season from 2008 to 2012.