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Research paper

Water use by broadleaved tree species in response to changes in precipitation in a mountainous area of Beijing

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ABSTRACT

Extreme weather events are expected to occur more frequently in the future, which may influence water distribution and uptake patterns in rocky mountainous areas of North China. To examine how plants respond and adapt to the extreme environment, we investigated water sources of the broadleaved tree species *Quercus variabilis* under a precipitation gradient (A: no natural precipitation, B: half of natural precipitation, C: natural precipitation, and D: twice the natural precipitation) using the stable isotope approach in the Beijing mountainous area. The results indicated that *Q. variabilis* exhibited considerable plasticity in the depth of water uptake and showed a strong dependence on deeper soil layers under the precipitation gradient. *Q. variabilis* mainly absorbed water from the 0–20 cm (20.02–28.61%) and 60–80 cm (22.81–29.44%) soil layers, and also used groundwater (26.32–30.54%) under the low soil water conditions of the A treatment. In the B treatment, *Q. variabilis* absorbed water from the groundwater (29.60–33.53%) and 60–80 cm (26.05–29.44%) soil layers and a small amount of water from 0 to 20 cm (10.67–12.25%). In the C and D treatments, the soil water content was greater than that of the B treatment; *Q. variabilis* still predominantly absorbed water from the 60–80 cm (26.88% and 27.35%, respectively) soil layer and groundwater (33.52% and 46.17%, respectively), and took minimal water from the 0–20 cm and 20–40 cm soil layers. We found that *Q. variabilis* showed no obvious responses to precipitation under the precipitation gradient, and its dimorphic root system allowed it to uptake different water sources under drought and humid environmental conditions and thus maintain its transpiration. Therefore, we can infer that *Q. variabilis* is well adapted to extreme precipitation events and has a strong adaptability to both extreme drought and flood conditions.

1. Introduction

The soil water available to trees predominantly comes from precipitation and to a lesser extent from groundwater recharge (Ehleringer, 1985). Therefore, precipitation is the critical factor that limits vegetation distribution, function, structure and growth (Dodd et al., 1998; Dube and Pickup, 2001). Normally, the effects of precipitation on tree growth depend on the amount of precipitation (Dobrowoski et al., 1990). Sala and Laurenroth (1982) reported that precipitation of 10 mm or less had no significant effect on perennial tree growth with deep roots, but it was important for grass and small shrubs with shallow roots. Small amount of precipitation only moisten the surface soil layer, but precipitation with large amount could penetrate then recharge deeper soil layers, which may explain the distribution patterns of functional tree roots (Gao and Reynolds, 2003). A large number of studies have shown that variations in precipitation amount could have a great impact on the ecosystem water balance and the water source of trees (Stephenson et al., 1990). For instance, Snyder and Williams (2000) found that with changes to the precipitation gradient, dominant tree species in the arid southwest of the U.S. utilize water from surface soil layers and switch to deeper soil layer and will change their functional and active rooting depth. Cheng and Lin (2006) explored the relationship between the amount of precipitation and water sources in perennial plants and found that dominant plants took advantage of water from different soil layers because of the different natural precipitation capacity. Kray et al. (2012) reported that *Ericameria nauseosa* exhibited strong dependence on water depth, and it absorbed water from the groundwater layer regardless of precipitation throughout the growing season. Furthermore, trees develop an extensive root system that extracts water from deeper soil layers but may also extract water from shallow soil layers when water is available near the soil surface (Oliveira et al., 2005). The pulse of moisture in the surface soil layer generated by a precipitation event is important for trees maintaining normal physiological activities during the dry season. Heavy precipitation events generate a pulse of moisture that can last few days, even weeks, but the pulse from small precipitation events may last only

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a few hours (Sala et al., 1981), which indicates that precipitation will affect the water use patterns of trees. In contrast, in arid areas where precipitation occurs stochastically, hydraulic redistribution is more frequent, wherein root systems of several woody plants can transfer water from moist regions to dry regions (Richards and Caldwell, 1987; Querejeta et al., 2007). The hydraulic redistribution process has been observed in a large number of plant species, especially those that grow in arid and semi-arid ecosystems (Sardans and Penuelas, 2014). Neumann and Cardon (2012) demonstrated that water moved via hydraulic redistribution by deep-rooted plants was reused by the plants themselves or neighboring plants in the shallow soil layer during dry periods. This indicates that hydraulic redistribution in the arid environment represents a mechanism by which plants adapt and it can effectively alleviate water stress and improve plant water use efficiency (Zeglin et al., 2013). Therefore, precipitation will have significant impact on water distribution and water uptake patterns of plants. Ren et al. (2012) predicted that extreme weather events would occur more frequently in the future and would lead to inevitable changes to precipitation patterns in seasonal drought areas.

Precipitation in the semi-arid regions of the North China is extremely variable both seasonally and spatially, thus plants must tolerate water stress during short floods or long dry periods. However, the role of precipitation for perennial trees growing in the Beijing mountain area remains unclear. It is also essential to understand how water utilization by trees could respond to precipitation changes by modelling future hydrological impacts on vegetation changes. Accordingly, exploration of the patterns of water uptake among dominant trees is necessary in semi-arid regions to examine the potential responses of perennial tree species in these fragile ecological environments. In this study, we controlled the amount of precipitation to investigate the patterns of water uptake among *Quercus variabilis*. We used the stable isotope technique and analyzed the hydrogen isotope ratio (δD) and oxygen isotope ratio ($\delta^{18}O$) values in tree branches, soil and natural springs to clarify the water source of *Q. variabilis* and its responses to these temporal changes in precipitation. The results of this study may have implications for future forest construction and management in this region.

2. Materials and methods

2.1. Site description

Our study was conducted at the National Forest Ecosystem Research Station (40°03′N, 116°05′E) of the Jiufeng National Forest in Northwest Beijing, China (Fig. 1a). The mean altitude of the study site is 450 m and the area has a warm temperate semi-humid and semi-arid continental monsoon climate region. The annual average air temperature is 11.6°. The temperature reaches a bottom at −15.0 °C in December and peaks at 38.7 °C in July. The annual mean precipitation is 660 mm in the study area, and approximately 70–80% occurs in the wet season, especially in July and August. Mean annual evapotranspiration is approximately 1100 mm. This region is predominated by *Q. variabilis* artificial pure forests, which were planted in the 1960s. The average depth of soil in the area is 80 cm and gravel is present within the soil profile. The texture of the surface soil (0–40 cm) is mainly clay with a lower density of gravel and the deep soil (> 40 cm) is mainly loam with a higher density of gravel

2.2. Experimental design

The experiment was conducted within twelve control trial areas, including four treatments and three replications for each treatment. The maximum trial area was highly limited by the uneven ground in mountains. The average slope of the ground of the experimental trials is 3°. In order to reduce the errors caused by different textures and slopes, the twelve trials (three groups) were set in three different places. The average horizontal distance between each group was about 54 m. Each group had a length of 20 m and width of 5 m. The treatments in the group were as follows: A (no natural precipitation), B (half of natural precipitation), C (natural precipitation), and D (double the natural precipitation) (Fig. 1b). The length and width of each treatment plot was 5 m and there were 3–6 trees in each treatment plot. The average height of the studied trees was 7.6 m with an average tree diameter at breast height of 10.4 cm. The maximum tree height was 8.8 m, thus we used 10-m-high frames to support the transparent plastic plates that were placed above tree canopies, avoiding the impact of tree growth and allowing us to control the precipitation. The transparent plastic plate had good transparency and ventilation and was positioned at the top of the canopy to ensure that there was no significant difference in temperature among the four treatments ($P < 0.05$). Half of the B treatment was covered by the transparent plastic plate to halve the natural precipitation. The entire A treatment was covered by the transparent plastic plate, which was tilted to ensure that no precipitation reached this area but it was tilted toward the D treatment in order to double the natural precipitation. The C treatment was uncovered to allow natural precipitation. We enclosed the trial treatments to the ground using impervious plastic board, preventing the study treatments from the effects of surface runoff or interaction between the test treatments. Grouting and fence measures were conducted to prevent water exchange between treatments. The grouting was carried out from the 30-cm soil layer to the bedrock layer. The impervious barrier in each treatment (the length of 5 m and width of 5 m) was buried in 30 cm of soil and exposed to 20 cm above the ground.

Q. variabilis is a deciduous broad-leaved tree, which is widely distributed across China and is usually grown on sunny slopes below 800 m above sea level in northern China. It is one of the most important

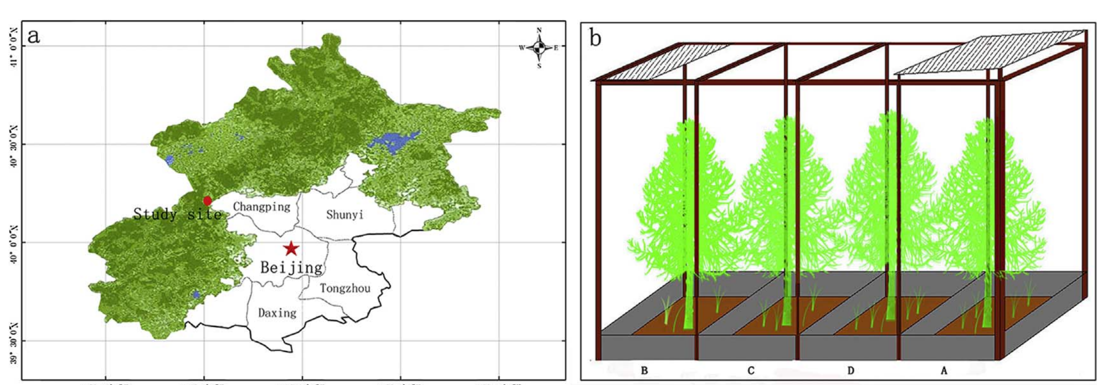

Fig. 1. Location of the study site and enclosed trial treatments. **a** Study site in Northwest Beijing, China, the red circle shows the study site; **b** Schematic of the four precipitation treatments (A–D) showing the enclosure and positioning of the plastic sheets (B received half of natural precipitation, C received natural precipitation, D received twice natural precipitation, and A received no natural precipitation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)