Forest Ecology and Management 289 (2013) 425–433

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Tree size, stand density, and the source of water used across seasons by ponderosa pine in northern Arizona

Lucy P. Kerhoulas [a,*], Thomas E. Kolb [b], George W. Koch [a]

[a] Northern Arizona University, Department of Biological Sciences, Merriam-Powell Center for Environmental Research, P.O. Box 5640, Flagstaff, AZ 86011, United States
[b] Northern Arizona University, School of Forestry, P.O. Box 15018, Flagstaff, AZ 86011, United States

ARTICLE INFO

Article history:
Received 17 August 2012
Received in revised form 18 October 2012
Accepted 19 October 2012
Available online 28 November 2012

Keywords:
Arizona
Seasonal precipitation
Water isotopes
Forest management
Stand density
Tree size

ABSTRACT

Understanding the dynamic relationships between seasonal water use, stand density, and tree size in semi-arid forests of the southwestern US is important for predicting climate change impacts and for tailoring forest restoration prescriptions to mitigate such impacts. Using hydrogen stable isotope ratio (δD) analyses of precipitation, soil water, and stem water over a 2-year sampling period, we found that winter precipitation was the dominant water source for ponderosa pines (*Pinus ponderosa* Dougl.) in northern Arizona in all seasons. Soil and stem waters were isotopically more enriched in high- than low-density stands. Isotopic analyses indicated large trees were more reliant on deep soil water than small trees. Our results indicate that management actions that maintain or create low-density stands of large deeply-rooted trees increase tree access to winter precipitation via deep soil storage and thus may help mitigate impacts of climate warming on tree health. Our findings provide new understanding of the complex relationships among seasonal water use, stand density, and tree size in a region where a drying climate puts increasing stress on forests.

1. Introduction

Climate change and the shift in forest management goals towards restoration present new challenges to forest ecohydrology. Recent climate change has reduced winter snow inputs and increased evaporative demand in forests of the western US and these trends are expected to continue with future warming (Seager et al., 2007). Concurrently, restoration thinning of dry, fire-prone western forests is increasingly being used to reduce fire risk arising from a century of fire suppression and a drying climate (Covington et al., 1997; Westerling et al., 2006). Restoration treatments reduce stand density and tree cover, and likely affect key ecohydrological processes (Kaye et al., 1999; Simonin et al., 2007).

Impacts of restoration treatments in ponderosa pine (*Pinus ponderosa* Dougl.) forests of the southwestern US have been studied on fire risk (Hurteau et al., 2008; Wiedinmyer and Hurteau, 2010), wildlife (Converse et al., 2006), understory communities (Moore et al., 2006), tree physiology and growth (Feeney et al., 1998; Skov et al., 2004, 2005; McDowell et al., 2006; Simonin et al., 2006; Kolb et al., 2007), and whole-ecosystem CO_2, water, and energy exchange (Dore et al., 2008; Montes-Helu et al., 2009; North et al., 2009; Dore et al., 2010). Reduced water stress and increased growth in residual trees after thinning have been repeatedly observed using a variety of measurements at several scales. At the leaf scale, increased predawn water potential, stomatal conductance, and photosynthetic rate in residual trees after thinning indicate increased water availability (Feeney et al., 1998; Kolb et al., 1998; McDowell et al., 2003, 2006; Skov et al., 2004; Wallin et al., 2004; Sala et al., 2005; Zausen et al., 2005; Simonin et al., 2006). At the whole-tree scale, thinning has been reported to increase soil-to-leaf hydraulic conductance (Skov et al., 2004; Simonin et al., 2006), resin flow (Kolb et al., 1998; McDowell et al., 2007), insect resistance (Kolb et al., 1998, 2007; Wallin et al., 2004; Zausen et al., 2005), and radial growth (Feeney et al., 1998; McDowell et al., 2003, 2006, 2007; Sala et al., 2005; Skov et al., 2005; Zausen et al., 2005). At the stand scale, eddy-covariance measurements show that thinning reduces drought limitation of ecosystem carbon uptake (Dore et al., 2008, 2010).

Impacts of restoration treatments on tree water sources are poorly understood. Precipitation in the southwestern US is bimodal, with winter and summer inputs dominated by different air circulations (Williams and Ehleringer, 2000). Winter precipitation from slow-moving Pacific frontal systems falls over extended periods of time with low evaporative conditions and therefore penetrates deep into the soil (Ehleringer and Dawson, 1992). In contrast, late summer monsoon precipitation is derived from air masses that originate in the eastern Pacific and the Gulf of Mexico and occurs in short, intense events when evaporation is high. These conditions largely restrict monsoon precipitation to upper soil layers (Simpson et al., 1972). Dendrochronological studies indicate that ponderosa pine growth responds more strongly to variation in

* Corresponding author. Tel.: +1 707 834 7209; fax: +1 928 523 7500.
E-mail address: lucykerhoulas@nau.edu (L.P. Kerhoulas).

0378-1127/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.foreco.2012.10.036

winter precipitation than summer precipitation (Fritts, 1966; Stahle et al., 2009). Thinning may influence tree use of seasonal precipitation inputs by altering canopy interception of precipitation. As stand density and canopy cover increase, snowpack and soil moisture recharge from winter precipitation typically decrease in part due to greater interception in dense stands (Baker, 1986; Tang and Feng, 2001; Dutton et al., 2005; Cook et al., 2007; Hu et al., 2010). Consequently, trees in dense stands may have to rely more on summer rains than trees in low-density stands, which can rely more on winter precipitation. Furthermore, variations in rooting depth related to tree size also may influence use of deep soil water because larger trees may have deeper roots and therefore greater access to deep soil water than smaller trees (Dawson, 1996). Thus, understanding how seasonal water use varies with stand density and tree size can inform forest management in the context of changing precipitation patterns driven by climate change.

Winter and summer precipitation inputs in inland areas of the southwestern US have distinct isotopic signatures that can enable determination of the seasonal source of water used by trees. Winter precipitation is more depleted in the heavier isotopes (^{2}H and ^{18}O) than summer precipitation (Dutton et al., 2005). For example, in Flagstaff, AZ, δD (^{2}H:^{1}H, ‰, V-SMOW) values of January and September precipitation are about −93 and −69, respectively, with the comparable δ^{18}O (^{18}O:^{16}O, ‰, V-SMOW) values being −13.6 and −10.1 (Bowen et al., 2005; Dutton et al., 2005). The combination of greater infiltration by the isotopically more depleted winter precipitation and greater evaporative enrichment of isotopically heavier summer precipitation creates a distinct isotopic gradient from heavy to light with increasing soil depth (Tang and Feng, 2001; Eggemeyer et al., 2008). Stable isotope analysis of water in precipitation, soil, and plants is commonly used to study plant reliance on distinct precipitation inputs and variation in soil water source among plant functional groups (Ehleringer and Dawson, 1992; Brunel et al., 1995; Eggemeyer et al., 2008). Using water isotope analysis, Dawson (1996) showed that different sized individuals of sugar maple (*Acer saccharum*) utilize water from different soil depths. In much of the southwestern US, the history of tree harvesting, recruitment, and fire suppression has produced forest structure dominated by two size and age classes of trees: larger trees established prior to European settlement in the 1890's and small trees established after fire suppression in distinct pulses such as in 1919 (Savage et al., 1996). Knowing how water source varies among these size classes can inform understanding of intraspecific competition and niche partitioning in this widespread species.

Northern Arizona has warmed significantly over the past half century (Hereford, 2007). Climate change models predict higher temperatures, decreasing snowpack, increasing aridity, and increasing variability of summer precipitation for the Southwest (Seager et al., 2007). Some climate models predict a substantial northward shift in the monsoon precipitation distribution (Houghton et al., 2001; Kim, 2002; Cook et al., 2004), possibly reducing summer precipitation to areas that now receive a large fraction of annual precipitation during summer, such as the southwestern

Table 1
Distribution of the 72 study trees in 2008 stand density classes over 1998 thinning treatment and tree size. Trees in the low, medium, and high stand density classes have a local basal area in the range of 1–10, 11–30, and 31–40 m^{2} ha^{-1}, respectively.

2008 Density Class	Size	1998 Thinning treatment				*n*
		Control	Light	Moderate	Heavy	
Low	Large	1	2	2	4	9
	Small	0	1	0	2	3
	n	1	3	2	6	12
Medium	Large	8	5	7	5	25
	Small	9	6	6	7	28
	n	17	11	13	12	53
High	Large	1	1	0	0	2
	Small	1	2	2	0	5
	n	2	3	2	0	7
	n	20	17	17	18	72

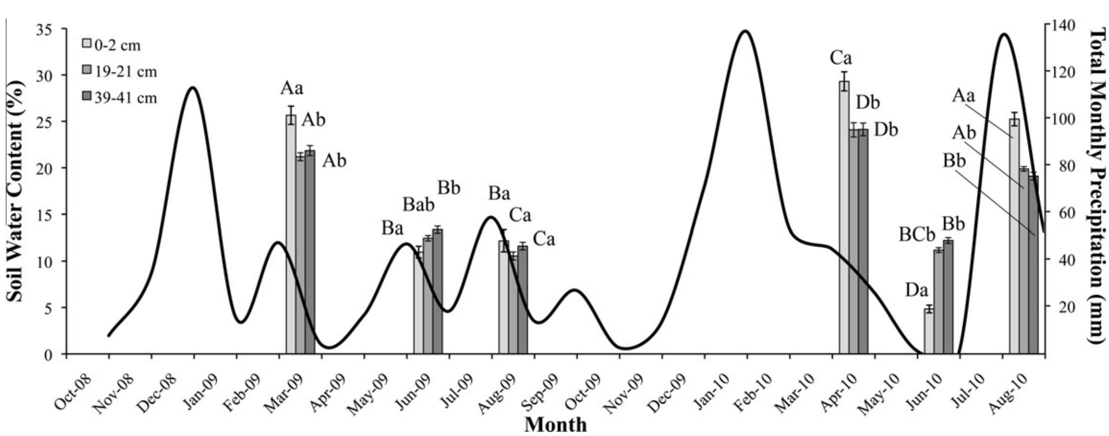

Fig. 1. Percent soil water at the 0–2, 19–21, and 39–41 cm depths for the six sampling months of our study. Average values are shown with standard error (s.e.). Data are pooled over stand densities and tree sizes. Within a month, depths not sharing the same lowercase letter are significantly different; within a depth, months not sharing the same capital letter are significantly different (α = 0.05). Total monthly precipitation (mm) is plotted for each month in our study period on the right-hand vertical axis (United States Historical Climatology Network, http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html).