The Ecohydrology and Management of Pinus Ponderosa Forests in the Southwest

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2. Montes-Helu MC, T Kolb, S Dore, B Sullivan, SC Hart, G Koch, BA Hungate. 2009. Persistent effects of fire-induced vegetation change on energy partititioning and evapotranspiration in ponderosa pine forests. Agricultural and Forest Meteorology. 149:491-500.

The Ecohydrology and Management of *Pinus ponderosa* Forests in the Southwest
Final Project Report – July 2010

George W. Koch, Ph.D. and Lucy P. Mullin, M.S.
Department of Biological Sciences, Northern Arizona University
Flagstaff, AZ 86011

a. Problem and Research Objectives

Population growth and the climate warming and drying place increasing pressure on water resources in the Southwest. Forests dominated by ponderosa pine (*Pinus ponderosa*) are common in southwestern uplands, supplying 70-90% of annual streamflow and therefore are key controllers of watershed-atmosphere interactions (Troendle 1983). Prior to Euro-American settlement in the mid-1880s, low tree density and a well-developed herbaceous understory characterized these forests (Moore et al. 1999). Fire exclusion, heavy grazing, and high seedling recruitment over the last century have increased tree density and decreased herbaceous vegetation in today's southwestern ponderosa pine forests (Savage et al. 1996, Covington et al. 1997), structural changes that have greatly increased risk of stand-replacing fires. A common approach to reduce fire risk and restore ecological health of southwestern ponderosa pine is thinning and controlled burning (Covington et al. 1997, Allen et al. 2002). Given the planned implementation of widespread forest restoration thinning, there is a pressing need to understand the effects of this management practice on water use and potential water yield in southwestern forests**.** Therefore, this project has focused on how changes in forest structure associated with management influence water use by individual ponderosa pine trees.

Because canopy structure and species composition strongly influence whole-system water exchange (Hollinger et al. 1999, Baldocchi 1997), large-scale restoration treatments will likely alter landscape water fluxes and ultimately regional climate (Sellers et al. 1996). Although reduced water use by trees and increased water supply to local streams is a potential benefit of restoration (Covington et al. 1997), little is known about how restoration will alter the components of plant transpiration and soil evaporation (evapotranspiration, ET) and sources of plant-transpired water (Simonin et al. 2007). By influencing the relative contributions of plant transpiration and soil evaporation to total ET, thinning will likely affect site water balance. A companion to this project, the NAU Carbon Flux Project, has used the eddy covariance technique to document how restoration thinning affects the water, energy, and carbon balance of ponderosa pine forests in northern Arizona (Dore et al. 2008, Montes-Helu et al. 2009; Dore et al. 2010). These data can now be used for scaling water balance over landscapes of the Southwest.

The specific focus of the WRRC-supported research by graduate student Lucy Mullin has been to examine the extent to which trees in thinned and unthinned stands depend on winter vs. summer water inputs to support their transpiration demands. This information provides the basis for understanding how future changes in the balance of inputs from these water sources may interact with stand structure to alter forest hydrology and potential water yield from Arizona forests.

The research supported by this WRRC grant has augmented, and benefited from, research supported by grants from federal agencies including the National Science Foundation, the USDA Forest Service, and the Department of Energy. This external funding has supported the aforementioned research on stand-level CO_2, water, and energy fluxes in ponderosa pine forests under different management conditions (see Dore et al, 2008; Montes-Helu et al. 2009; Dore et al. 2010). Although the eddy-covariance research was not supported by this WRRC grant, it provides valuable ecosystem-scale context for understanding the implications of the WRRC-funded research.

The research supported by this WRRC grant is ongoing, with field sampling, lab measurements, and data analyses in progress and scheduled for completion in 2011. The research that has been supported by the WRRC grant has involved a great deal of labor-intensive field sampling to collect soil and plant samples that are frozen prior to water extraction and subsequent water isotope analysis. The extractions are extremely time-intensive, requiring roughly an entire day to extract water from 12 samples, after which the samples are submitted to the Colorado Plateau Stable Isotope Laboratory for determination of deuterium/^{1}H (δ D) and oxygen ^{18}O/^{16}O (δ^{18}O) ratios. To date, graduate student Lucy Mullin has processed nearly 2000 samples and is awaiting data back from the isotope lab on roughly half of these. The large workload for Ms. Mullin has precluded her planned involvement in the study of sapflow (whole tree water use) at the site of the eddy covariance studies of ecosystem water, energy, and CO_2 exchange (Dore et al, 2008; Montes-Helu et al. 2009; Dore et al. 2010). The sapflow measurements have been conducted by Dr. Mario Montes-Helu under the auspices of the NAU Carbon Flux Project. Ms. Mullin continues to interact with the Carbon Flux team because that study and her own have considerable conceptual overlap.

Given the realities of the Ms. Mullin's workload constraints, her research under this WRRC grant has focused on the following hypotheses about water use by ponderosa pine in relation to tree size and stand density. Preliminary results addressing these hypotheses are described in Section C., Principal Findings and Significance.

Hypotheses

1) During the most active growing season, water at greater depths in the soil profile is derived from winter snow while water at shallower depths is primarily derived from summer rain.
2) Soil in thinned stands has greater winter precipitation recharge than soil in unthinned control stands.
3) Thinned *P. ponderosa* stands rely more heavily on winter precipitation while dense stands rely more on summer precipitation.
4) Larger ponderosa pines rely more heavily on water deeper in the soil profile than do the smaller ponderosa pines that dominate unthinned stands.
4) *P. ponderosa* trees use heartwood as a water source when soil water is depleted.

b. Methodology

The bulk of the work under this grant has examined how tree size and stand density affect the use of summer and winter precipitation by ponderosa pine in northern Arizona. The methods for the related eddy-covariance study are detailed in Dore et al. (2008) and Montes-Helu et al. (2009).

The study sites were 10 km northwest of Flagstaff, AZ (N35°15'58",W111°42'1", elevation 2200m) in the Flagstaff Urban Wildland Interface (FUWI) located within the Fort Valley Experimental Forest (USDA Forest Service, Rocky Mountain Research Station). The forest is dominated by *P. ponderosa* and has three 17 ha control (unthinned) plots and three 17 ha heavily thinned plots. The basic study design involved 72 trees, 36 large (diameter at breast height, DBH, >60 cm) and 36 small (DBH 12 – 19 cm). The trees were evenly sampled from randomly chosen areas having a range of tree densities (stems per hectare) established by earlier thinning treatments (Fulé et al. 1999, Skov et al. 2004). We measured plant and soil relative water content and the isotopic signature of water in precipitation, soil, the water conducting system of trees (branch and trunk xylem) in March, June, and August of 2009 and in April of 2010. Paired measurements of water isotopes in precipitation and the water used by trees have provided the opportunity to determine the importance of water inputs during different seasons and received from different atmospheric sources (Flanagan et al. 1992, Lin et al. 1996).

Hydrogen and oxygen stable isotope composition in water were measured using an Off-Axis Integrated Cavity Output Spectroscopy (ICOS) instrument (Los Gatos Research, Los Gatos, CA) at Northern Arizona University's Colorado Plateau Stable Isotope Lab (CPSIL). Precipitation (rain and snow) was collected during each major event. Soil samples were taken from three depths (0-5 cm, 20 - 25 and 40 – 45 cm) during each season and beneath the crown of each of the 72 study trees. Branch segments were collected with a pole pruner from the lower crown on the south side of each tree. Main trunk samples were collected with an increment corer, which also provided samples for planned cellulose oxygen isotope analysis (see below). Water was extracted from soils, branch, and main trunk samples using a cryogenic vacuum line.

Samples collected for analysis of tree ring oxygen isotopes in cellulose are in storage pending analyses to begin fall 2010. These measurements will allow reconstruction of the variation in water source over time in relationship to interannual precipitation variation and in response to thinning. For this analysis we will cross date cores and focus on the last 20 years of growth (ten pre-thinning years and ten post-thinning years).

c. Principal Findings and Significance

A principal finding from this ongoing research is that water isotope composition can be used to track inputs and use of seasonal precipitation in ponderosa pine forests. Figure 1 shows the pattern of hydrogen isotope composition (δD) in precipitation and soil water during late winter (March), late spring (June), and during the summer monsoon season (August). Precipitation inputs shift from highly depleted δD values (c. -100‰) in winter to less depleted values (c. -20‰) in summer, consistent with the different sources of regional moisture and storm temperature. Cold winter storms from the north Pacific are expected to have more depleted δD values than warmer summer rains that originate in the Gulf of Mexico. Soil water carries the isotopic signature of source precipitation, with some enrichment (becoming less negative) as a result of preferential evaporation of lighter isotopes. The deeper soil (40cm) shows little seasonal variation in isotopic composition, remaining around a value (c. -90‰) that reflects the dominant input of winter snow, which melts and infiltrates to recharge deep soils. Shallower soil layers (20 cm and surface) are more variable and generally more enriched (less negative δD values) as a result of evaporative fractionation and because they are influenced by inputs of the isotopically more-enriched summer precipitation. *These results support our hypothesis that during the most active growing season, water at greater depths in the soil profile is derived from winter snow while water at shallower depths is primarily derived from summer rain.*

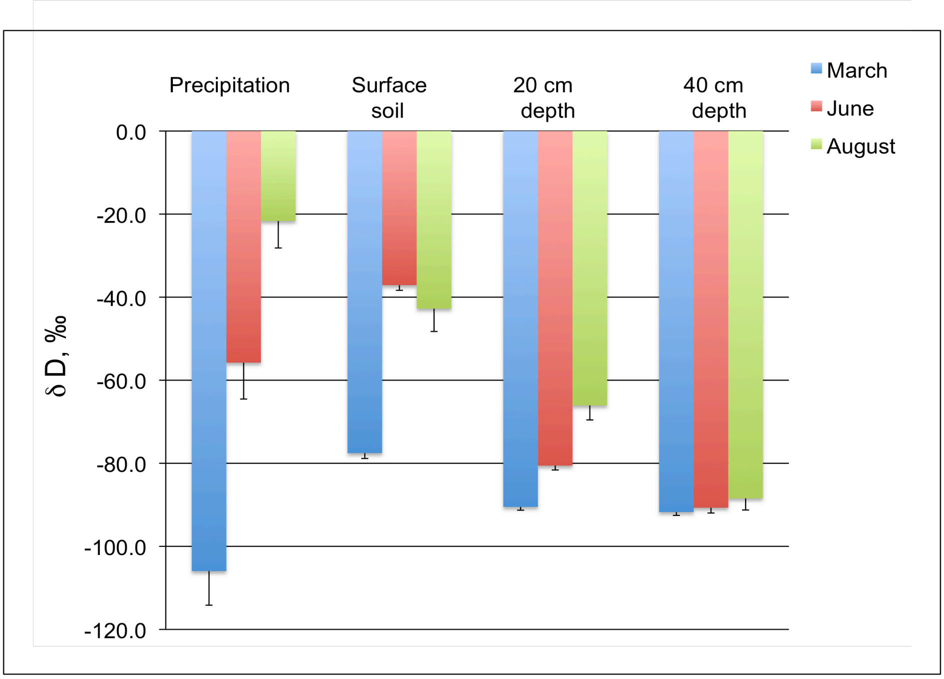

Fig. 1. Variation with depth and season in hydrogen isotope composition of precipitation and soil water during spring, summer and fall at the Ft. Valley ponderosa pine restoration site, northern Arizona. Note that deep soil water (40cm) has a stable isotopic composition while shallower water is more variable and reflects changing precipitation inputs. Values are means (± 1 s.e.) of 40 to 72 samples for each time period and measurement location.

A second principal finding of our research to date is that trees of different size classes (Figure 2) and in stands of different densities (Figure 3) rely primarily on winter rather than summer precipitation. The δD values of water in the conducting tissue (xylem) of trees ranged from about -84‰ to -96‰ across seasons and trees of different sizes (Figure 2A), values reflecting the winter precipitation inputs to deeper soil layers seen in Figure 1. Even during the monsoon season (August), water derived from winter storms is apparently the dominant source for ponderosa pines.

Although winter precipitation clearly dominates water used by ponderosa pine, there was some sensitivity of xylem water δD values to tree size (Figure 2) and the basal area density of neighboring trees (Figure 3). Smaller trees tended to have higher (less negative) δD values, (Figure 2), likely because they are more shallowly rooted and drawing water from intermediate soil layers (c. 20 cm) which have less depleted δD values (Figure 1). Trees in the lowest density stands (< 10 m^2 ha^{-1}) had significantly lower xylem water δD values than trees in all other basal area density classes (Figure 3A). Presumably, at low stand density there is less canopy interception of winter (and summer) precipitation, greater infiltration of precipitation, and less competition for soil water, factors that collectively drive xylem water toward values more similar to winter precipitation. These results are consistent with hypotheses 2, 3, & 4: *2) Soil in thinned stands has greater winter precipitation recharge than soil in unthinned control stands; 3) Thinned P. ponderosa stands rely more heavily on winter precipitation while dense stands rely more on summer precipitation*; *4) Larger ponderosa pines rely more heavily on water deeper in the soil profile than do the smaller ponderosa pines that dominate unthinned stands.* A more thorough test of hypothesis 2 awaits careful analysis of soil moist content, which will complement the soil water isotope data and allow estimation of the dynamics of quantity of water, as well as its source, in different soil layers.

In the very densest stands xylem water δD was more negative than in stands of somewhat lower density, although not the lowest density stands (Figure 3A). We think that these trees in extreme high density conditions may use primarily winter precipitation because the closed canopy structure intercepts spring and summer precipitation, which then evaporates without adding significantly to plant accessible soil water. Thus, trees at very high and very low density may be more reliant on winter precipitation than the intermediate density stands.

Interestingly, the water content (% moisture) of the sapwood of larger trees (Figure 2B) and trees in the lowest density stands (Figure 3B) is *lower* than for smaller trees and trees in higher density stands. Although this could be interpreted as indicative of greater water stress in these trees, this would not be consistent with these trees' apparently greater access to more reliable, winter-derived soil moisture in the deeper soil layers. Instead, our current interpretation of this curious result is that the wood anatomy of these trees is such that smaller diameter conducting cells with a higher cell wall fraction are produced, resulting in lower water content per wood volume.

The mean hydrogen isotope composition (δD) of winter precipitation was -105‰, while summer precipitation averaged about -22‰. These two values provide the end points for a two-member mixing model to resolve the relative contribution of winter and summer precipitation to plants. Development of that model is underway and requires analysis of changes in water isotope composition as precipitation water infiltrates soils and is subject to evaporative enrichment.

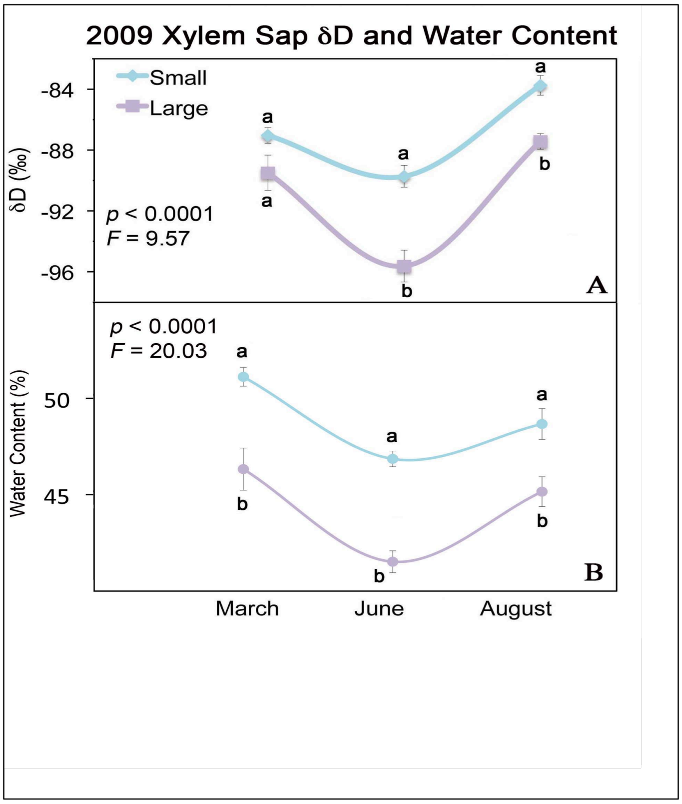

Figure 2. Xylem water hydrogen isotope composition (δD) and water content in large (> 60 cm diameter) and small (12 - 19 cm diameter) ponderosa pine trees at three seasonal sampling periods.

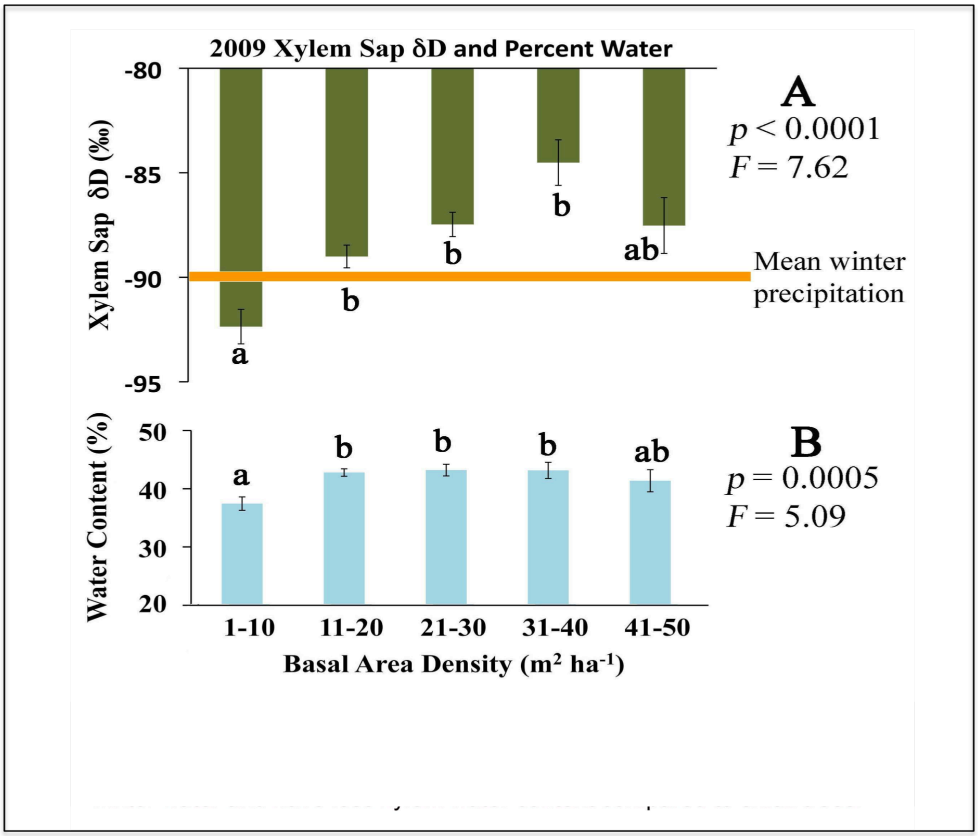

Figure 3. Xylem water hydrogen isotope composition (δD) and water content in ponderosa pine trees in stands of different densities. Note: recent analyses of additional precipitation data indicate that mean δD of winter precipitation averages about -105‰, lower than the c. -90‰ shown.

Significance. A major conclusion from the present study is that ponderosa pine trees in northern Arizona rely primarily on winter precipitation, regardless of the time of year. This implies that future climatic change that affects the amount, form, or timing of winter precipitation may be more influential in driving productivity changes than climatic shifts in summer precipitation. This conclusion is consistent with studies based on correlations between tree-ring growth patterns and climatic variables (e.g. Adams and Kolb, 2004). The stable isotope technique used in the present study has the advantage of definitively identifying the source of water that supports plant transpiration at any point in time. Although summer precipitation may be a minor quantitative source of moisture to ponderosa pine trees, it is important to note that the summer monsoon has a major effect of lessening atmospheric moisture stress by increasing the water vapor concentration of the air. Because vapor pressure deficit is a major influence of stomatal conductance and photosynthesis, the summer monsoon may in fact be critically important to the productivity of ponderosa pines even though it does not directly act as an important water source. In effect, the monsoon, by reducing vapor pressure deficity, likely acts to lessen transpiration rates, allowing higher stomatal conductance and photosynthesis than during periods of lower humidity, such as in the late spring (May, June) pre-monsoon period. Moreover, the monsoon, by providing some soil water input and increasing humidity, also reduces the evaporation of the soil moisture derived from winter inputs. Thus, it is likely not correct to conclude that climatic change that brings less summer precipitation would have little influence over the growth of ponderosa pine.

d. Ongoing Work.

As mentioned, this project is ongoing, with considerable sample processing and data analysis yet to be completed. The analysis of cellulose oxygen isotope composition of tree rings, scheduled to begin fall 2010, will provide important insights to the past use of winter vs. summer precipitation. In combination with standard dendrochronological methods, these measurements will allow testing whether the apparent dependence on winter precipitation is seen consistently across years having different winter vs. summer precipitation.

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