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The influence of thinning on components of stand water balance in a ponderosa pine forest stand during and after extreme drought

K. Simonin [a,b,*], T.E. Kolb [a,b], M. Montes-Helu [a,b], G.W. Koch [b,c]

[a] School of Forestry, Northern Arizona University, Flagstaff, AZ 86011-5018, USA
[b] Merriam Powell Center for Environmental Research, Northern Arizona University, Flagstaff, AZ 86011-5018, USA
[c] Department of Biological Sciences, Northern Arizona University, Flagstaff, AZ 86011-5018, USA

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Abstract

To understand the effect of restoration thinning on the water balance of upland semi-arid ponderosa pine (*Pinus ponderosa*) forests of the southwestern US, we compared the components of forest water balance between an unthinned plot and a thinned plot using a paired water balance approach. Forest overstory transpiration (E_O) was estimated from tree sapflow scaled to the plot level. Understory evapotranspiration (E_U) was estimated from the difference between throughfall precipitation and changes in soil water content measured in trenched plots that excluded tree roots. The thinning treatment in 2001 reduced plot basal area by 82% and leaf area index by 45%. Difference in stand-level evapotranspiration (E) between the thinned and unthinned plots, and partitioning of E between E_U and E_O during the first post-treatment summer and spring, varied between drought and non-drought periods. The importance of E_U in stand-level E was greater in thinned compared with unthinned plots and increased during extreme drought when E_O was low due to stomatal closure. Our results highlight the importance of drought and climate as factors determining the impact of thinning on water balance in southwestern ponderosa pine forests.

Keywords: Arizona; Evapotranspiration; Forest management; *Pinus ponderosa*; Transpiration

1. Introduction

Forest uplands dominated by ponderosa pine (*Pinus ponderosa*) occur in the headwaters of most watersheds in the western US. These forests provide an important link in watershed-atmosphere interactions and supply approximately 70–90% of annual stream flow in the western US (Troendle, 1983). In contrast to the high tree density of current ponderosa pine forests of the southwestern US, prior to Euro-American settlement in the mid-1880s these forests were characterized by a low tree density and a well-developed herbaceous understory (e.g., Moore et al., 1999). Fire exclusion, high seedling recruitment, heavy grazing, and other factors have led to increased tree density and decreased herbaceous vegetation over the last century (Savage et al., 1996; Covington et al., 1997).

Thinning to reduce tree density is one of the most common approaches proposed for restoration of southwestern watersheds and understory plant communities (Covington et al., 1997; Allen et al., 2002). The effect of stand density on water yield has been investigated in numerous studies for riparian and lowland forests in mesic environments (Bosch and Hewlett, 1982; Stednick, 1996), but fewer studies have been performed in upland forests in arid and semi-arid environments

* Corresponding author at: Department of Integrative Biology, University of California Berkeley, Valley Life Sciences Building, CA 94720-3140, USA. Tel.: +1 510 642 1054.
E-mail address: ksimonin@berkeley.edu (K. Simonin).

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(Huxman et al., 2005). Semi-arid forest landscapes, such as the ponderosa pine forests of northern Arizona, represent regions where potential evapotranspiration far exceeds precipitation. As such, surface runoff (R) and drainage (D) are generally considered minor components of site water balance for most of the hydrologic year (Kaye et al., 1999; Huxman et al., 2005). However, changes in vegetation cover may affect site water balance by influencing the relative contributions of plant transpiration and soil evaporation to total ecosystem evapotranspiration (E). For example, plants generally increase the depth to which soil water contributes to both understory evaporation (E_U) and overstory transpiration (E_O) (Dawson, 1996), and at the same time alter soil surface energy budgets and thus overall rates of soil evaporation (Breshears et al., 1998).

The influence of tree thinning on ponderosa pine forest water balance in the southwestern US has been addressed for R (Baker, 1986) and snowpack depth (Ffolliott et al., 1989). In addition, D has been predicted using an ecosystem model for a ponderosa pine stand treated with thinning and prescribed burning to produce a stand structure similar to the pre-Euro-American settlement condition (Kaye et al., 1999). These studies suggest that thinning increases water yield during the late winter and early spring months. However, understanding the relative contribution of individual flux components, such as E_U and E_O, to the water budget of ponderosa pine forests in semiarid regions remains limited. Hydrologic fluxes contributing to forest water balance can be described by:

$$\Delta\mathrm{SWS} = P_T - R - D - E \quad (1)$$

where ΔSWS is the change in soil water storage within the rooting zone, P_T the throughfall precipitation, R the surface runoff, D the drainage, and E is total evapotranspiration (Chapin III et al., 2002). The partitioning of forest stand P_T between R, D and E directly influences regional hydrologic cycles. For example, E returning to the atmosphere may support future precipitation events and influence canopy gas exchange through a boundary layer feedback (Jarvis and McNaughton, 1986; Chapin III et al., 2002), whereas R and D contribute directly to water yield of streams and springs (Bosch and Hewlett, 1982; Baker, 1986).

This study examines how heavy tree thinning affects forest stand water balance and its components in a dense, upland, ponderosa pine forest in northern Arizona for one and two years after thinning using a paired water balance approach. Based on studies in mesic environments, as forest leaf area decreases E should also decrease because of the dominant role of tree transpiration in stand E (Running and Coughlan, 1988; Granier et al., 1996, 2000; Kergoat, 1998; Waring and Running, 1998). However, predicting the effect of thinning on E for upland semi-arid ponderosa pine forests is complicated by: (1) potentially large rates of soil evaporation in site water balance (Kurpius et al., 2003), (2) the amount of stimulation of transpiration of understory plants and overstory trees, and (3) the influence of overstory leaf area on radiation and precipitation interception (Loshali and Singh, 1992; Naumburg and DeWald, 1999; Stogsdill et al., 1989; Simioni et al., 2003). Because potential E greatly exceeds actual E in semiarid regions we hypothesized that thinning would increase both stand-level E and temporal changes in SWC because the reduction in stand leaf area would be over-compensated by greater throughfall precipitation, greater soil moisture availability for plant transpiration, and greater radiant energy at the soil surface to drive soil evaporation.

2. Methods

2.1. Study site

Our study site was a dense (stand basal area = 77.7 ± 5.8 m^2 ha^{-1}, tree density = 3953 ± 517 trees ha^{-1}) multi-cohort *P. ponderosa* forest (Table 1) located approximately 7 km southwest of Flagstaff, Arizona, at an elevation 2080 m, in the Northern Arizona University Centennial Forest. The understory herbaceous community dominated by, *Festuca arizonica, Elymus alymoides*, and *Bouteloua gracilis*. The most common soil types for the study site area are: (1) Typic Argiborolls, fine montmorillonitic, deep gravelly loam and (2) Mollic Eutroboralfs, clayey-skeletal, montmorillonitic, moderately deep cobbly loam (Miller et al., 1995). Annual precipitation in Flagstaff averages 542 mm and commonly occurs as approximately equal amounts of winter snow and late summer (July–September) rain (Sheppard et al., 2002, National Climatic Data Center). In 2002, an extreme drought

Table 1
Ring counts by classes of diameter at breast height (DBH) for trees destructively harvested for whole tree leaf area suggest a multi-cohort tree age structure at the study site

DBH (m)	Ring count	S.E.
<0.10	37	3
0.16–0.20	67	1
0.21–0.25	59	2
0.26–0.30	69	1
0.31–0.35	70	1

S.E. = 1 standard error.