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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

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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

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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 $\mathrm{m^2\ ha^{-1}}$, tree density = 3953 ± 517 trees $\mathrm{ha^{-1}}$) 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.

occurred in northern Arizona; total precipitation 12 months prior to August 2002 was the lowest in recorded history and 52% below the 1950–2000 average (National Climatic Data Center).

The effect of stand thinning on forest stand water balance was evaluated using a paired water balance comparison of two adjacent plots within a 0.154 ha stand. Similarity between plots was investigated in 2001 prior to the thinning treatment. First, basal area (A_B) was measured for each plot in four circular 0.0078 ha sub-plots by measuring the A_B of every tree in the sub-plots. Second, volumetric soil water content within the first 15 cm of mineral soil was compared between plots ($n = 10$) on July 19 and August 4, 2001, using time domain reflectometry (Soilmoisture Equipment Corp., Santa Barbara, CA), by randomly assigning five sample sites along two transects. Third, herbaceous cover was estimated in 20 subplots per treatment using a 1 m^2 grid composed of 100, 10 cm^2 cells. Herbaceous cover was estimated on August 3, 2001 and September 26, 2003, before and after thinning.

2.2. Thinning treatment

One randomly selected plot was thinned between August 6–9, 2001, following guidelines that emphasized leaving the largest diameter trees in an even spacing in order to reduce fire hazard. Thinning reduced stand A_B by 82% and leaf area index (LAI) by about 45%. LAI of the unthinned plot was 1.30 $m^2\ m^{-2}$ compared to 0.71 $m^2\ m^{-2}$ for the thinned plot. LAI was estimated from allometric relationship between tree DBH and whole-tree projected leaf area derived on site during the thinning treatment (see Section 2.3 below). Basal area was about evenly distributed among DBH classes greater than 0.05 m in the unthinned plot, whereas about 50% of the A_B in the thinned plot was in the 0.31–0.35 m DBH size class after thinning (Fig. 1). The thinned and unthinned plots were 869 and 633 m^2, respectively, and separated by a skid trail. We recognize that both plots were relatively small and thus our water balance evaluation may suffer from edge effects.

2.3. Leaf and sapwood areas

Whole-tree projected leaf area (A_L) was measured on the full range of tree sizes (0.056–0.325 m DBH) at both plots in August 2001. Leaves were collected from the entire crown of each tree, dried (70 °C until weight stabilized), and weighed. Prior to drying, projected leaf area was measured (Agvis Imaging System, Decagon Devices, Pullman, WA) on a random sub-sample of leaves from each tree to calculate specific leaf area (SLA, $m^2\ g^{-1}$). Whole-tree A_L (m^2) was the product of SLA and total leaf dry weight (g). We predicted A_L of all trees in the plots with a linear regression between DBH and crown A_L ($r^2 = 0.95$, Simonin et al., 2006).

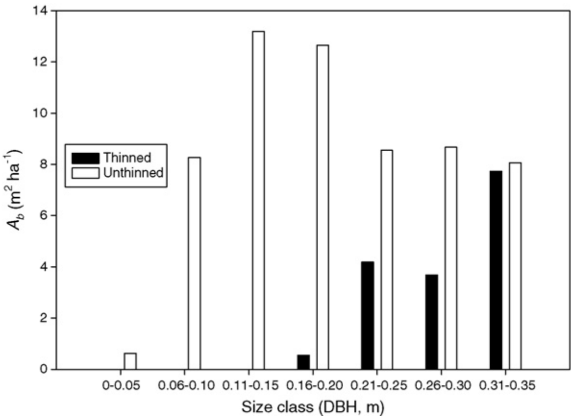

Fig. 1. Basal area (A_B) distribution among tree diameter classes (DBH) for thinned and unthinned plots.

Sapwood area (A_S) at breast height (1.3 m above ground) was measured on the same 11 trees sampled for whole-tree leaf area. A cross-section of the bole was removed at breast height, sapwood was distinguished from heartwood visually though natural changes in wood color, and bromocerol green stain was used to confirm visual determination (Kutscha and Sachs, 1962). Diameter of sapwood was measured at four locations on each cross section, and used to calculate A_S. We predicted A_S for all trees in the plots based on a linear regression between A_S and DBH ($r^2 = 0.98$, Simonin et al., 2006).

2.4. Soil water content

Volumetric soil water content during the 2002 growing season and spring of 2003 was measured in both plots using time domain reflectometry (TDR, Soilmoisture Equipment Corp., Santa Barbara, CA), and converted to a linear value (θ, mm). θ was measured at the end of May, June, July, August, September, and October 2002, at 10 random locations (five in each plot).

In the spring of 2003 we expanded our sampling of θ in the thinned plot by an additional five locations intentionally placed in canopy gaps in order to sample over greater variation in understory herbaceous growth and overstory canopy cover. We compared mean monthly θ within the first 30 cm of soil between the original five random locations and the five additional locations to determine if the original sampling design provided an accurate measure of θ. We found no significant location ($p = 0.85$) nor time × location ($p = 0.26$) effects on mean monthly θ between May 28 and August 24, 2003. Therefore, we concluded that our original sampling design provided an accurate measure of θ in the thinned plot in both years of the study.

2.5. Local water balance

We adjusted the water balance model Eq. (1) to the conditions of our study site: (1) R was not considered because both thinned and unthinned plots had low slope ($<10\%$) and we did not observe runoff after rains, (2) D was not considered as hydrological models of southwestern ponderosa pine forests suggest no D during summer months (Kaye et al., 1999). Furthermore, soil water content at the study site was well below field capacity for most of the duration of our study. Field capacity was $0.335 \pm 0.008\ \mathrm{m^3\ water\ m^{-3}}$ soil, or 100 mm for the first 30 cm soil depth, based on direct measurements of θ in replicated ($n = 4$) locations in a $0.5\ \mathrm{m^2}$ plot 48 h after slow saturation of soil 80 L of water (Cassel and Nielsen, 1986). θ at the study site was less than 100 mm in the top 30 cm of soil for the duration of our study except for one measurement in March, 2003, when $\theta = 100$ mm (Simonin et al., 2006). Therefore, our local water balance model for the entire soil profile was:

$$\Delta \mathrm{SWS} = P_\mathrm{T} - E_\mathrm{U} - E_\mathrm{O} \tag{2}$$

where E_U is understory evapotranspiration (mm), and E_O is overstory (tree) transpiration (mm). Because we were interested in ΔSWS over the entire soil profile that supports plant roots, we did not estimate ΔSWS by temporal changes in θ because θ was measured only to a depth of 30 cm, and tree roots were deeper than 30 cm. We compared ΔSWS between the thinned and unthinned plots during three periods when P_T, E_U and E_O were measured concurrently: July 26–August 1, 2002, during a period of low precipitation and high VPD, August 2–13, 2002, during a period of high precipitation from summer rains and moderate VPD, and May 10–June 1, 2003, during a period of high θ produced by late winter precipitation and low VPD. Although E_U and P_T were monitored during other portions of the growing season we were unable to compare water balance components over a broader range of seasonal moisture conditions due to power failure with the sap flux system. Gaussian error propagation was used to estimate mean and standard error for ΔSWS.

2.6. Water balance inputs and outputs

2.6.1. Precipitation throughfall, P_T

We captured P_T in each plot using 10, 1 L plastic bottles with 10 cm diameter funnels. Bottles were placed 1 m from locations used to measure θ and were evenly distributed over open spaces and areas beneath tree canopies. A small volume of mineral oil was put into the plastic bottle to prevent losses due to evaporation. The volume of collected precipitation was measured with a graduated cylinder and volumes were converted to a linear amount (mm). Throughfall was measured within two days of rainfall events. Stemflow was not considered in the calculation of P_T for two reasons: (1) rainfall intensity was low averaging $2.0\ \mathrm{mm\ h^{-1}}$ and (2) rainfall duration was generally less than 3 h. The longest rainfall was a 7 h event that occurred outside the time period when site water balance was evaluated.

2.6.2. Understory evapotranspiration, E_U

We estimated E_U, which includes transpiration of understory herbaceous plants and soil evaporation, by measuring changes in soil water content within the first 30 cm of soil in areas where tree roots were excluded. Observations from soil pits at the study site showed that roots of herbaceous plants occurred in the top 30 cm of soil. A circular (2 m diameter) trench was dug to a depth of 30 cm. Inside the trench we buried a 30 cm tall aluminum ring to exclude tree roots. Two pairs of TDR rods were installed vertically to depths of 15 and 30 cm in the center of the trenched plot. With tree roots excluded, ΔSWS was equal to $P_\mathrm{T} - E_\mathrm{U}$. As such, E_U from the first 30 cm of soil for the thinned and unthinned plots was estimated using the following equation:

$$\bar{\theta}_i + \bar{P}_\mathrm{T} - \bar{\theta}_\mathrm{f} = E_\mathrm{U} \tag{3}$$

where $\bar{\theta}_i$ and $\bar{\theta}_\mathrm{f}$ are the mean initial and final θ in the trenched plots for a measurement period, respectively, and $\bar{P}_\mathrm{T}$ is the mean throughfall precipitation. θ was measured weekly between July 26 and August 13, 2002 (every 5–7 days) and three times between May 10 and 28, 2003 (every 8–9 days) at 0–15, 15–30 and 0–30 cm soil depths. Gaussian error propagation was used to estimate mean and standard error for E_U.

2.6.3. Overstory transpiration, E_O

Whole-tree sap flux was measured using Granier-type heat dissipation sensors (Granier, 1985,1987) at two depths (0–2 and 2–4 cm) and two aspects (north and south) in the sapwood. A pair of heated and unheated thermocouple junctions (TC) housed in 2 cm long × 1.63 mm diameter stainless steel hypodermic needles (0–2 cm sensor depth) and 4 cm long × 1.63 mm diameter hypodermic needles (2–4 cm sensor depth) was inserted radially in the sapwood. Sensors were placed 10 cm apart vertically on the bole at 1.3 m above the ground. The downstream TC junction was heated by a 2 cm long 29–33 Ω heating coil at 0.2 W (Granier, 1985). The upstream TC junction was unheated and served as a reference. A power regulator was used at each sap flux tree to insure delivery of 0.2 W of power for each sensor. To minimize thermal gradients, sensors were insulated with reflective insulation wrapped around the circumference of the tree. Sensors were powered by 12 V batteries recharged by solar panels.

We measured sap flux on two trees in each of the 5 cm DBH classes found in the unthinned (0.01–0.05, 0.06–0.10, 0.11–0.15, 0.16–0.20, 0.21–0.25, 0.26–0.30, and 0.31–0.35 m) and thinned plots (0.16–0.20, 0.21–0.25, 0.26–0.30, and 0.31–0.35 m). Two depths and two aspects were sampled in trees with a DBH greater than 15 cm to account for radial and azmuthal variation in sap flux (Phillips et al., 1996; Lu et al., 2000; Fischer et al., 2002). Trees in the 0.11–0.15 m DBH class were instrumented with sensors at two depths (0–2 and 2–4 cm) on the north aspect only. Trees <0.11 m in DBH were instrumented with a single sensor (0–2 cm depth) on the north aspect only. Voltage produced by TC junctions was measured by CR10X dataloggers and AM416 multiplexers (Campbell Scientific Inc.). Leads from the sap flux probes were connected in a single-ended fashion with measurements taken every 30 s and averaged every 15 min. The 15-min averages were recorded as a temperature difference between the heated and unheated junction. Using an empirical relationship developed by Granier (1985,1987), sap flux (F_s, mm H_2O m^{-2} sapwood s^{-1}) at the two probe depths was calculated using the temperature difference between the heated and unheated probes. The 2 cm sensor measured F_s across the 0–2 cm xylem depth. The 4 cm sensor measured F_s across the 2–4 cm xylem depth.

Post-treatment sapflow data were collected July 26–30, 2002 (minimum and maximum air temperature 11.1 and 29.6 °C, respectively; minimum and maximum vapor pressure deficit (VPD) 0.12 and 4.42 kPa, respectively) at the end of an extreme drought characterized by four continuous months of low tree Ψ_{pre} (<-1.2 MPa with minimum of -2.0 MPa, Simonin et al., 2006), and August 8–10, 2002 (minimum and maximum air temperature 8.0 and 30.9 °C, respectively; minimum and maximum VPD 0.26 and 3.92 kPa, respectively), which occurred after the start of late-summer rains that increased tree Ψ_{pre} to between -1.6 and -1.0 MPa (Simonin et al., 2006). Sapflow data also were collected the following spring, May 12–23, 2003 (minimum and maximum temperature -4.4 and 19.3 °C, respectively; minimum and maximum VPD 0.02 and 1.97 kPa, respectively), after winter recharge of soil water when tree Ψ_{pre} was very high (-0.4 MPa, Simonin et al., 2006).

To determine plot-level transpiration of trees (E_O, mm day^{-1}), we applied 15-min average F_s for each tree DBH class to the total sapwood area per DBH class for the entire stand using the following equation:

$$E_O = \sum_{i=7,4} (\bar{F}_{0-2} \times A_{S0-2} + \bar{F}_{2-4} \times A_{S2-\text{heartwood}}) \quad (4)$$

where i represents the seven DBH classes in the unthinned plot and the four classes in the thinned plot, F_{0-2} and F_{2-4} are the mean 15-min sap-flux densities over N and S aspects at the 0–2 and 2–4 cm sensor depths summed over a 24 h period, respectively, and A_{S0-2} and $A_{S2-\text{heartwood}}$ are the total sapwood areas (m^2) corresponding with the 0–2 and 2–4 cm sensor depths, respectively, for each DBH class. Daily mean E_O was used for days when E_O was not measured (due to instrument power failure). This gap-filling approach was used for 21 days over the entire study.

Our measurements of whole-tree transpiration are based on the assumption that sap flux beyond the 4 cm depth was uniform and equal to flux at the 2–4 cm depth. For most tree size classes the first 4 cm of sapwood represented >60% of the total sapwood. Furthermore, because sapwood of trees in both plots formed under similar environmental conditions prior to thinning, we assumed a functionally similar radial profile of variation in sap flux for trees in each plot. We did not test this assumption and acknowledge the potential for diurnal variations in the contribution of deep sapwood to whole-tree sap-flux as previously shown for *Pinus* species (Ford et al., 2004).

3. Results

3.1. Pretreatment

Prior to thinning, there was no significant difference in A_B between the thinned and unthinned plot (Simonin et al., 2006). Soil water content was almost identical between thinned and unthinned plots prior to treatment with no significant difference between tree predawn water potential between the two plots (Simonin et al., 2006). Herbaceous cover was slightly higher in the thinned plot (11%) compared to the unthinned plot (2%). Overall, the results of our pretreatment comparisons indicate similar tree density, soil water content, and herbaceous cover at both plots prior to thinning, which is not surprising considering that both plots were part of the same small stand.

3.2. P_T and soil water content

Thinning consistently increased P_T during periods of high P_T in both 2002 and 2003 (Fig. 2). In 2002, θ at 0–30 cm was consistently greater in the thinned compared with the unthinned plot (Fig. 3A), with larger differences at 15–30 cm below the soil surface (Fig. 3C) than 0–15 cm below the soil surface (Fig. 3B). In 2003, thinning had little effect on θ (Fig. 3A–C).

3.3. ET_U

In plots where tree roots were trenched, θ in 2002 was lower in the thinned compared with the unthinned plot (Fig. 4A), and the difference was caused by lower θ at 15–30 cm (Fig. 4C), not 0–15 cm (Fig. 4B). The same pattern occurred in 2003 at 0–30 cm (Fig. 4D), but the difference was largely caused by lower θ in the thinned plot at the 0–15 cm depth (Fig. 4E), not at 15–30 cm (Fig. 4F). When $\Delta\theta$ was combined with P_T values in Eq. (3), E_U in the thinned plot was nearly three times greater than E_U in the unthinned plot between July 26 and August 1, 2002, 45% greater between August 2 and August 13, 2002, and 32% greater between May 10 and June 1, 2003 (Table 2).

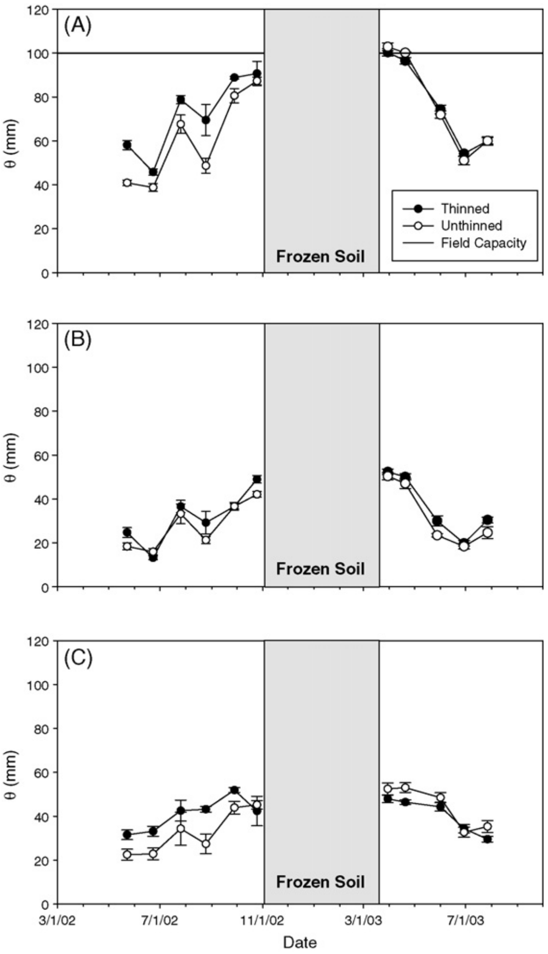

Fig. 3. Mean monthly soil moisture content (θ) in 2002 and 2003 for thinned and unthinned plots at: (A) 0–30 cm, (B) 0–15 cm, and (C) 15–30 cm below soil surface. Bars show 1 S.E.

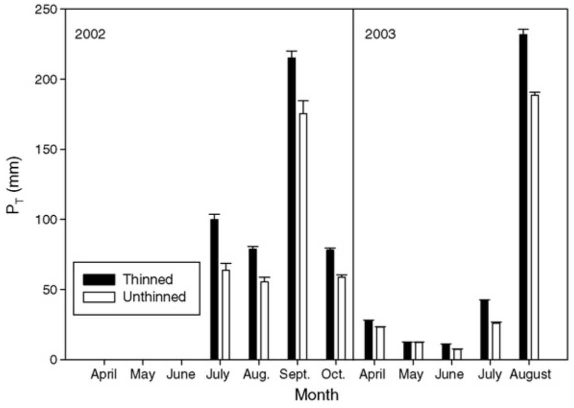

Fig. 2. Monthly throughfall precipitation (P_T) in thinned and unthinned plots from April to October 2002 and April to August 2003. Bars show 1 S.E.

3.4. E_O

Thinning increased individual-tree transpiration for all tree size classes during most measurement periods (Simonin et al., 2006). When transpiration was scaled to the plot level, thinning decreased E_O by 28% for July 26–30, 2002 (0.40 and 0.29 mm day^{-1}, respectively, unthinned and thinned) and by 51% for May 12–23, 2003 (3.9 and 1.9 mm day^{-1}, respectively). However, E_O was 53% greater in the thinned plot than the unthinned plot for August 8–13, 2002 (1.1 and 0.72 mm day^{-1}, respectively).

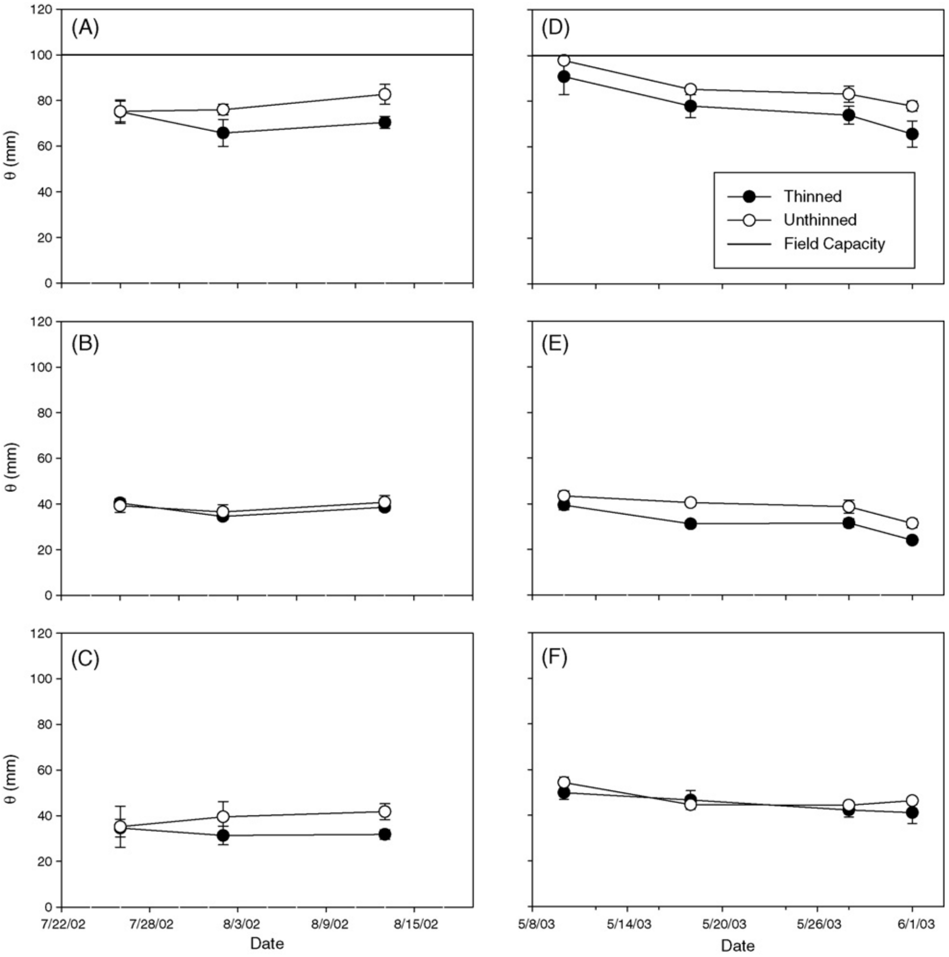

Fig. 4. Mean soil moisture content (θ) at tree-root trenched sites for thinned and unthinned plots from July 26 to August 13, 2002 (A–C) and from May 10 to June 1, 2003 (D–F) at 0–30 cm (A and D), 0–15 cm (B and E), and 15–30 cm (C and F) below the soil surface. Bars show 1 S.E.

3.5. ΔSWS

When plot-level values of E_U, P_T, and E_O were used in Eq. (2), *SWS* decreased more in the thinned plot than the unthinned plot between July 26–August 1, 2002, and August 2–13, 2002 (Table 3). In contrast, SWS decreased more in the unthinned plot than the thinned plot between May 10 and June 1, 2003 (Table 3).

Table 2
Understory evapotranspiration (E_U) calculated using Eq. (3) ($\bar{\theta}_i + \bar{P}_T - \bar{\theta}_f = E_U$) during periods of low, moderate, and high soil moisture

	θ_i (mm)	P_T (mm)	θ_f (mm)	E_U (mm)	E_U (mm/day)
Low soil moisture (July 26–August 1, 2002)					
Thinned	75.1 ± 5.1	15.4 ± 0.32	65.8 ± 5.9	24.7 ± 7.8	3.5
Unthinned	75.2 ± 5.2	9.1 ± 0.62	76.0 ± 2.3	8.3 ± 6.1	1.2
Moderate soil moisture (August 2–August 13, 2002)					
Thinned	65.8 ± 5.9	40.3 ± 0.96	70.4 ± 2.6	35.7 ± 6.5	3.2
Unthinned	76.0 ± 2.3	31.1 ± 2.2	82.7 ± 5.8	24.4 ± 6.6	2.2
High soil moisture (May 10–June 1, 2003)					
Thinned	90.7 ± 9.8	10.9 ± 0.27	65.6 ± 9.0	36.1 ± 13.4	1.7
Unthinned	97.8 ± 2.4	7.2 ± 0.81	77.8 ± 4.8	27.2 ± 7.4	1.3

Where P_T, throughfall precipitation and θ_i, initial soil water content, and θ_f, final soil water content. All values are means ± standard error.

Table 3
Change in soil water storage (ΔSWS) calculated with Eq. (2) ($\Delta SWS = P_T - E_U - E_O$) for thinned and unthinned plots the first post treatment summer during periods of low (July 26–August 1, 2002) and moderate (August 2–13, 2002) soil water content and the following wet spring (May 10–June 1, 2003)

	P_T (mm)	E_U (mm)	E_O (mm)	ΔSWS (mm)
July 26–August 1, 2002				
Thinned	15.4 ± 0.29	24.7 ± 7.8	2.1 ± 0.13	−11.4 ± 8
Unthinned	9.1 ± 0.79	8.3 ± 6.1	2.8 ± 0.21	−2.0 ± 6
August 2–13, 2002				
Thinned	40.3 ± 0.96	35.7 ± 6.5	12.1 ± 0.55	−7.5 ± 7
Unthinned	31.1 ± 2.2	24.4 ± 6.6	7.9 ± 0.46	−1.2 ± 7
May 10–June 1, 2003				
Thinned	10.9 ± 1.7	36.1 ± 13.1	43.7 ± 2.5	−68.9
Unthinned	7.2 ± 5.1	27.2 ± 5.4	89.7 ± 4.14	−109.7

Where P_T, throughfall precipitation and E_U, evapotranspiration and E_O, overstory transpiration. All values are means ± standard error.

3.6. Herbaceous cover

Herbaceous cover was low prior to thinning in both the thinned and unthinned plots, 11 and 2.4%, respectively. At the end of the second post-treatment growing season (September 25, 2003) herbaceous cover had increased to 28.5% in the thinned plot and to 7.2% in the unthinned plot.

4. Discussion

4.1. Effect of thinning on water balance

4.1.1. P_T and θ response to thinning

The effect of the thinning that occurred in late summer 2001 on soil θ varied between 2002 and 2003. Forest canopy interception was a high percentage of gross annual rainfall as thinning increased P_T by an average of 33% during summer and fall 2002 (July–October) and 20% during spring 2003 (April–June). Elevated P_T in the thinned plot contributed to increased θ at the 0–30 cm soil depth above θ in the unthinned plot between July and September, 2002 (Fig. 3A–C). For the remainder of the study (October 2002–August 2003), θ was similar in thinned and unthinned plots because higher P_T and lower stand-level E_O in the thinned plot was compensated by higher E_U (Fig. 3, Table 2).

4.1.2. E_U response to thinning

Several factors may have contributed to greater E_U in the thinned plot compared to the unthinned plot. First, soil evaporation was likely greater in the thinned plot. Soil evaporation occurs in two stages: (1) the constant-rate stage controlled by energy input as influenced by light penetration through the canopy, atmospheric turbulence, and soil albedo, and (2) the falling rate stage controlled by overall soil moisture and hydraulics (Suleimann and Ritchie, 2003). As such, direct evaporation from soil is generally constrained to upper soil layers (Saravanapavan and Salvucci, 2000; Suleimann and Ritchie, 2003) and is highest in open sites, because shade from overstory canopy cover and forest floor litter reduces light penetration (Morecroft et al., 1998) and soil temperature (Scholes and Archer, 1997). Thinning of southwestern ponderosa pine forests increases light penetration to the forest floor (Naumburg and DeWald, 1999; Meyer et al., 2001) resulting in higher soil temperature (Covington et al., 1997) and increased throughfall precipitation (this study) all of which contribute to greater potential soil evaporation. A recent study of stand water balance in a ponderosa pine plantation in California (Kurpius et al., 2003), where soil evaporation accounted for about 50% of stand E during summer and fall, supports our interpretation that thinning increased evaporation of soil water.

A second likely component of higher E_U in the thinned plot compared to the unthinned plot was greater transpiration by herbaceous plants. Greater light intensity and greater P_T that follow thinning have been shown to increase growth, and thus water use, of herbaceous plants in southwestern ponderosa pine forests (Moore and Deiter, 1992; Moore et al., 2006). In our study, herbaceous cover increased more between 2002 and 2003 in the thinned plot (11–29%) than in the unthinned plot (2–11%). Also, diurnal changes in VPD and temperature reported in the understory of thinned southwestern ponderosa pine stands (Meyer et al., 2001) suggest considerable E_U, as light energy is converted to latent heat energy.

Our assumption of no drainage may have affected our estimate of E_U in spring 2003 when θ reached field capacity (March, 2003). However, we measured higher

E_U in the thinned compared with the unthinned plot in 2002 when θ was low and drainage did not occur and in 2003 when θ was high, suggesting higher E_U in the thinned plot regardless of variation in θ.

4.1.3. E_O response to thinning

The effect of thinning on stand-level E_O in 2002 was not easily predictable from differences in overstory canopy leaf area between the thinned and unthinned plots, and is not consistent with most previous studies that have reported a positive relationship between stand-level E_O and stand leaf area (Breda and Granier, 1996; Granier et al., 1996; Santiago et al., 2000). Between July 26 and August 13, 2002, which followed the most severe drought in the recorded history of northern Arizona, stand-level E_O was 3.5 mm higher in the thinned plot despite the decrease in canopy leaf area. This result occurred because lower overstory canopy leaf area in the thinned plot was overcompensated by higher leaf-level transpiration compared with the unthinned plot (Simonin et al., 2006). Higher leaf-level transpiration in the thinned plot likely resulted from several factors, including higher soil θ because of higher P_T, higher canopy exposure to sun (Jarvis and McNaughton, 1986; Jones, 1992), and perhaps less stomatal sensitivity to high VPD in the thinned plot because of higher θ (Goldstein et al., 2000). Also, water stress during the severe drought of 2002 may have cavitated xylem more for trees in the unthinned compared with the thinned plot. Predawn Ψ of trees in the unthinned plot was consistently lower than for trees in the thinned plot during the 2002 drought, -1.9 and -1.5 MPa, respectively (Simonin et al., 2006), and approached levels known to cavitate ponderosa pine xylem (Piñol and Sala, 2000).

In contrast to 2002, our results for E_O in 2003 are consistent with most previous studies (Breda and Granier, 1996; Granier et al., 1996; Santiago et al., 2000). The effect of thinning on E_O in spring 2003 after substantial winter recharge of θ was directly related to differences in tree leaf area between thinned and unthinned plots. Between May 10 and June 1, 2003, E_O was 46 mm, or 105%, greater in the unthinned plot which had much greater overstory canopy leaf area than the thinned plot. Cavitation of xylem that might have occurred in the unthinned plot during the 2002 drought was likely gone as cavitation in conifer xylem is often reversed after wet winters (Sperry et al., 1994). Moreover, soil θ was similar in thinned and unthinned plots in 2003, thus differences in leaf-level transpiration between plots were smaller in 2003 than 2002 (Simonin et al., 2006) as leaf-level transpiration and stomatal conductance of ponderosa pine are negatively affected by low soil water availability (Goldstein et al., 2000; Kolb and Stone, 2000; Simonin et al., 2006).

4.2. Components of E

The effect of thinning on the partitioning of stand water flux between E_U and E_O varied with soil θ and E_O. When soil θ and E_O were low following extreme drought (July 26–August 1, 2002), E_U was 92% of stand-level E in the thinned plot, and 75% in the unthinned plot (Table 3). When θ and E_O were higher after the onset of monsoon rains (August 2–13, 2002), E_U was 75% of stand-level E in both the thinned and unthinned plots due to a relative increase in E_O in the thinned plot (Table 3). In spring 2003 (May 10–June 1) when E_O was again high because of recharge of θ from winter P_T, E_U was 45% of stand-level E in the thinned plot and 23% in the unthinned plot (Table 3). Thus, the importance of E_U in stand-level water flux was greater in thinned compared with unthinned plots and increased during extreme drought when E_O was low due to stomatal closure.

4.3. Effect of thinning on ΔSWS

Our results suggest no recharge of water into soil below the rooting zone or to ground water during the periods when concurrent measurements of P_T, E_O, and E_U allowed estimation of ΔSWS (July–August 2002, May–June 2003). During these periods, ΔSWS was negative in both thinned and unthinned plots, which indicates that water flux from the forest by E_O and E_U exceeded inputs from P_T. This interpretation suggests that the higher soil θ at the 0–30 cm soil depth in the thinned compared with the unthinned plot in July–September 2002 did not result in more movement of water below the rooting zone. We know from observations in two soil pits at the study site that tree roots occurred at least 80 cm deep. Thus, the higher soil θ at the 0–30 cm depth in 2002 in the thinned plot compared to the unthinned plot likely was captured and transpired by tree roots that occurred deeper than 30 cm. Overall, our results are consistent with the results of a modeling analysis which concluded that positive effects of heavy thinning on water outflow from ponderosa pine forests occur only in wet winters (Kaye et al., 1999).

5. Conclusion

The results of our paired water balance experiment, models of water outflow after thinning (Kaye et al., 1999), and comparisons of surface runoff in watershed experiments (Baker, 1986) all suggest that effects of thinning on water outflow from ponderosa pine forests in northern Arizona depend heavily on climatic conditions and time since thinning because these factors influence the magnitude of differences in P_T, E_O, and E_U between thinned and unthinned stands. Our results and a recent water balance study of a ponderosa pine plantation in California (Kurpius et al., 2003) show a substantial contribution of E_U to stand-level E that under extremely dry conditions can compensate for lower stand-level E_O in thinned stands. Clearly, effects of stand thinning on water balance components in southwestern ponderosa pine forests cannot be easily predicted solely from differences in tree leaf area. Future research should address how stands with similar leaf area but different canopy structure influence site water balance. Differences in the structural organization of overstory canopy leaf area may influence the partitioning of water outflow between E_U and E_O due to its affect on soil moisture availability and light transmittance to the understory as seen in other conifer forests (Roberts, 1983; Oker-Blom and Kellomaki, 1983; Van Pelt and Franklin, 2000; Law et al., 2001).

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