

Short-term selective thinning effects on hydraulic functionality of a temperate pine forest in eastern Canada

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Abstract

Forest plantations are commonly used to restore the ecological and hydrological functionality of landscapes. In this study, we investigated the hydrologic response of a 74-year old pine plantation forest in southern Ontario, Canada to a selective thinning, wherein 30% of trees were harvested in winter of 2012. Tree-level and ecosystem-level water fluxes were monitored from 2011 to 2013 using sapflow and eddy-covariance techniques, and were compared with an adjacent 39-year old pine plantation forest that was not thinned. In the 74-year-old forest, transpiration declined after thinning in the 2012 growing season, while tree-level water transport increased despite a severe drought. Time lag between sapflow and ecosystem evapotranspiration showed that the older stand had a significantly shorter time lag when compared to younger stand, particularly in the thinning year. Linear regression modeling indicated this was likely due to higher soil moisture status in the older stand versus the younger forest. Hydraulic redistribution of soil water was apparent during drought periods in both forests, and did not appear to be negatively affected by the thinning treatment in the older forest. We conclude that selective low density thinning did not negatively impact the forest's response to seasonal drought, and that the availability of more soil moisture as a result of thinning may improve the resilience of the forest to future climatic extreme events such as drought.

Introduction

Reforestation and afforestation have become increasingly common in North America. Lands cleared for timber or agricultural use, then repurposed for forest plantations, have been recognized as integral carbon sinks and local weather and soil erosion moderators (Restrepo & Arain, 2005; Nilsen & Strand, 2008; Saunders *et al.*, 2012). Once the planted trees reach an

economically desirable stage, and/or the canopy has become closed, silvicultural thinning practices are often employed to harvest some of the trees and also to stimulate growth in remaining individuals. In conifer stands, this generally occurs at about 30-40 and then at 60-80 years of age, depending on the density of the plantation and soil conditions (Yemshanov *et al.*, 2005). Thinning disturbances can have both positive and negative effects on the forest and its recovery. We have summarized some of the water-related impacts in Figure 1.

In this study, we focus on the water dynamics of a recently thinned 74-year old temperate pine plantation forest in southern Ontario, Canada and compared it with an adjacent 39-year old un-thinned stand. We incorporated three years of tree and canopy-level water fluxes as well as biometric and soil moisture measurements to explore the following questions:

1. How does thinning affect soil moisture?

Soil moisture response to thinning is largely dependent upon interactions between thinning intensity and climate. Tree removal impacts a forest's water balance by reducing canopy interception, which increases the proportion of precipitation reaching the forest floor for soil recharge (Slodick *et al.*, 2011; Qiu *et al.*, 2012). Inter-tree competition for water is decreased, as more water for transpiration (E_t) is available per tree (Reid *et al.*, 2006). Conversely, as thinning intensity (i.e. proportion of basal area removed) increases, the associated reduction in canopy cover exposes the soil to higher temperature fluctuations, wind and radiation (Son *et al.*, 2004), thus increasing soil water evaporation. Furthermore, the remaining trees are exposed to greater radiation and wind loading, which can lead to water stress (Reid *et al.*, 2006). Ma *et al.* (2010) found that the net effect of thinning upon soil moisture was positive across six thinning treatments of mixed-conifer stands, when basal area was reduced by 12.4 - 66.0%. However,

Simonin *et al.* (2007) observed a relative decrease in soil moisture in an 82%-thinned Ponderosa Pine stand when compared to an un-thinned control stand.

2. How does thinning affect root density and hydraulic redistribution?

Roots play an important role in forest water balance, both through direct transport of water for *E_t* and through hydraulic redistribution. Following thinning, fine root production may increase (López *et al.*, 2003; Campbell *et al.*, 2009; Olesinski *et al.*, 2012), partially offsetting an overall decline in the extent of below ground root architecture of the forest. This production may be tied to either canopy expansion, as the remaining trees have more space to maximize foliage and thus photosynthesis (Claus & George, 2005; Hendricks *et al.*, 2006), or understory growth, as more sunlight reaches the forest floor.

Hydraulic redistribution (HR) is the passive movement of water along tree roots resulting from a gradient in soil water potential (Brooks *et al.*, 2002). It plays a role in restoring soil water content during drought (Burgess *et al.*, 1998; Warren *et al.*, 2007). Severe forest disturbances, when dominant trees are removed, kill active roots and prevent water from deeper, more moist soil horizons from being redistributed to shallower layers by HR (Bradford *et al.*, 2014). Studies in the literature have not explicitly evaluated the effect of thinning on HR, so it is unclear whether thinning would result in an increase or decrease in HR. Given the observed increase in soil moisture in the root zone following thinning (Bréda *et al.*, 1995; Covington & Fule, 1997), as well as the increase in fine root production, we hypothesize that compared to pre-thinned conditions the HR capacity of the forest will not be reduced after thinning.

3. How will time-lag between sapflow and evapotranspiration be affected by thinning?

Investigating how efficiently trees are supplied with water, before and after thinning, can illustrate changes in forest hydraulic functionality. As tree height increases, greater tensional force is needed to transport water through xylem to leaves for photosynthesis, and potential for conduit damage during drought (cavitation) increases (Koch *et al.*, 2004). Water transpired at tree crown-level is a combination of water drawn from the soil, and water that has been stored in plant tissues. The primary reservoir is the stem, although roots, shoots and branches also hold small amounts of water (Waring & Running, 1978; Köcher *et al.*, 2013). There is a lag between sapflow measured in the stem (at about 1.3m height) and the actual transpiration of water by stomata at the leaf-level. The proportion of stored water versus soil water used, and the lag between sap-flow and stomatal transpiration, can vary based primarily on weather conditions and soil moisture availability, as well as tree species and their characteristics. For example, Phillips *et al.* (1997) found that as soil moisture decreased, departure from a mean time lag (from sapflow to evapotranspiration) increased in Loblolly pine forests.

As trees grow, their transpiration lag may remain constant despite ageing. Phillips *et al.* (1997) found that different-sized Loblolly pines had a similar lag, which was ascertained as a result of physiological adjustment with growth to maintain tree water transport velocity. In a study of five temperate broad-leaved species, Köcher *et al.* (2013) observed a positive relationship between stem water storage and the lag between sapflow and crown transpiration. In this instance, wood density, which was species-specific, was more influential than sapwood area in explaining stem water storage potential, and thus transpiration lag.

Methods

Study Sites

The two forest sites are located at Turkey Point, near Lake Erie in Southern Ontario, Canada. These adjacent Eastern White Pine (*Pinus Strobes L.*) stands were planted in 1939 and 1974 (henceforth referred to as TP39 and TP74). Tree density at TP39 prior to the 2012 thinning was 413 ± 181 trees ha⁻¹, and at TP74 it is 1583 ± 118 trees ha⁻¹ (Kula, 2014). Further stand characteristics are given in Table 1. Understory species at TP39 include secondary growth white pines, black cherry, hemlock, white birch, and black and white oak, and the forest floor vegetation features bracken fern, poison ivy, Canada mayflower, Allegheny blackberry, and mosses (Restrepo & Arain, 2005). TP74 has almost no understory, with only sparse emerging hardwood tree species such as black oak and mosses. The topography at both sites is flat. The soil at both sites is sandy (~98% sand, 1% sit, <1% clay) and well drained, with low to moderate water holding capacity. The water table depth from the ground surface is about 6-7 m (measured in a water well at TP39 site).

The TP39 stand was managed by the Ontario Ministry of Natural Resources (OMNR) as a shelterwood silvicultural system, and received two partial cuts: one pre-commercial thinning in 1983 and a selective thinning in February-March 2012 (Elliott *et al.*, 2011). In 1983, about 103 tonnes ha⁻¹ of wood was removed and in 2012, approximately 60 tonnes ha⁻¹ of wood was removed. The 2012 operation reduced the stand basal area by 13% to 321 ± 111 trees ha⁻¹. Leaf area index (LAI) measured prior to thinning was 8.6 (Chen *et al.* (2006) and it reduced to 5.3 (35% reduction) after the thinning (Table 1).

Water flux and meteorological measurements

Ecosystem-wide water, carbon and energy fluxes were continuously measured using closed-path

eddy covariance (CPEC) systems at each site. Flux and meteorological sensors were installed on top of scaffolding towers at 28 and 20m heights at TP39 and TP74, respectively. Flux of water vapor (F) was calculated using the following equation, as outlined by Baldocchi et al. (1998):

$$F = \overline{w'c'} \quad (\text{Equation 1})$$

Where w' is vertical wind speed, measured by a 3D sonic anemometer (CSAT3, Campbell Scientific Inc. (CSI)) and c' is water vapor concentration measured by an infrared gas analyzer (IRGA, Li-7000, LI-COR Inc.). Fluxes were measured at 20 Hz and averaged over half-hourly intervals. In our flux analysis program, flux footprints were calculated using the Klujn et al. (2003) model. Fluxes were discarded for all half-hours where less than 90% of the measured flux originated from within the bounds of the forest of interest. Meteorological variables such as net radiation, incident and reflected photosynthetically active radiation (PAR), air temperature (Ta) and relative humidity, wind speed and direction and precipitation (P) were also measured (see Peichl *et al.*, (2010) for further details on flux and meteorological instruments).

Sapflow probes were installed at a height of 1.3 m above the tree base, on the north-facing side, in twenty-three trees at TP39 and fourteen trees at TP74. Some sensors had long periods of missing or bad data, and were excluded from the study. This left a total of 11 sensors at TP39 and 10 sensors at TP74. Sapflow trees were at least 2.6 m apart and located in a 20m \times 20m and 15m \times 20m plots near the towers at TP39 and TP74 respectively. Characteristics of sapflow trees are given in Table 1. Prior to installing the sensors, bark was scraped off to reveal the sapwood surface, the interface between bark and phloem. Sapwood depth was sampled using a wood core, and the amount of non-conducting sapwood in contact with the sensor was measured; corrections were made for any non-conducting tissue, following Clearwater *et al.* (1999) and McLaren *et al.*

(2008). The sampled trees included above average, near average, and average diameter trees, to capture within-stand variability (Kostner *et al.*, 1992; Mackay *et al.* 2012). The sensors were re-installed each spring to avoid signal loss due to sap-accumulation and tree growth, and were protected by a reflective foil-coated bubble wrap.

Each sensor consisted of two individual thermocouple probes (1.3-mm in diameter and 30-mm long), with the upper consistently heated and the lower unheated probe. The temperature difference (ΔT) measured between the upper and lower probes produces a dimensionless flow index, K was used to calculate sapflow velocity (J_s) following Granier *et al.* (1987). Continuous measurements of J_s (m s^{-1}) were averaged over half-hourly intervals from January 1, 2011 to December 31, 2013, following Granier (1987).

Transpiration for each tree was calculated as:

$$E_{ti} = \rho_w \times J_{si} \times \left[\frac{A_{si}}{A_{wi}} \right] \quad (\text{Equation 2})$$

Where i denotes the sample tree, ρ_w is the density of water (1000 kg m^{-3}) and A_{si}/A_{wi} is the ratio of sapwood area to total wood area. Next, E_{ti} was scaled to stand level transpiration per unit ground area by averaging all trees' E_{ti} , then multiplying this value by stand basal area (BA, m^2):

$$E_t = \frac{\sum_{i=1}^n E_{Ti}}{n} \times BA \quad (\text{Equation 3})$$

We calculated the time lag between J_s and ecosystem evapotranspiration (E) measured by the eddy covariance system following Lundblad and Lindroth (2002). This lag time summarizes the time taken by the water to travel from the bottom of stem (at 1.3m height) as measure by sapflow sensors to loss of water from canopy as evapotranspiration as measured by the eddy covariance system. This time lag is a corollary of hydraulic limitation, with longer lag time suggesting a greater limitation of water supply from root to foliage. We used it to explore differences in

hydraulic limitations between our two different aged stands, as well as between pre- and post-thinning years.

Lag was estimated in the June-August period for days which were preceded by at least two days with P of less than 0.5 mm, reducing interference from tree and soil evaporation rainfall response (i.e., a reduction or halt of sapflow as found by Silva *et al.*, 2001). This left 48, 37, and 36 days in 2011, 2012 and 2013 (respectively). The diurnal time series of J_s (mean of all sensors) was progressively shifted by one half-hour and regressed against the diurnal E time series, and the best, significant fit (defined by r^2 at $\alpha < 0.05$, for $n = 48$ half-hours of a day) was taken as the lag time for that day (following Lundblad and Lindroth, 2002). For each day tested, J_s was shifted for 24 half-hours, testing for lag times from 0 to 12 hours.

Fine root measurements

At both TP39 and TP74, soil cores were taken at six points along a 30 m transect in September 2014. First, a 20 x 20 cm segment of the litter layer was removed down to the top of the mineral soil. Then a 5.4 cm diameter auger was used to extract soil cores from 0-15 and 15-35 cm depths. The samples were then oven-dried at 65°C. For each soil sample, fine (<2mm) and small (2-5mm) roots were isolated and weighed. Live and dead roots were not discriminated during analysis. We compared root analyses results with a previous study at our sites by Peichl *et al.* (2006).

Soil moisture and hydraulic redistribution

Soil volumetric water content (θ) was continuously measured by CS615 probes (Campbell Scientific Inc.) at 5, 10, 20, 50, and 100 cm depth at two points within each site, except for the

100 cm depth at TP74 which had only one point of measurement. The average of the two probes was taken for each depth. Root zone θ (0-25 cm) was obtained by a depth-weighted integration of the 5, 10, and 20 cm probes, and the 50 and 100 cm probes were integrated to obtain θ across the deeper soil layer from 45-105 cm.

Following Meinzer *et al.* (2004) and Brooks *et al.* (2002), hydraulic redistribution (*HR*) at our sites was quantified as the difference between the minimum θ of one day and the maximum of the next day. To isolate *HR* rather than capillary rise, calculations were restricted to the 30 days of lowest θ in each growing season. Although *HR* can be both horizontal and vertical, the configuration of our soil moisture sensors restricted *HR* calculations to the vertical plane only. As with *Js-E* lag, values were only kept for days when no P over 0.5 mm day⁻¹ was recorded for the previous two days. As the topography at both sites is flat, and the water table depth from the ground surface is about 6-7 m, the contribution of lateral hydraulic redistribution and capillary rise to variation in measured volumetric water content were considered to be negligible.

Data quality control, gap filling and statistical analysis

Meteorological, flux and sapflow data were quality controlled for spikes and missing periods following Peichl *et al.* (2010) and Brodeur (2014). For missing half-hourly sapflow values, a neural-network training tool in Matlab (The Mathworks, Inc.) was used to estimate *Js* values, using the same year's meteorological data for training. To predict *Js* for the missing time periods, incident PAR, vapour pressure deficit (VPD), soil temperature, *Ts* (5 cm depth) and θ in the root zone (0-25 cm) were used for each sensor. Statistical analysis was performed using cleaned, non-gap filled data.

To investigate changes in tree water use in relation to environmental variability between pre-and post-thinning years, we constructed multivariate linear models of daily J_s for each year, using daily mean PAR, $\theta_{0-25\text{ cm}}$, and VPD as shown below:

$$J_s = I + PAR$$

$$J_s = I + PAR + \theta_{0-25\text{ cm}}$$

$$J_s = I + PAR + \theta_{0-25\text{ cm}} + VPD \quad (\text{Equation 4})$$

Model evaluation for all analyses was performed using the second-order Akaike information criterion (AICc), a metric that considers a model's parsimony in addition to its fit by incorporating the number of free parameters, thus evaluating a model's performance removed from a complexity bias (Bozdogan, 2000). In each distinct analysis scenario, the models' AICc were re-expressed as Akaike weights (w_i) to compare their relative probabilities of accurately representing the measured data (Wagenmakers & Farrell, 2004). All statistical analyses were performed using Matlab.

Results

Meteorological trends

In 2012, growing season (April to October) mean T_a was 9% higher, while total P was 3 % higher than the 30-year norm values in the region. 2013 was notably well-watered: rainfall exceeded the 30-year norm by 24% (Table 2, Figure 2a). θ was consistently higher at TP39 compared to TP74 during all three study years as shown by Figure 2 c-d. In 2011, VPD was

greater at TP74, however in 2012 and 2013 TP39 experienced slightly higher atmospheric dryness (Figure 2b).

Changes in canopy openness and root density

LAI at TP39 declined significantly after thinning in early 2012 ($p < 0.001$), while TP74 had a slight, non-significant decline. LAI remained similar between 2012 and 2014 at both sites. The ratio of half-hourly *VPD* between the two sites (TP39/TP74) increased significantly from 0.77 in 2011 to 1.05 in 2012 ($p < 0.001$), which suggested an increase in canopy-atmosphere coupling and atmospheric demand at TP39 after thinning due to the increase in canopy openness.

Fine and small root biomass from soil coring showed high spatial variability. Compared with results from Peichl *et al.* (2006), the only significant change was an increase in fine root biomass at TP39 (t-test, $p < 0.01$), with no detectable change in root distribution at TP74 (Figure 3a,b).

Tree- and stand-level water fluxes

Sapflow velocity and transpiration had different interannual trends at TP39. Following thinning at TP39, 2012 cumulative growing season *Et* declined and did not return to previous levels during the study (Table 3, Figure 4a), while 2012 *Js* increased compared to 2011 (Table 3, Figure 4c). At TP74, however, both *Js* and *Et* declined from 2011 to 2012 (Table 3, Figure 4b,c). At both sites, *Js* was highest in 2013, and for TP74 the 2013 growing season had the greatest cumulative *Et*. Ecosystem-level *E* was consistently higher at TP39, with growing season totals increased from year to year at both sites (Table 3).

Interestingly, 2011 and 2013 were comparable in their growing season climate (Table 2), yet the differences in E_t and E between TP39 and TP74 were quite different (Table 3), reflecting the thinning disturbance. In 2011, TP39 transpired about 54% more and its ecosystem evapotranspiration was 13% higher compared to TP74, yet by 2013 TP39 transpired about 9% less than TP74, while its total annual evapotranspiration was higher by 12% compared to that of TP74.

At both sites in 2011 and 2012, E_t followed a biannual peak pattern, with the first, highest peak around June, a dip during seasonal drought through July and August, and a second, lower peak in early fall then a decline as the growing season drew to a close in October (Figure 4a,b). The seasonal patterns in E_t and J_s were reflective of the precipitation patterns at the site (cf. Figure 2 and Figure 3). In both 2011 and 2012, there was less precipitation in the early growing season compared to 2013, which resulted in the mid-season drought around July, causing E_t and J_s to decline. In contrast, in 2013 May was unusually wet, and this extra early season supply of water kept the trees watered enough to ameliorate any effect of mid-season drought on J_s and E_t . Overall, E_t declines during seasonal drought were relatively more severe at TP74 compared to TP39.

Stepwise linear modeling of J_s showed that tree-level water use at TP39 maintained a similar relationship with environmental variability between 2012 pre- and post-thinning years. The model incorporating PAR, $\theta_{0-25\text{cm}}$, and VPD was most parsimonious from 2011 to 2012 at the thinned site and the un-thinned site (Table 4). In 2013, the thinned site was best represented by only PAR, while the un-thinned site continued to be best represented by PAR, $\theta_{0-25\text{cm}}$, and VPD.

Sapflow-evapotranspiration lag

The relationship between lagged sapflow and evapotranspiration was fairly strong (25th to 75th percentile r^2 of 0.81 – 0.91 and 0.76 – 0.93 at TP39 and TP74, respectively). Sapflow at both sites generally trailed evapotranspiration measured by the eddy covariance system by 0-1.5 hours (Figure 5, Table 5). The daily lag time between the two sites was significantly different in all years ($p < 0.001$ for 2011-2012, $p < 0.05$ for 2013), with TP39 having consistently shorter lag.

Hydraulic redistribution

Our estimations of hydraulic redistribution (*HR*) tended to be of higher magnitude at TP74 than TP39 throughout the study period, which corresponded with the site's lower soil moisture accommodating greater differential in soil water potential for passive transport (Figure 6). *HR* at both sites was more frequent in the 0-25 cm layer (*HR* exceeded 0 mm day⁻¹ for 112 versus 103 days at TP39, and 116 versus 99 days at TP74), although uplift in the lower 45-105 cm layer was relatively higher at TP74 (2.2 ± 1.1 versus 1.8 ± 1.5 mm day⁻¹ for the study period). At both sites, there was no significant change in *HR* in the 0-25cm soil layer from 2011 to 2012 ($\alpha < 0.05$). For *HR* in the 45-105 cm soil layer, only TP74 showed a change ($p = 1.4e-04$).

Discussion

Tree level water dynamics

Sapflow dynamics

A relatively severe seasonal drought occurred during the 2012 growing, following the thinning treatment conducted earlier in the year. The summer of 2012 was also warmer compared to the other two years and 30-year norm. The rise in *J_s* at TP39 following thinning was in contrast to

the expected drought response of J_s , which generally decreases during drought periods, as seen at TP74. In the following 2013 year, which was well watered throughout the summer, both sites' J_s rose as expected. The higher soil moisture and lower VPD during 2013 would have accommodated stomatal openness rather than closure from frequent summer drought stress as observed in other years (McLaren *et al.*, 2008; MacKay *et al.*, 2012).

Previous studies in forests of Oak (Bréda *et al.*, 1995) and Lodgepole pine (Reid *et al.*, 2006) have found that forest thinning results in greater soil moisture availability and can lead to a higher rate of transpiration among the remaining trees. Without a paired study of a thinned and un-thinned plot at our forest, it was not possible to directly conclude that thinning allowed greater soil moisture. However, it is logical to conclude that the decrease in stem density allowed more soil water per tree, and this was likely a key component of the J_s increase at TP39. Additionally, if we compare 2011 and 2013 fluxes (Table 3), one can see that in 2013 the difference between E and E_t , which represents soil evaporation and understory transpiration, more than tripled (i.e. 47 mm ha^{-1} vs 155 mm ha^{-1}) at TP39, as expected when the canopy opens up due to thinning, versus declining at TP74 (i.e. from 128 mm ha^{-1} to 79 mm ha^{-1}). In a study monitoring the effects of a gradient of thinning intensities (14-66% of basal area removed) in a mixed conifer forest, Ma *et al.* (2010) found soil moisture and VPD to increase in all treatment plots, which aligned with our results. In contrast, when Simonin *et al.* (2007) investigated forest response to a more intensive thinning (82% of basal area removed), the authors found a resultant decrease in soil moisture. The thinning at our site was of a low enough intensity (i.e. 13% of basal area) to result in a soil moisture increase, which could support a rise in sapflow velocity in the remaining trees. A consistent relationship between J_s and environmental variability during

2011 (pre-thinning) and 2012 (post-thinning), at our thinned and un-thinned sites, suggested that thinning management did not alter tree water use response to climate.

Tree sapflow - site evapotranspiration lag

In our study, stem flow to evapotranspiration ($J_s - E$) lag suggested that tree size and age did not significantly restrict timing of water transport from the roots to the leaves, as previously demonstrated by Philips *et al.* (1997). Our estimates of time lag (Table 5) were within the range of previous studies such as Kocher *et al.* (2013), Saugier *et al.* (1997), Granier *et al.* (1996), and Perämäki *et al.* (2001). The consistently lower lag at TP39 versus TP74 during summer might reflect a height-compensation response that serves to reduce hydraulic limitation, and may also suggest an absence of significant xylem cavitation that would have reduced tree capacity for water transport. Accordingly, the influence of soil moisture on $J_s - E$ lag may have been greater than that of tree height when comparing lag between the sites, with seasonal drought amplifying such differences. Kocher *et al.* (2013) found that stem storage was nearly depleted past a soil water dryness threshold. In our study, TP74 had consistently lower soil moisture than TP39, so the younger site likely reduced water uptake earlier at the onset of dry conditions. Further, both sites showed a decline in lag time in 2013, suggesting that the drought of the previous year may not have resulted in xylem cavitation, which would have subsequently increased hydraulic limitation and transport time from stem to canopy.

Ecosystem scale water dynamics

Evapotranspiration

Relatively high T_a in 2012 resulted in substantial atmospheric demand (Figure 2), which in the

absence of concurrent low supply of water would have led to high Et at both sites. However, at the TP39 site, Js increased as expected, while total Et decreased from 2012 to 2013. It suggested that Et at the TP39 site was not responding to a decline in water supply, as was the case at TP74 site where both Js and Et declined in 2012. Rather, the increase in tree Js and decrease in Et at TP39 site, which followed stand thinning, was due to a decrease in water-conducting sapwood area from 31.5 to 23.7 m² ha⁻¹. At TP74 site, the decline in both Js and Et was likely tied to the 2012 growing season drought. The consistency of *E* between sites and years showed a rising importance of soil evaporation in the forest water balance during drought and following thinning. As discussed in previous studies of thinned and un-thinned stands (Simonin *et al.*, 2007; Raz-Yaseef *et al.*, 2010), greater canopy openness allows more solar radiation to reach the forest floor, and thus more evaporation of shallow soil water. This effect may be more pronounced during such hot and dry periods as experienced during 2012 growing season, when transpiration was suppressed due to stomatal closure and more energy was available for soil water evaporation.

Changes in root density

Contrary to results from Peichl *et al.* (2006), we did not find TP74 to have a higher fine root density than TP39. Compared with results from this previous study, the only significant change was an increase in fine root biomass at TP39 (t-test, $p < 0.01$), with no detectable change in root distribution at TP74. Both the 2012 and 1983 thinning treatments may have allowed an expansion of understory vegetation and native Carolinian species, which are both sources of fine root production. Previous studies report that peak fine root abundance corresponds with timing of a forest's canopy closure (Vogt *et al.*, 1983; Helmisaari *et al.*, 2002; Claus & George, 2005), as

fine roots are important in supplying water and nutrients for foliage growth. However, in 2014 peak LAI was $4.8 \text{ m}^2\text{m}^{-2}$ at TP39, and thus did not show an increase from the $5.9 \text{ m}^2\text{m}^{-2}$ peak LAI of 2012 after thinning. This led us to surmise that understory rather than canopy expansion was likely the source of new fine roots. However, the contribution of White Pine fine root expansion to the increase could be decisively ruled out, as there may be a lag between root production and tree foliage expansion.

Soil moisture and hydraulic redistribution

Hydraulic redistribution (*HR*) appeared to restore soil moisture in the 0-25 cm root zone during dry spells at both TP39 and TP74, which was likely a valuable input for understory and forest floor plants with shallow root systems. During the lowest soil moisture periods in 2011 and 2012, *HR* was commonly lower than 0.5 mm per day at TP39 and TP74, similar to studies by Brooks *et al.* (2002), Meinzer *et al.* (2004), and Warren *et al.* (2005). However, values that fluctuated as high as 1.6 (TP39) and 1.8 (TP74) mm day^{-1} were more dubious, and may have reflected capillary rise rather than the root-associated *HR* mechanism. The 2013 case in particular was suspect, as even the driest period was interspersed with high-rainfall events (i.e. up to 40 mm day^{-1}). It is probable that *HR* is present at the two forests when soil moisture is below a dryness threshold consistent with seasonal drought for a prolonged period of time, as was observed in 2011 and 2012. A previous study at our site identified a 0-25cm value of 0.07 as the site's drought threshold, based on *Et* decline (McLaren *et al.*, 2008). Our results show that soil moisture remained around this threshold value during the 2011 and 2012 seasonal drought periods, possibly due to *HR*. During non-drought periods, *HR* was not detected (Figure 4). This was likely due to sufficient root zone soil moisture in the vicinity of the sensors, although

stemflow during precipitation events may have resulted in a moisture gradient surrounding individual trees, possibly resulting in passive transport of water via *HR*. Future studies, using soil water potential probes (Warren *et al.*, 2005, 2007) or root sapflow sensors (Burgess *et al.*, 1998; David *et al.*, 2013) to support soil moisture measurements are recommended for a more in-depth assessment. Without a paired study it was difficult to conclude whether the removal of roots with thinning impacted passive soil water movement, although the apparent presence of *HR* during the summer drought of 2012 did suggest that sufficient root structure remained following thinning. It thus appears that the gradient in soil water potential was the limiting factor of *HR* at the thinned site, rather than the available capacity of water transport conduits.

Conclusion

This study demonstrated the response of a temperate white pine plantation forest in eastern Canada to a selective thinning treatment that reduced basal area by 13%. Transpiration in the thinned stand declined following the treatment, however tree-level water transport increased. In contrast, tree-level water transport decreased at a nearby un-thinned white pine stand, due to drought in the growing season of the thinning year. This suggested increased availability of water supply to individual trees following the thinning, despite a decline in water input.

Ecosystem evapotranspiration did not appear to be impacted by the thinning, likely due to a more open canopy accommodating increased soil evaporation and understory transpiration. These divergent trends in transpiration and sapflow velocity following tree harvesting suggested the presence of a physiological response tied to structural change, independent from environmental variability, which drove the increase in sapflow velocity at the treated stand. To investigate the role of understory expansion, leading to increased stand transpiration, future work on hydrological impacts of thinning may benefit from species surveys before and after treatment. We conclude that the thinning treatment did not compromise the hydraulic functionality of our mature white pine stand and potentially allowed the stand to become more effective in withstanding seasonal drought stresses.

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Table 1: Stand and sapflow tree characteristics. Pre-thinning values are given in parentheses.

	TP39	TP74
Age (years) as of 2013	74	39
Stem density ^a (trees ha ⁻¹)	321 ± 111 (413 ± 181)	1583±118
Mean tree height (m)	23.4 ± 2.31 m (23.2 ± 3.90 m)	13.5 ± 1.47 m
Basal area* ^a (m ² ha ⁻¹)	36.0 (40.9)	40.0
Sapwood area* ^a (m ² ha ⁻¹)	23.7 (31.5)	26.3
Maximum Leaf Area Index, LAI ^b (m ² m ⁻²)	5.3 (8.6)	6.7
Number of trees for sapflow measurements	11	10
Mean height of sapflow trees ^c (m)	20.9± 2.0	10.7 ± 0.6
Mean basal area of sapflow trees* ^c (cm)	40.2 ± 5.7 (41.5 ± 6.9)	19.3 ± 3.6

* Measured at 1.3 m height from the tree base

^a Data from 2012 and 2011 (pre-thinning), respectively, as reported by Kula (2013)

^b Maximum annual LAI measured in 2011 (pre-thinning) and 2014, respectively, by Dr. Jing Chen's group at the University of Toronto (unpublished, personal communication)

^c Measured in 2011 (pre-thinning), and 2014

Table 2: Growing season (April-October) climate.

Year	Ta (°C)	P (mm)
2011	15.3	715
2012	16.2	571
2013	15.3	741
30-year-norm*	14.9	632

*Based on a nearby Delhi CDA weather station data from 1981-2010

Table 3: Growing season ecosystem-level evapotranspiration (E), transpiration (E_t) and mean sapflow velocity (J_s) at the TP39 and TP74 sites.

Year	E (mm)		E _t (mm)		J _s (mm s ⁻¹)	
	TP39	TP74	TP39	TP74	TP39	TP74
2011	411	364	364	236	1.44E-05	5.59E-06
2012	436	386	216	200	1.95E-05	4.75E-06
2013	447	400	292	321	2.24E-05	8.01E-06

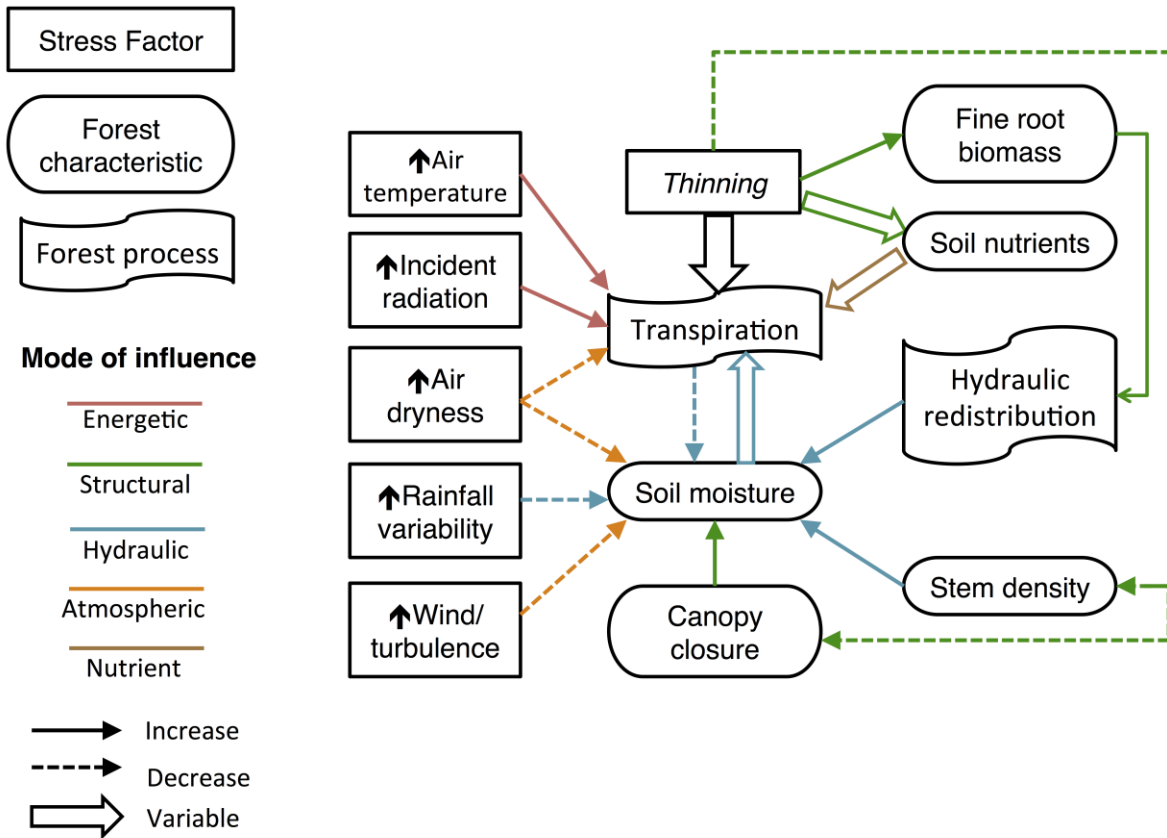
Table 4: Model r^2 , AICc, Δ AICc, and Akaike weights (w_i) from stepwise linear modeling of daily sapflow velocity (J_s) values with $\theta_{0-25\text{cm}}$, vapor pressure deficit (VPD), and photosynthetically active radiation (PAR). The w_i signifies models' relative probabilities of representing the measured data. All models were significant at $\alpha < 0.001$.

			θ_{0-25}	$\theta_{0-25+VPD}$	$\theta_{0-25+VPD+PAR}$
TP39	r^2	2011	0.47	0.52	0.58
		2012	0.48	0.56	0.62
		2013	0.46	0.65	0.66
TP74		2011	0.41	0.24	0.53
		2012	0.45	0.37	0.53
		2013	0.42	0.44	0.56
TP39	AICc	2011	-2723.3	-3956.5	-4350.2
		2012	-2723.5	-3970.3	-4371.1
		2013	-2612.2	-3498.1	-4397.9
TP74		2011	-4516.1	-4838.6	-4576.4
		2012	-4529.9	-4877.7	-4575.5
		2013	-4013.5	-3772.3	-4500.0
TP39	w_i	2011	0.00	0.00	1.00
		2012	0.00	0.00	1.00
		2013	0.00	0.00	1.00
TP74		2011	0.00	1.00	0.00
		2012	0.00	1.00	0.00
		2013	0.00	0.00	1.00

Table 5: Mean *E-Js* lag time for June-August period in 2011-2013 at TP39 and TP74 sites, for days which were preceded by at least two days with < 0.5 mm precipitation. For a given day, *E* was progressively lagged by 30-minute increments, and compared at each lag with the same day's *Js* time series. A total of 24 half-hour shifts were performed, testing 0-12 hours of lag. The lag treatment with the highest r^2 ($p < 0.05$) over $n = 48$ half hours determined that day's lag time. Lag times were calculated for 48, 37, and 36 days in 2011, 2012 and 2013, respectively.

Year	Mean <i>E-Js</i> lag time (hours)	
	TP39	TP74
2011	0.6±0.4	1.4±1.3
2012	0.6±0.3	1.8±1.5
2013	0.5±0.9	1.1±0.7

Figure 1: Concept map of how thinning treatment might affect transpiration of a forest ecosystem under various climatic stress factors. Arrows illustrate the hypothesized modes of impact through hydraulic, structural, energetic, atmospheric and nutrient limitation.



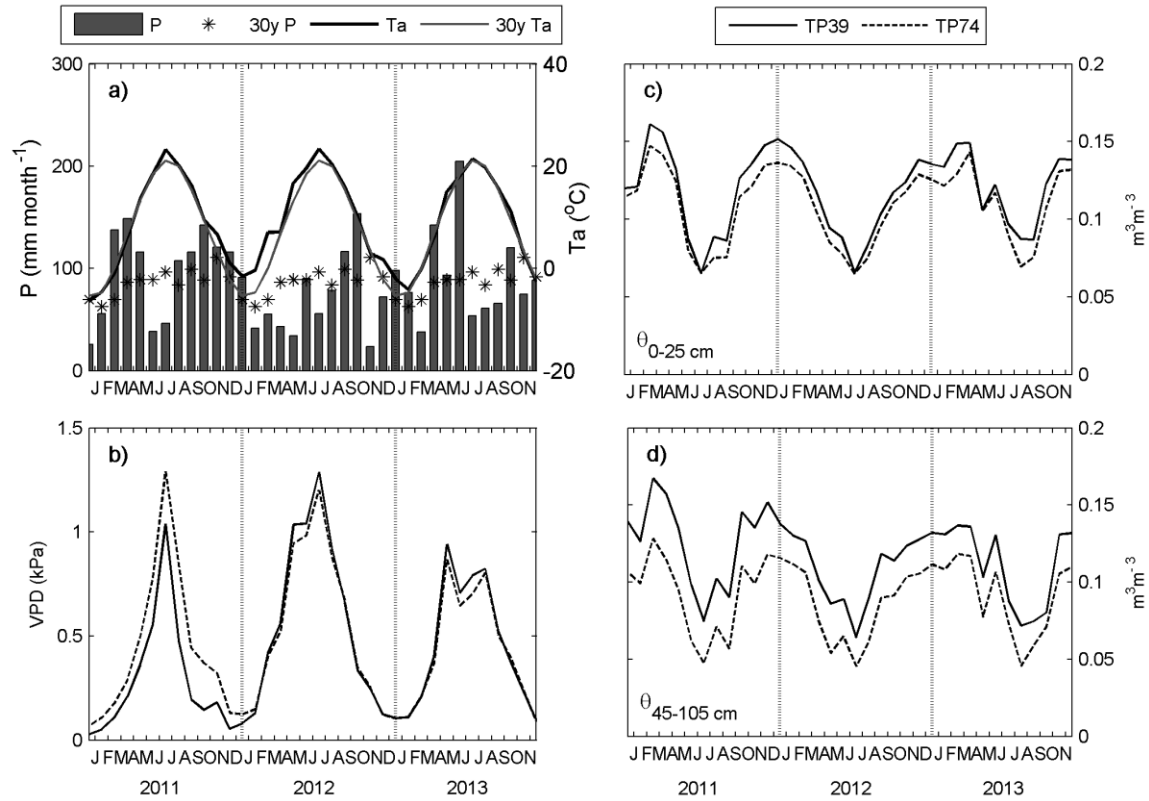


Figure 2: (a) Monthly precipitation (P) and air temperature (T_a) at TP39 with 1981-2010 30-year-norms from the nearby Delhi weather station included for comparison, (b) vapor pressure deficit (VPD), and (c-d) soil moisture at 0-25 and 45-105 cm depths from 2011-2013 at both TP39 and TP74.

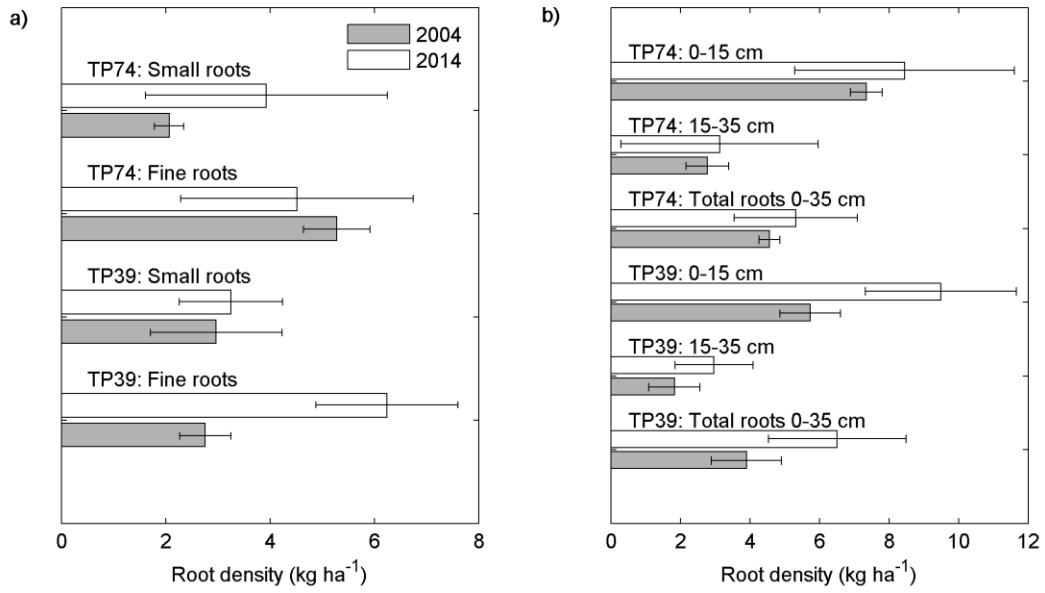


Figure 3: From 2004 and 2014 sampling at TP39 and TP74, (a) small and fine roots biomass across 0-35 cm, and (b) total root biomass at 0-15 and 15-35 cm depth classes.

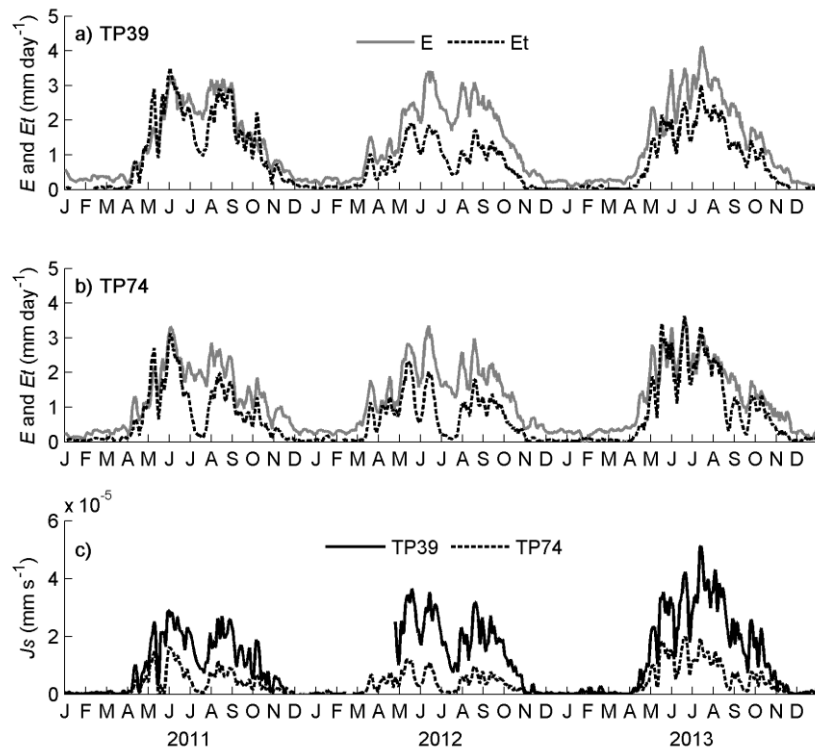


Figure 4: Daily total values of sapflow-derived canopy transpiration (Et) and eddy-covariance measured ecosystem evapotranspiration (E) at TP39 (a) and TP74 (b), and daily averaged sapflow velocity (Js) across all sensors at each of TP39 and TP74, presented as a 7-day moving average (c).

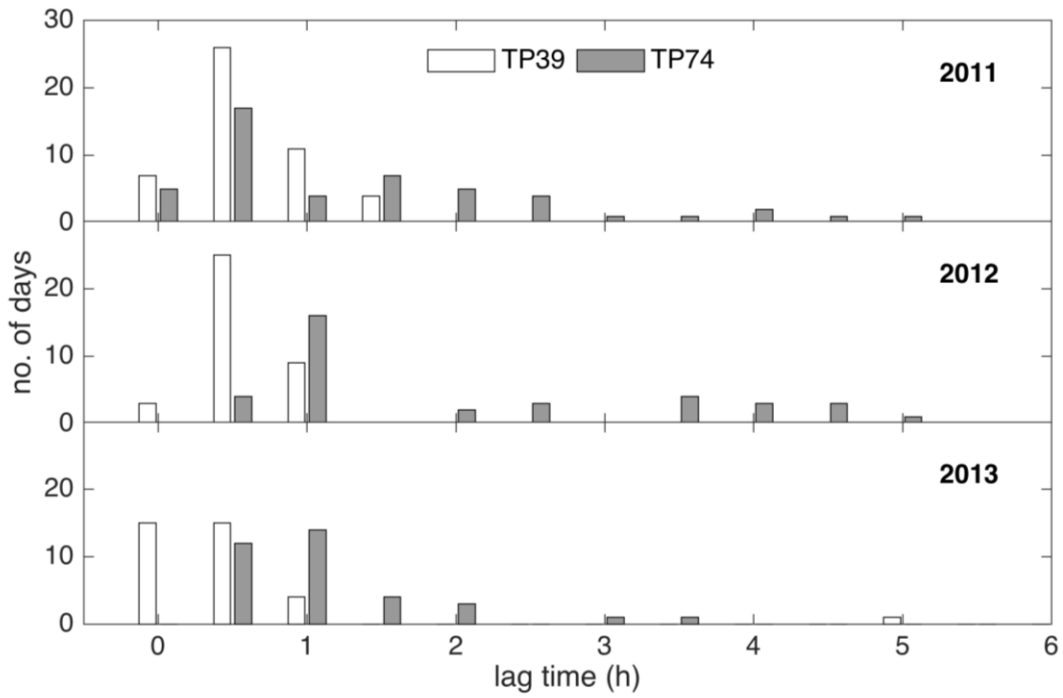


Figure 5: The frequency of daily lag time between sapflow and ecosystem evapotranspiration in the June-August period for 2011 to 2013.

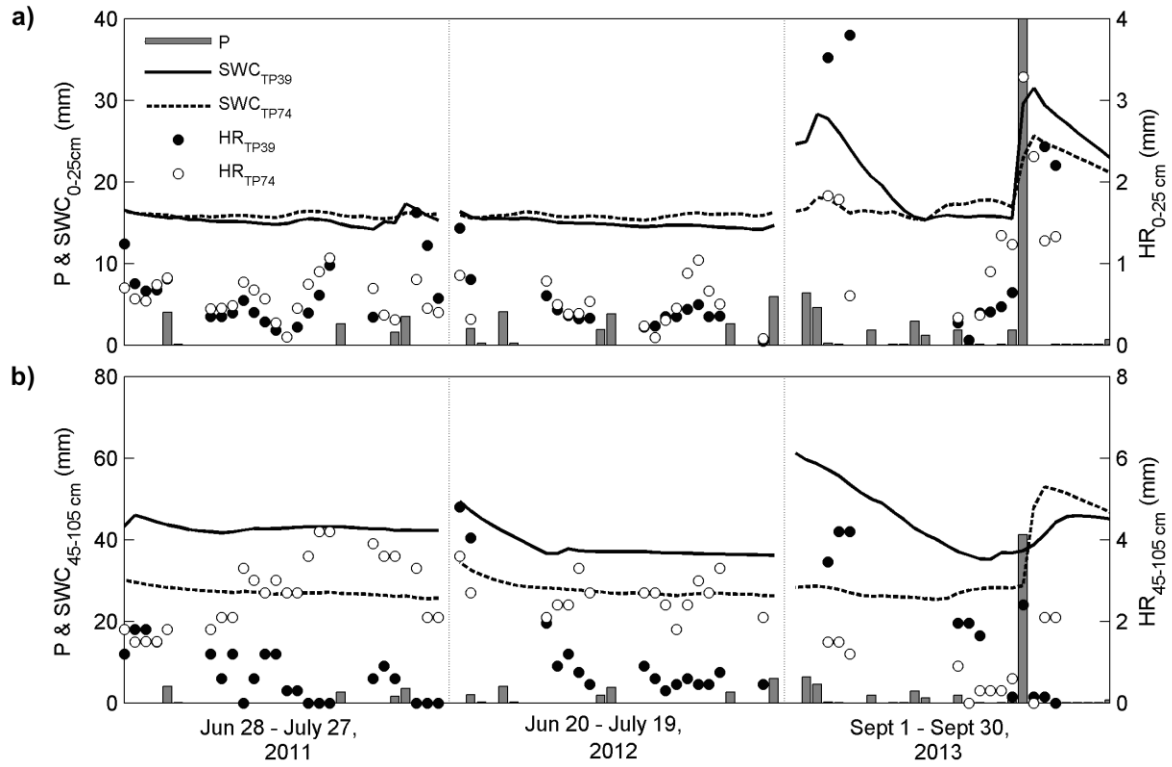


Figure 6: Hydraulic redistribution (HR) and soil water content (SWC) at 0-25 cm depth (a) and 45-105 cm depth (b), and precipitation (P) during seasonal drought. HR values for are given for days in which the two previous day's P did not exceed 0.5 mm.