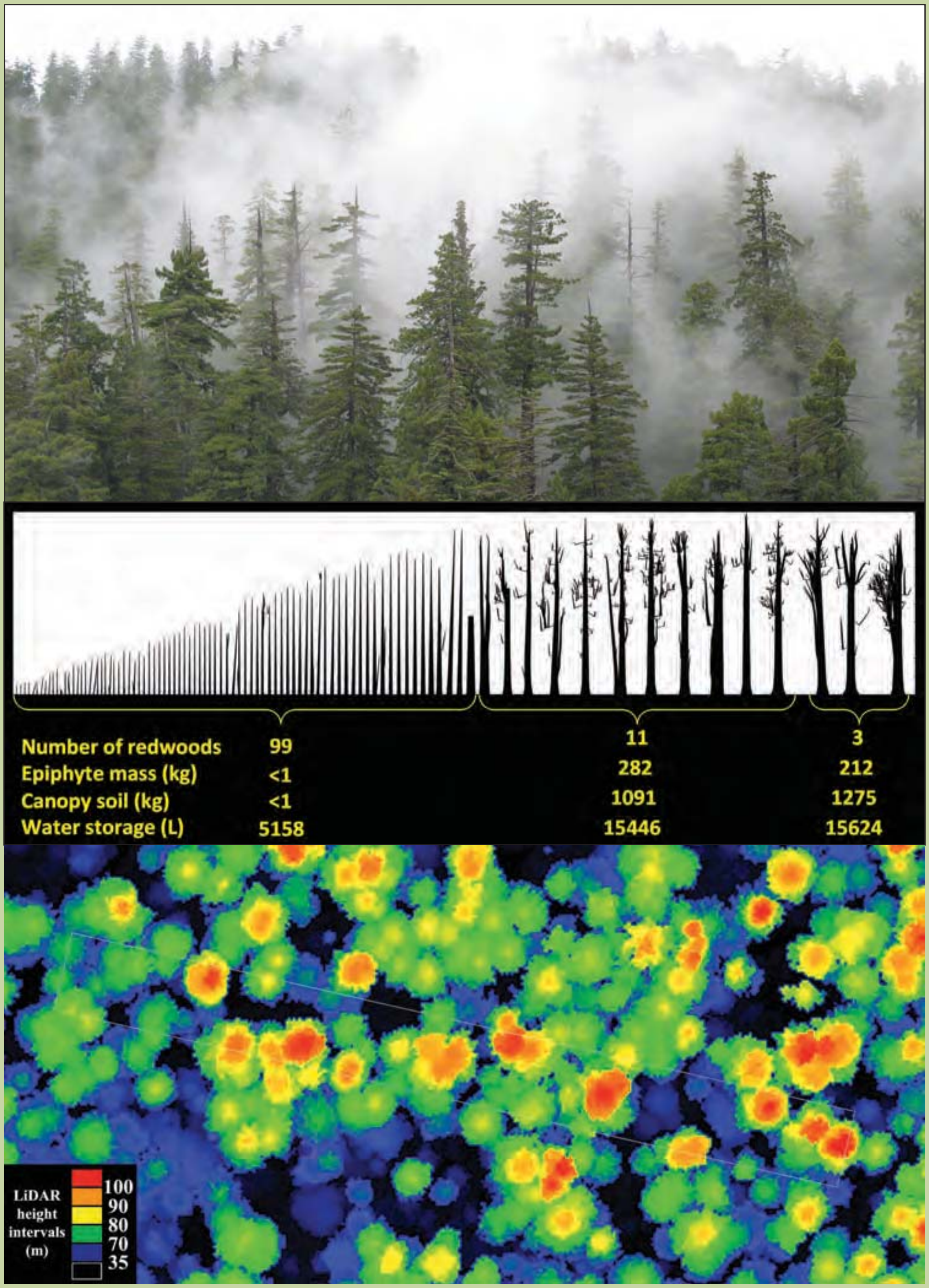
United States
Department of
Agriculture

Forest Service

Pacific Southwest
Research Station

General Technical
Report
PSW-GTR-238
April 2012

Proceedings of the Coast Redwood Forests in a Changing California: A Symposium for Scientists and Managers



Summer Water Use by Mixed-Age and Young Forest Stands, Mattole River, Northern California, U.S.A.

Andrew Stubblefield[1], Max Kaufman[1], Greg Blomstrom[2], and John Rogers[3]

Abstract

Resource managers have noted a decline in summer flow levels in the last decade in the Mattole River watershed, Humboldt County, California. Reduced river flows pose a threat to endangered coho and chinook salmon in the watershed, as stream heating is inversely proportional to discharge. While the cause of the reduced flow is unclear, several factors have been cited: increased groundwater pumping from residential development in the area, regional climate shifts tied to global warming, and the recovery of forest cover after widespread deforestation in the 1950s and 1960s. The goal of this project was to gain insight into the effect of stand age and composition on forest water consumption. Quantitative information on tree and stand level transpiration was collected in order to inform comprehensive hydrologic budgets being developed for the Mattole River watershed under existing conditions and resulting from prospective forest management activities. Granier thermal dissipation probes were inserted into 18 Douglas-fir (*Pseudotsuga menziesii*) trees in mixed and even-aged stands in order to record water use over the course of the 2008 summer dry season. Trees ranged in size from 10 to 91 cm diameter at breast height (DBH). A tight relationship was found between sapwood area (cm^2) and water use (liters/season, $y = 7.68x – 638.6$, $r^2 = .86$). Strong positive relationships were also found between DBH (cm) and water use ($y = 92.40x – 1068.4$, $r^2 = .90$), and for basal area (cm^2) and water use ($y = 1.261x + 241.57$, $r^2 = .94$). The relationship between basal area and water use was much steeper for the youngest trees ($y = 3.42x – 233.15$. $r^2 = .76$), indicating a steep increase in water use with increasing tree size at the lower end of the size range. This information was used to model stand level water use with the current composition and under future scenarios using Forest Vegetation Simulator. Results indicate that the water use of Mattole River forests will decline in coming decades as the high numbers of young (< 5 cm DBH) trees decline from canopy closure and stem suppression.

Key words: sapflow, transpiration, *Pseudotsuga menziesii*, forest management, water balance, coastal California, Forest Vegetation Simulator.

Introduction

Resource managers have noted a decline in summer flow levels in the last decade in the Mattole River watershed, northern California, U.S.A. (*fig. 1*). While the cause of the reduced flow is unclear, several factors have been suggested: increased groundwater pumping from residential development in the area, regional climate shifts tied to global climatic disruption and the recovery of forest cover after

---

[1] Professor and Graduate Student, respectively, Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA 95521. (aps14@humboldt.edu; jedi717@gmail.com).
[2] Consulting Forester, Baldwin, Blomstrom, Wilkinson and Associates, Arcata, CA 95521.
[3] Director, Institute for Sustainable Forestry, Redway, CA 95560.

Figure 1—Study site location, Mattole River watershed, California.

widespread deforestation in the 1950s and 1960s. Reduced flows pose threats to aquatic conditions as the amount of stream heating is inversely proportional to discharge. Tributary drainages have gone completely dry in recent summers, or been limited to isolated pools. Mattole River salmonid populations are declining for three threatened species under the U.S. Endangered Species Act: coho salmon (*Oncorhynchus kisutch*), chinook salmon (*O. tshawytscha*), and steelhead trout (*O. mykiss*).

The goal of this research is to gain insight into the effect of stand age and composition on forest water consumption. By collecting quantitative information on tree and stand level transpiration we hope to inform comprehensive hydrologic budgets being developed for the Mattole River watershed under existing conditions and resulting from prospective forest management activities.

To examine water use for trees of different size and stands of different composition we instrumented 11 trees in a young stand and seven trees in an adjacent mature stand with thermal dissipation probes. We then used relationships between tree size and water use in conjunction with outputs from the forest growth model Forest Vegetation Simulator (Dixon 2002) to estimate changes in stand water use as the trees mature, canopy closure and stem exclusion processes take place. Given the tight relationship between leaf area index and sapwood area observed by other researchers (Waring et al. 1982) we hypothesized that larger dominant trees found in the mature stand would show greater maximum transpiration rates, daily and seasonal water consumption levels than younger trees and suppressed, understory trees, but that on a stand basis, water use would be reduced in mature stands because of lower numbers of stems per acre.

Study area

The study was conducted at two adjacent sites near Ettersberg, California in the Mattole Watershed, Humboldt County (40°9′ N, 123°59′ W, elevation ~300 m). Dominant tree species were Douglas-fir (*Pseudotsuga menziesii*), tanoak (*Lithocarpus densiflora*), and pacific madrone (*Arbutus menziesii*). Stands were located midslope, with SE aspect. Southern Humboldt County has a Mediterranean climate with cool rainy winters and hot dry summers. Average annual precipitation is 110 cm.

The first site was a mature stand composed of large Douglas-fir (61 to 91 cm Diameter at Breast Height (DBH)) with a mid story of tanoak in the larger size classes (30 to 46 cm DBH), and an understory of smaller tanoak and suppressed Douglas-fir. The stand was closed except to the east, which was bordered by a dirt road. The second site was a densely stocked with small Douglas-fir (10 to 25 cm DBH) with occasional larger black oak and pacific madrone, and a small component of tanoak. This stand was estimated to be 20 years old. The canopy was closed.

Materials and methods

The technique used for this study was measurement of individual tree water use with thermal dissipation probes (Granier 1985). In this method pairs of probes are inserted in predrilled holes in the xylem of the tree bole. The probes are linked to dataloggers which continually record temperature. The upper probe of each pair is heated. The lower probe serves as a reference. The rate of sap flowing through the hydroactive xylem is determined by the amount of cooling of the heated probe relative to the reference probe.

The method has been validated by comparison with other techniques such as heat pulse methods (Swanson 1994), gravimetric measurements of pot-grown saplings (McCulloh et al. 2007), and micrometeorological flux measurements (Kostner et al. 1998). Thermal dissipation probes have been used in a numerous applications since their development. Examples include evaluating sapflow in Douglas-fir stands (Moore et al. 2004) and scots pine and spruce stands (Granier et al. 1996).

TDP-80 probes (Dynamax, Inc., Houston, Texas) were used at the mature stand. Instrumented trees are described in *table 1*.The probes consist of 80 mm hypodermic needles fitted with copper-constantan thermocouples. They are inserted into predrilled holes in the sapwood in pairs with an upper probe 40 mm above a lower probe. The upper probe has a constantan heating wire in addition to the thermocouple wire. The lower probe acts as a reference probe, giving the temperature of the sapwood without heating. The temperature difference between the needles is at its greatest when sap flow velocity is minimal and as flow increases the upper needle cools and the difference in temperature decreases. This temperature difference is recorded with Campbell Scientific 1000x Dataloggers (Campbell Scientific Inc, Logan, Utah). The TDP-80 probes have two thermocouples mounted in each probe, allowing for measurement of temperature changes at two depths within the sapwood. TDP-30 and TDP-50 probes were used at the young stand. These probes are a more appropriate length for smaller trees with thinner sapwood (30 mm and 50 mm needles respectively) and have only one thermocouple per needle.

Average sap flow velocity V (cm/s) is calculated from the expression:

$$V = 0.0119*K\text{^}1.231$$

where the dimensionless parameter K is:

$$K = (\Delta Tm - \Delta T)/\Delta T$$

ΔT is the measured difference in temperature between the heated probe and the reference probe. ΔTm is the maximum value of ΔT when there is no sap flow. (Grenier 1987).

Detailed observations have indicated that when a portion of the probe is inserted into inactive xylem, heat is attenuated more slowly, introducing a bias into probe readings (Clearwater et al. 1999). To adjust for this bias, a correction factor was used when the probe lengths were longer than the measured sapwood depth.

Table 1—*Characteristics of trees instrumented with sapflow sensors, Mattole River watershed, California, 2008.*

Species*	**Dia. at breast ht (cm)**	**Sapwood cross section (cm^2)**	**Basal area (cm^2)**	**Probe length[#] (cm)**
Douglas-fir	9	52	66	5
Douglas-fir	12	67	107	5
Douglas-fir	12	78	117	3
Douglas-fir	14	95	148	8
Douglas-fir	16	139	195	3
Douglas-fir	18	166	241	5
Douglas-fir	19	190	277	5
Douglas-fir	19	227	293	5
Douglas-fir	20	207	324	5
Douglas-fir	27	401	569	5
Douglas-fir	37	270	1051	8
Douglas-fir	42	397	1413	8
Douglas-fir	55	685	2364	8
Douglas-fir	76	771	4591	8
Douglas-fir	90	1023	6422	8
tanoak	38	865	1110	8
tanoak	52	1490	2088	8

*Douglas-fir (*Pseudotsuga menziesii*), tanoak (*Lithocarpus densiflorus*).

#Trees with 3 and 5 cm probes had one sensor per probe and one probe was placed in each tree. Trees with 8 cm probes had two sensors per probe, and two probes per tree.

The recommended correction factor (Clearwater and others 1999) is:

$$\Delta Tsw = (\Delta T - b\Delta Tm) / a$$

where ΔTsw is the change in temperature of the sapwood, ΔT is the recorded change in temperature of the probe relative to the reference probe, ΔTm is as defined above, a is the proportion of the probe in active xylem, and b is the proportion of the probe in inactive xylem.

The correction factor was not applied for the 80 mm probes as they have two sensors within the probe, one at 15 mm and one at 70 mm. Sap velocity (cm/s) is converted to sap flow rate (cm^3/s) by multiplying by the sapwood area of the tree, determined by coring techniques. The flow rate is then converted to volumes by summation of rates over the time period of interest.

Thermal shielding was installed to insulate the probes from direct sunlight. Two 48 hr power-down tests were conducted in which the heating elements were turned off to verify that the probes were properly insulated, with minimal heating from solar radiation. Probe readings were taken every 60s with the mean value recorded every

30m on dataloggers equipped with 32-channel multiplexers (CR1000, Campbell Scientific, Inc., Logan, UT).

Sapwood area was determined for each tree by the following procedure. Tree DBH was measured with a tape. The thickness of the bark was subtracted from the DBH. The thickness of the sapwood was determined by radial increment boring. Water conducting vascular tissue was identified by semi-translucent properties. Once the radius of the tree and the radius of the sapwood were measured, the radius of the heartwood could be estimated and the following equation applied:

$$SA = \pi (R_T^2 - R_H^2)$$

where SA is sapwood area, R_T is radius of tree (without bark) and R_H is radius of heartwood.

Basal area (BA) was calculated for all plots using tree diameter and the plot expansion factor for a ½ ha (1/5th ac) circular plot to get total BA/ac (cm^2). All trees were tallied within the plot. Species, diameter, and crown ratio were collected on every tree.

Continuous data was collected at 30 min intervals from July 6 to October 8, 2008. Data was summed into 24 hr daily totals. Daily totals were summed to create growing season totals for the period. Regression equations were developed between growing season water use and tree diameter, sapwood diameter and basal area. Sap flux density was calculated by converting liters to kg water, then dividing by sapwood basal area (m^2).

The next step was to generate estimates of seasonal water use for representative stands of the Mattole River watershed moving forward through time. A representative stand was created for a year 2005 starting point using an average created from four Forest Inventory Analysis plots (FIA). FIA is the U.S. Department of Agriculture's national forest inventory program (Woudenberg et al, 2010). The stand composition was then modeled through time using the U.S. Department of Agriculture, Forest Service Forest Vegetation Simulator (FVS, Dixon 2010). Output was generated for 20 size classes (0 to 101 cm) of DBH at 5 year increments for the period 2005 to 2055. Output used for this study included average DBH within each size class, trees/ha, and basal area/ha. FVS output was then used to estimate total growing season water use for each age class at each 5 year increment using the regression equation developed for basal area.

Results

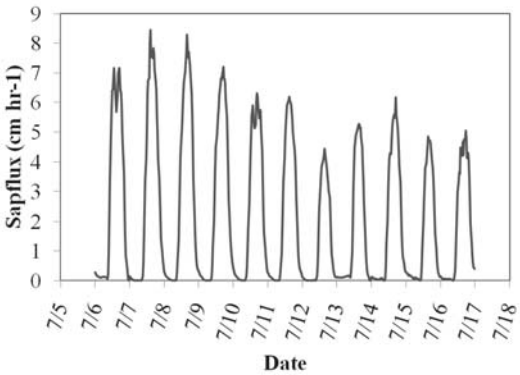


Figure 2—Daily sapflux, June 6 to17, 2008, Mattole River watershed.

Sapflow was observed to rise and fall with solar radiation levels. Representative samples of the daily continuous and weekly data for individual trees are shown in *fig. 2* and *3* respectively. A steady decline in transpiration was observed over the course of the season as soil moisture declined. This matches a drawdown in discharge in the Mattole River (*fig. 3*). The first rainstorm of the fall (Oct 2, 2008) caused a spike in transpiration readings. Total water use for each tree over the growing season is shown in *table 2*. A tight relationship was found between Douglas-fir sapwood area and water use (y = 7.6861x – 638.59, r^2 = .86). Strong positive relationships were also found between Douglas-fir diameter at breast height (DBH, cm) and water use (y = 92.397x - 1068.4.4, r^2 = .90), and for basal area (cm^2) and water use (y = 1.2611x +241.57, r^2 = .94). Regressions were also strong when the smaller trees in the young stand were analyzed separately. The relationship between basal area and water use was steeper for the young stand than for the larger trees (y = 3.423x – 233.15, r^2 = .76) indicating a steep increase in water use with increasing tree size at the lower end of the size range. To compare water use by tree size, seasonal water use for each tree was divided by the basal area of the tree. A higher range of water use was found for the smaller trees, as compared to the higher end of the size range. Trees below 30 cm DBH had an average water use/ unit basal area of 2.2 (± 1.2) l per cm^2, while trees larger than 30 cm DBH averaged 1.2 (± 0.5) l per cm^2. Mean sap flux density ranged from 123 to 976 kg per m^2 per day. A linear trend was not observed between sapwood area and mean sap flux density.

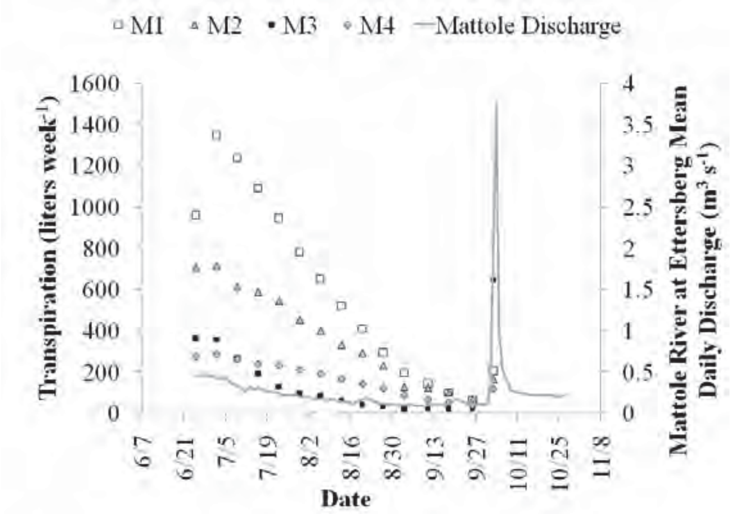


Figure 3—Sapflow in mature Douglas-fir over the 2008 growing season and Mattole River discharge. M1 to M4 refer to individual trees.

Table 2—*Water use in instrumented trees, Mattole River watershed, June 25 to October 8, 2008.*

Basal area (cm^2)	Season water use (liters)	Water use per unit basal area (liter cm^{-2})	Sap flux density (kg m^{-2} d^{-1})
Douglas-fir (*Pseudotsuga menziesii*)			
66	150	2.3	307
107	291	2.7	462
117	122	1.0	166
148	133	0.9	149
195	415	2.1	318
241	458	1.9	294
277	219	0.8	123
293	1415	4.8	663
324	711	2.2	365
569	1786	3.1	474
1051	2476	2.4	976
1413	2343	1.7	628
2364	2038	0.9	317
4591	5383	1.2	743
6422	8948	1.4	931
Tanoak (*Lithocarpus densiflorus*)			
1110	1817	1.6	223
2088	5849	2.8	418

There were not sufficient instrumented tanoak trees to create independent regressions. The data from the two tanoak trees appears to follow the general linear relationship of the Douglas-fir. Adding the two data points to the Douglas-fir data changes the regression equation only minimally ($y = 1.312x + 355.52$, $r^2 = 0.87$).

The initial forest species composition for 2005, determined from FIA plots, indicates a dominance by small Douglas-fir and tanoak trees (10 to 30 cm DBH), with a few larger pacific madrone (20 stems per ha). *Figure 4* shows basal area.

Forest Vegetation Simulator runs indicated a rapid attainment of canopy closure and stem suppression with a steep drop off in individual tree numbers over time. For example in the smallest size class (0 to 5.1 cm DBH), Douglas-fir drops from 525 to 95 trees per ha by 2055, and tanoak drops from 1929 to 887 trees per ha by 2035. As would be expected, a gradual increase in basal area is observed for surviving trees.

These trends are reflected in estimates of stand water use over time generated from applying water use data from this study to the Forest Vegetation Simulator output for future stand conditions. A drop in overall water use was shown for Douglas-fir species (489 to 385 m^3 per ha, *table 3*). This decrease resulted directly from the greatly reduced numbers of young trees. While mid and larger sized trees increased their water use over the time period, they were a much smaller proportion of total water use, so their impact was minimal. For example, summing the water use of the smallest four size classes (0 to 15 cm, DBH) we find a decrease over 50 years from 127 to 23 m^3 per ha, while the largest four size classes (86 to 102 cm, DBH) increased from 65 to 101 m^3 per ha.

Similar results were found for the tanoak and Douglas-fir. While water use of larger trees increases, its effect is eclipsed by the decrease in water use from stem suppression of younger trees. Overall water use drops from 2188 to 1506 m^3 per ha over the season. The largest trees increase water use from 46 to 170 m^3 per ha, while the smallest trees decrease from 813 to 23 m^3 per ha.

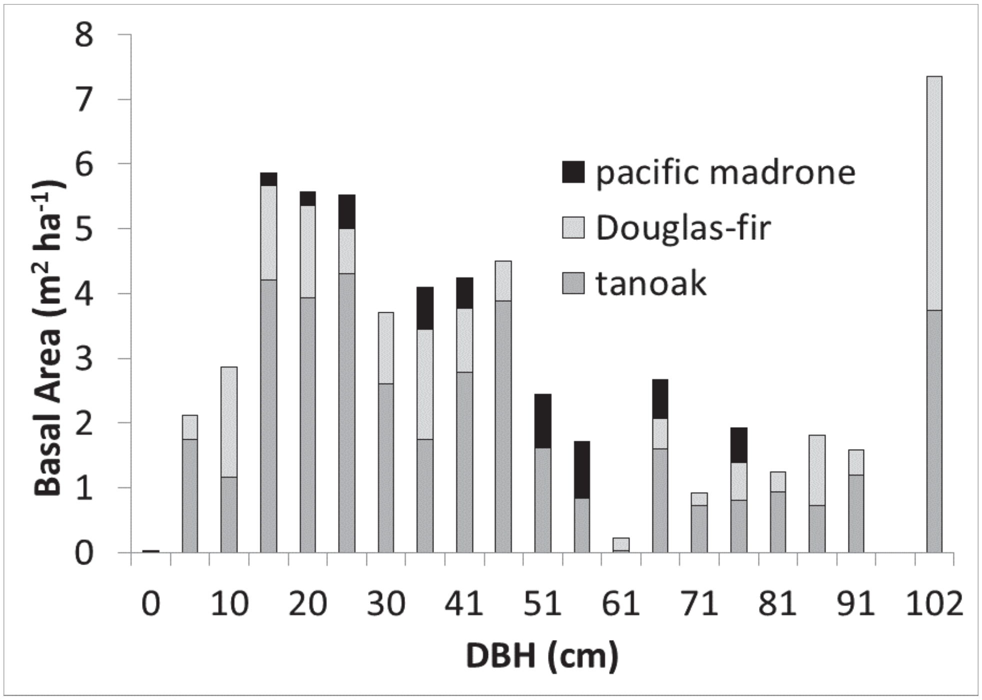


Figure 4—Mattole River watershed forest composition, basal area by DBH size class.

Discussion

Thermal dissipation probes were successfully used to quantify individual tree water use over the growing season, June to October, 2008. The October spike in water use resulting from a rainstorm indicates the sensitivity of tree growth to soil moisture and indicates the sensitivity of the method to fluctuations in tree growth. This was also observed by correlation of solar radiation measurements to measured sapflow: it decreased during cloudy days. Mean sap flux density values closely match values measured by Moore et al. (2004) for similar-aged Douglas-fir in western Oregon.

A tight relationship was found between measures of tree size: basal area, DBH, sapwood area, and tree water use. Previous research (Kostner et al. 1998) indicates that the number of trees measured were sufficient to characterize stand variability for Douglas-fir but not for tanoak. The high r2 values of the regressions are evidence that the variability of individual tree water use was sufficiently captured by the size of the sample.

Table 3—*Growing season water use in Douglas-fir estimated from sapflow measurements and Forest Vegetation Simulator output, Mattole River watershed, 2005 to 2055.*

Size Class (cm)	**2005**	**2015**	**2025**	**2035**	**2045**	**2055**
0.0	127	97	69	34	28	23
5.1	47	29	22	33	26	20
10.2	83	76	54	8	5	1
15.2	37	30	43	76	36	15
20.3	28	34	25	23	53	47
25.4	12	30	27	24	13	31
30.5	17	11	24	22	20	16
35.6	26	16	11	20	27	15
40.6	14	31	27	17	15	31
45.7	9	10	24	25	21	16
50.8	0	16	14	23	25	2
55.9	0	0	11	24	26	2
61.0	3	0	8	4	23	40
66.0	6	3	0	8	5	15
71.1	3	4	4	5	10	3
76.2	8	6	2	2	6	15
81.3	4	10	6	3	1	5
86.4	14	4	10	7	4	2
91.4	5	15	13	12	7	4
96.5	0	4	12	16	15	0
101.6	46	48	51	62	79	95
TOTAL	489	474	456	448	445	395

Individual tree water use was then combined with forest growth model predictions to estimate water use under future conditions. The predicted changes in forest vegetation should be accurate and representative of the Mattole as the input conditions were from four standard Forest Inventory Analysis plots surveyed in the watershed, the FVS model has been widely applied and validated, and was run by experienced practitioners.

The model assumes a stable climate, no thinning or harvest activity, and lack of major disturbance such as fire, windstorm or severe disease outbreak. If we make these assumptions for the purposes of isolating the impact of forest vegetation on water yield, the model output points to two strong and competing trends in forest composition that would stand drive water use. The first is the growth of the stand. We have shown a linear increase in water use with tree size. As the stands age over the next fifty years they will be composed of larger trees and might thus be expected to use more water. The second trend is stem suppression. As the trees grow the canopy closes and the trees begin to compete for available light. Suppressed trees eventually die out. The current composition of high numbers of very small (<5 cm DBH) trees indicates that the total number of trees will drop substantially in coming decades.

Our results strongly support the conclusion that stem suppression will be the dominant trend affecting water use in the Douglas-fir dominated portions of the Mattole river watershed. Water use will be expected to decline in a steady fashion as the number of trees declines. A further implication of this finding is that clearcut harvesting of existing stands would not be beneficial for water yield in the basin beyond the initial regeneration period. It would result in a new crop of dense small trees, and delay the stem exclusion stage that much longer. Selective harvest of small and mid size trees might be expected to increase water yields without producing a thicket of young trees if remnant trees were able to quickly grow into the light gaps.

The results are less conclusive regarding tanoak which is the more dominant species in the Mattole River watershed because only two trees were instrumented. The two trees had similar mean sap flux density values as the Douglas-fir. The water use predictions made using the basal area regression that included tanoak would indicate that stem suppression is also the dominant process affecting water yield for this species over the next fifty years. The numbers of small tanoak in the watershed are quite high.

One way to assess the robustness of this conclusion is to test the sensitivity of the conclusion to input assumptions. To perform this sensitivity test we increased the water yield slope by 50 percent for tanoak (from 1.3123x + 355.52 to 1.968x + 355.52) and then looked at resulting water use predictions for the whole stand over the period 2005 to 2055. The water yield continued to show a decrease over this time period (1927 to 1439 m^3 per ha) as compared to the original (1699 to 1111 m^3 per ha).

Previous research supports our finding of diminished water use with stand age. A sapflow study in western Oregon (Moore et al. 2004) determined that young mature Douglas-fir stands (40 yr) had 3.27 times higher water use than old growth Douglas-fir (450 yr) stands for a similar time period (June to October, 2000). They attributed this difference to greater sapwood area per unit basal area and greater sap flux density in the younger stand, as well as greater numbers of mesic angiosperms. Phillips et al. (2002) found reduced hydraulic conductance in older Douglas-fir stands as compared to young and mature trees.

Conclusions

Sapflow measurements in the Mattole River watershed show strong relationships between total seasonal tree water use and basal area, DBH and sapwood basal area for Douglas-fir. Water use measurements combined with stand growth modeling indicate that the water use of Mattole River forests will decline in coming decades as the high numbers of young (< 5 cm DBH) trees decline from canopy closure and stem suppression. Decreased water use is expected to have beneficial effects on aquatic ecosystems.

References

Clearwater, M.J.; Meinzer, F.C.; Andrade, J.L.; Goldstein, G.; Holbrook, N.M. 1999. **Potential errors in measurements of nonuniform sap flow using heat dissipation probes.** Tree Physiology 19: 681-687.

Dixon, G.E., compiler. 2002. **Essential FVS: a user's guide to the forest vegetation simulator.** Internal Report. Fort Collins, CO: US Department of Agriculture, Forest Service, Forest Management Service Center. 193 p.

Granier, A. 1985. **Une nouvelle methode pour la mesure du flux de seve brute dans le tronc des arbres.** Annales des Sciences Forestiers 42:81-88.

Granier, A.; Biron, P.; Breda, N.; Pontailler, J.Y.; Saugier, B. 1996. **Transpiration of trees and forest stands: short and long term monitoring using sapflow methods.** Global Change Biology 2: 265-274.

Kostner, B.; Granier, A.; Cermak, J. 1998. **Sapflow measurements in forest stands: methods and uncertainties.** Annales des Sciences Forestiers 55: 13-27.

McCulloh, K.A.; Winter, K.; Meinzer, F.C.; Garcia, J.A.; Lachenbruch, B. 2007. **A comparison of daily water use estimates derived from constant-heat sap-flow probe values and gravimetric measurements in pot-grown saplings.** Tree physiology 27: 1355-1360.

Moore, G.W.; Bond, B.J.; Jones, J.A.; Phillips, N., Meinzer, F.C. 2004. **Structural and compositional controls on transpiration in 40- and 450-yr-old riparian forests in western Oregon, USA.** Tree physiology 24: 481-491.

Phillips, N.; Bond, B.; McDowell, N.; Ryan, M.G. 2002. **Canopy and hydraulic conductance in young, mature, and old Douglas-fir trees.** Tree Physiology 22:205-211.

Swanson, R.H. 1994. **Significant historical developments in thermal methods for measuring sap flow in trees.** Agricultural and Forest Meteorology 72:113-132.

Waring, R.H.; Schroeder, P.E.; Oren, R. 1982. **Application of pipe model theory to predict canopy leaf area.** Canadian Journal of Forest Research 12: 556-560.

Woudenberg, S.W.; Conkling, B.L.; O'Connell, B.M.; LaPoint, E.B.; Turner, J.A.; Waddell, K. L. 2010. **The Forest inventory and analysis database: database description and users manual version 4.0 for Phase 2**. Gen. Tech. Rep. RMRS-GTR-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 336 p.