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Environmental Defense Fund

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1. Executive Summary

In this white paper on the Sierra Nevada Watershed Ecosystem Enhancement Project (SWEEP), we make the case that upstream management of Sierra Nevada forests can significantly increase the value of downstream water resources by shifting water towards higher value uses and optimizing the timing of runoff. The focus of this paper is on the west-side mixed-conifer forests at elevations of about 1500-3600 m (5000-12,000 ft), which are highly productive owing to the availability of sufficient water, predominance of above-freezing temperatures and presence of other conditions necessary for growth.

California has a Mediterranean climate, with wet winters and dry summers. Precipitation falling as rain on Sierra Nevada forests enters the soil and is partitioned between evapotranspiration and runoff. Much of the rainfall leaves the forest as evapotranspiration, owing to ample water storage in the subsurface and temperatures that allow growth year round. At higher elevations, e.g. above elevations of 1800-2100 m depending on both latitude and microclimate, which are dominated by snow rather than rain, the snowpack provides an important seasonal storage of water that, together with subsurface-water storage, provides the water needed for forest growth over the summer and fall. Forest thinning to reduce vegetation and thus evapotranspiration will result in a higher fraction of precipitation, particularly snowmelt, leaving the mountain forest as runoff.

Historically, the unique character of Sierra Nevada forests was defined by tall trees, relatively mild climate and low forest density.

Historically, the unique character of Sierra Nevada forests was defined by its tall trees, relatively mild climate and low forest density. In many areas, current forest densities are much higher than historical values. Forest thinning can also influence the timing of snowmelt and runoff. That is, a less-dense canopy can allow snow to reach the ground rather than be held in the canopy; and strategic spacing of forest openings will limit early season sunlight reaching the forest floor and retard snowmelt.

First-order estimates based on average climate suggest that reducing forest cover by 40% of maximum levels across a watershed could increase water yields by about 9%.

In this paper we review the forest hydrology literature relevant to management of conifer forests in the Sierra snow zone, as that management affects the timing and amount of snowmelt runoff. In order to understand the conceptual and practical challenges, we summarize the key elements of forest energy budget, with specific reference to the Sierra Nevada, and describe several relevant case studies. Although principles that govern the mountain water cycle are well known and models of water and energy balance are informed by field measurements in some areas, there is a severe knowledge gap that limits quantitative predictions of the effects of forest thinning on Sierra Nevada water and energy cycles. Nevertheless, generalizations from reviews of paired catchment studies carried out elsewhere suggest that Sierra

Nevada conifer forests contain ecological attributes with a high potential for water-yield gains. Historical studies of forest harvesting in the Sierra Nevada have shown increases of between 14 and 34% in snow accumulation. Treatments that increase snow accumulation help increase water yield during low flows, when water resources' economic and ecosystem values are highest.

Sustained, extensive treatments in dense Sierra Nevada forests could increase water yield by up to 16%.

Preliminary estimates based on average climate information suggest that in the Sierra Nevada, treatments that would reduce forest cover by 40% of maximum levels across a watershed could increase water yields by about 9%.

Note that this white paper focused on forest management effects on the water balance. Impacts on wildlife habitat, forest health, and fire behavior were not analyzed. The projections and models reported here are designed to describe the potential for modifying water yield and timing. Before implementation of any strategy, a wider consideration of the consequences on forest structure and function would be necessary.

Because of the potential for water-yield increases and extended snow storage, the SWEEP project has developed a plan to evaluate forest thinning related to water yield in representative headwater catchments in the Sierra Nevada, as a basis for extending these treatments to broader areas of the Sierra Nevada. To that end, we outline an experiment that could be carried out in the Onion Creek Experimental Forest, Tahoe National Forest, Placer County, California that could test silvicultural treatments designed to modify the water balance of mixed-conifer, snow-dominated catchments. The treatments are based on a leaf area index (LAI) approach (O'Hara 1998) to forest management, which is well-suited to water yield and timing objectives. Our initial estimates are that treatments could increase water yield as much as 16% and extend snow storage, i.e. delay snowmelt, by days to weeks.

Even small increases in water yield or improvements in the timing of water flow in the large area of mixed-conifer forest are important because of the high value of water used by both hydroelectric facilities and downstream users.

2. Introduction

The Sierra Nevada contains the headwaters of 24 major river basins, with the majority of the runoff being on the west side and draining into the Central Valley (Figure 1). Most of these are east-west trending watersheds that dissect the Sierra into steep canyons. The major vegetation zones of the Sierra form readily apparent large-scale elevational patterns. A broad conifer zone begins at 300-900 m (1000-3000 feet) elevation on the west and 900-1500 m (3000 -5000 feet) on the east side. Under pre-European conditions, fires and other disturbance events regularly burned patches of trees, leaving openings that passed through continuous but distinctive phases as they aged. This succession of a forest through time between major disturbances is important for plants and animals that use different stages as habitat. Within the last 100 years, human influence increased in which resource use was more regulated and forest and range protection was emphasized. Suppression of fires became a primary goal of federal, state and private efforts (Fites-Kaufmann et al. 2007).

Figure 1. Satellite image of California showing snow-covered Sierra Nevada. Courtesy of NASA

Sierra Nevada ecosystem services. The forests of the Sierra Nevada deliver important benefits to the citizens of California and the rest of the world. With the extensive exploitation that began with the 1849 gold rush, the Sierra Nevada has provided considerable timber, feed for grazing animals, and irrigation water for local agriculture. Over the past half century, the development of water projects for regional irrigation systems and hydroelectric power surpassed all other products and services in terms of financial payments (Stewart 1996). Other benefits, or “ecosystem services” derived from Sierra Nevada forests include clean air, fresh water, wildlife habitats, nutrient cycling, carbon storage, and recreational opportunities. The concept of valuing ecosystem services has recently received considerable attention as a means to ensure investment and management of sustainable ecosystems (e.g., Millennium Ecosystem Assessment 2003, Collins and Larry 2007, Daily and Matson 2008, Smail and Lewis 2009). However, there are only a few instances when ecosystem values have been quantified and mechanisms developed to compensate landowners for providing these services. For example in 1996, New York City valued the quality of water delivered from their primary watershed in the Catskill Mountains to be between $6-8 billion in capital costs and $300 million in annual operating costs. These estimates were based on the expenses associated with building and operating a water filtration plant required to meet federal standards for water quality. New York chose to avoid these costs by investing more than $1.5 billion to maintain the natural and social integrity of the Catskills and thereby ensure the quality of their water (Chichilnisky and Heal 1998, Jackson et al. 2001). To date, New York's watershed investment program has provided the financial, technical, and political support to reduce non-point pollution from farms, improve forest management, restore stream corridors, upgrade local sewage treatment systems, remediate leaky septic fields, and acquire conservation easements of sensitive ecosystems (www.nyc.gov/dep). Essential to New York's success was the means to compensate landowners (individuals and communities) for the ecosystem services their lands deliver. Without this link, there is limited incentive to protect or improve these services. One of the most valuable services provided by Sierra Nevada forests is the clean water that flows downhill to fuel California's economy and support freshwater, estuarine, and terrestrial ecosystems. About two thirds of the precipitation that falls on the Sierra Nevada is evaporated or transpired by vegetation and one third runs out of the region in streams and rivers. In an average year, the Sierra Nevada receives 27 percent of the state's annual precipitation and provides more than 60 percent of the state's consumptive use of water (estimates based on authors' calculations from data in Department of Water Resources 2005). Sierra forests do more than just supply water; they store water and even out the runoff over the spring, summer and fall. Much of the state's precipitation falls in the winter as snow and is stored in that form during the wet winter months (Figure 2). The slow melting of snow in the spring and storage of water in the subsurface provide the water necessary for vegetation to grow as well as the flows of water for downstream use, including the generation of hydropower at the Sierra Nevada's many hydroelectric generation facilities. Storage of water as snow acts as an upstream reservoir that augments the capacity of downstream reservoirs. On average, the volume of snowpack storage is estimated to be greater than the reservoir capacity in either the San Joaquin or Sacramento basins (Figure 2).

Photo 1. Dense forest in North Fork, American River basin

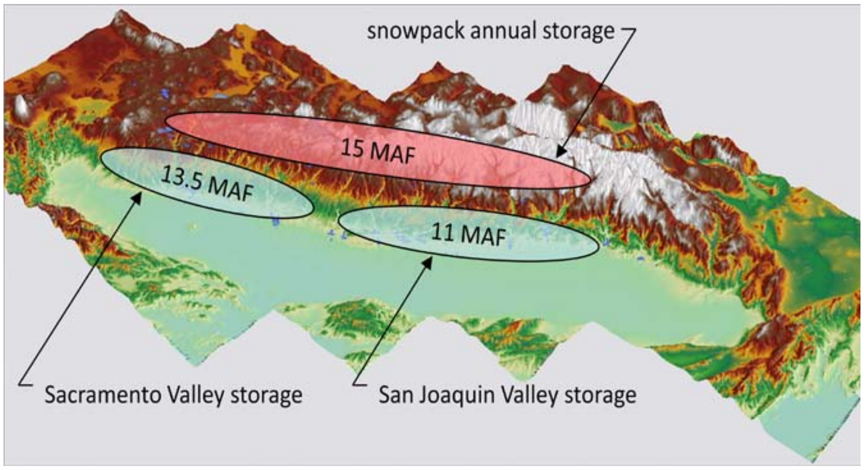

Figure 2. Storage capacity of the Sierra Nevada snowpack in comparison to dams and reservoirs. Information from the California Department of Water Resources. MAF = million acre feet of water. Note than 1 million acre feet equals 1.23 x 10^9 m^3.

Snowpack retention is a valuable ecosystem service, but the forest landowners who provide this service derive no economic return from this service. As it becomes increasingly apparent that runoff in future decades cannot be as effectively captured by a reservoir and canal system built in past decades (Moser et. al. 2009), greater attention is being paid to strategies towards designing cost-effective adaptation strategies.

Hydropower in the Sierra Nevada. Water from Sierra Nevada forests has significant financial value to downstream users when it is used to generate "carbon-free" hydroelectric power and when it is eventually diverted to agricultural and municipal users. In 1996, the economic value of water from Sierra forests, as indicated by the revenue generated from its use, was as much as $75 per acre-foot (Stewart 1996).Generating electricity from water flowing downhill provides nearly half of the economic value of water runoff from the Sierra (Table 1). With the probable increase in the value placed on carbon-free energy and the reduced water that can be diverted out of rivers and the Delta, the relative value of water runoff may increase substantially.

Table 1. Revenue in dollars per acre-foot of water runoff for three regions of the western slope of the Sierra Nevada (Stewart 1996). 1 acre-foot = 1233 m^3.

Watershed	Value of agricultural and municipal uses	Hydroelectric revenues	Total value
Sacramento	36	31	67
San Joaquin	39	36	75
Tulare Lake	32	17	49
Sierra – West Side	36	31	67

The hydroelectric revenue from any additional acre-foot of water depends on how much of the water's drop in elevation is captured in hydroelectric turbines. Some of the runoff from high in the Sierra Nevada generates power for hundreds of meters (thousands of feet) of drop at a series of dams. Runoff from high elevations that goes through a series of turbines can generate considerably more revenue than the average hydroelectric value of $31 per acre-foot ($0.025 per m^3). Many watersheds along the crest of the Sierra Nevada with values for additional runoff of $40 per acre-foot ($0.033 per m^3) or greater are legally zoned as wilderness or reserves. However, the North Fork of the Feather River, the American River, and the San Joaquin River stand out as areas where the potential for additional revenue is significant and where a considerable fraction of the watersheds are managed for multiple benefits by private and public entities (Figure 3).

Climate change and Sierra Nevada water. California's water supply is particularly vulnerable to the forces of climate change. This vulnerability is due to both the supply of water and the infrastructure built to manage this water (Department of Water Resources 2010). Global general circulation models project generally drier conditions in California, particularly in regard to water supply (Vicuna 2006). Specifically, they project that critical water shortages will become more common compared to the historical record. It is worth noting that the projections of reduced precipitation are less certain and less severe than the predicted temperature increases (Miller et al. 2009). By 2050, snowpack storage is expected to decline by 25% because of a warming climate (Department of Water Resources 2008). Warmer temperatures lead to more precipitation falling as rain and an earlier snowmelt (Kapnick and Hall 2010). Less precipitation falling as snow means less storage and a greater potential for high peak flows followed by droughts. This change will lead to the loss of considerable economic value as less water will be available for irrigating high-value crops and less hydroelectric power will be available to match high summer electricity demands. The warming, drying climate will have direct negative effects on supply of water from and storage of water within Sierra Nevada forests.

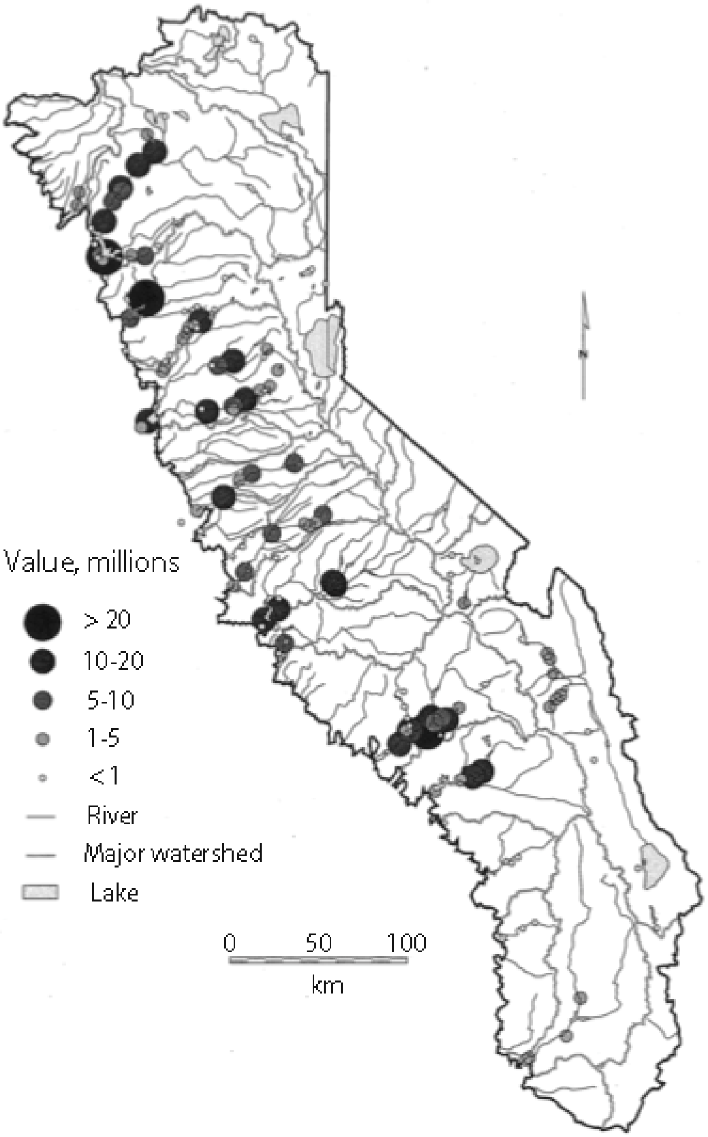

Figure 3. Average hydroelectric revenue at 2.5 cent per kwh for 122 dams in the Sierra Nevada. From Stewart 1996.

Photo 2. Partially thinned stand with understory, North Fork, American River basin

One of the few ways that California can address the negative impacts of climate change on water yield and storage in the Sierra Nevada is through changes to the forest vegetation. At the most basic level, trees move water from the soil to the atmosphere, reducing surface flow and downstream yield. In the winter, a portion of the snow caught in branches evaporates or sublimates and reenters the atmosphere without ever melting. Reducing the total amount of evapotranspiration from vegetation could potentially increase the amount of water flowing downstream. Reducing the current forest canopy cover and related evapotranspiration could also bring forest stands closer to historic conditions where regular fires across the landscape resulted in much lower levels of forest canopy cover than we have today (Collins 2011). Regional water budgets suggest that around 70 percent of total precipitation is evapotranspired by native vegetation in the Sierra Nevada (Department of Water Resources 2005). The density of trees can also affect the storage of snow in a forest. In general, overly dense forest stand structures result in a higher proportion of snowpack in tree canopies rather than on the forest floor, where it is more protected from solar radiation. Therefore, a relatively open stand structure consisting of fewer, larger trees where understory vegetation is controlled could enhance snowpack retention. The impacts of specific forest management prescriptions on water yield and snowpack involve multiple factors. The need for site-specific analysis of the link between forests and water is the key motivation for this project.

Focus of this study. Under SWEEP we explore the delivery of ecosystem services by Sierra Nevada forests, specifically on water yield and water storage. SWEEP tests the contention that forest management can be optimized to increase total water yield and to extend the spring snowpack. In short, SWEEP asks: Can Sierra Nevada forests be managed to provide more water at the right time of year for California?

SWEEP also plans to quantify the economic value of these water-related services (e.g. snowpack retention, water storage, increased yield, and flow attenuation). The final link will be to connect the beneficiaries of enhanced water storage and yield with the landowners providing them through new types of markets. In other words, water users that benefit from changes in forest management might be willing to pay upstream landowners to provide these services. That in turn would become a powerful financial incentive for landowners to invest in beneficial management practices. Ultimately, SWEEP hopes to develop policy and institutional mechanisms for an ecosystem services market that maximizes benefits to water users, forest landowners, and the forest ecosystem.

The SWEEP team is a multidisciplinary group of foresters, ecologists, hydrologists, and policy experts from University of California Berkeley, University of California Merced and staff of the Environmental Defense Fund.

3. Background on Forest Hydrology

Water and energy budget in mountain forests. Wet winters and dry summers distinguish the mountain water cycle in the Sierra Nevada. The seasonal snowpack is a critical component of this water balance. At lower elevations, the snowpack melts shortly after being deposited by a cold storm, but at higher elevations the snowpack typically accumulates from December until March or April andthen melts from April through June or July. The elevation at which precipitation falls as snow varies from storm to storm and often varies during an individual storm. In the high Sierra Nevada, total annual precipitation ranges from a low of about 60 cm (24 in) in the south to a high of more than 200 cm (79 in) in the north (Figure 4). Across much of the forested Sierra Nevada, precipitation is partitioned between runoff and evapotranspiration (Box 1).

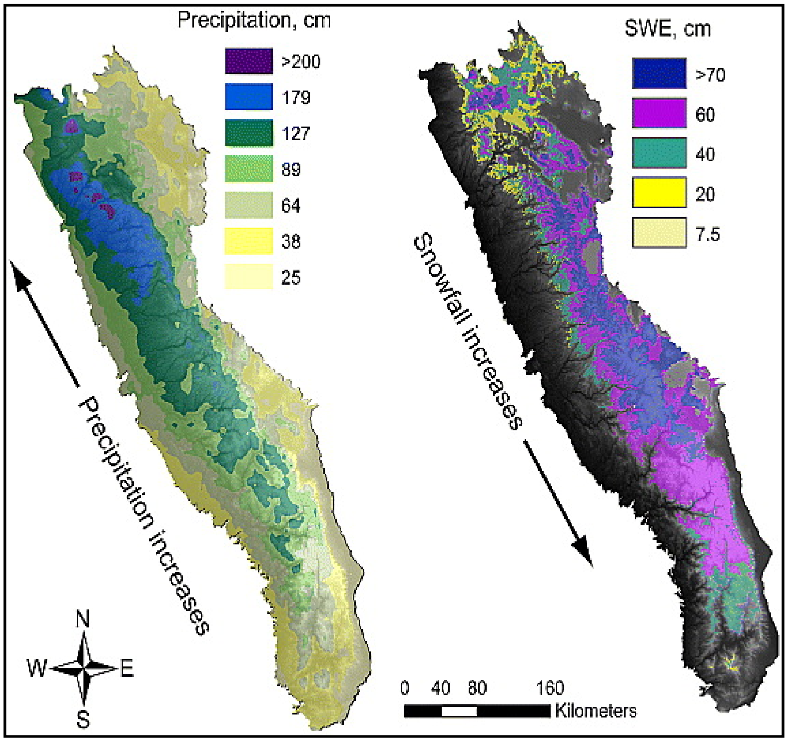

Figure 4. Average precipitation and snow water equivalent (SWE) in the Sierra Nevada (Bales et al, 2006).

The energy balance in the forest determines when snow melts (Box 2). Snow melt is driven by temperature and vapor density gradients within the snow caused by heat exchange at the snow surface and at the snow–soil interface (Marks et al. 1999; Pomeroy et al. 1998). Forest cover reduces the energy from the sun and the influence of wind on snow melt. The energy balance on sub-canopy snow is dominated by radiation, with incoming shortwave irradiance modified by the canopy shading and longwave irradiance increasing from canopy thermal emissions (Link et al., 2004; Sicart et al., 2004; Pomeroy et al., 2009). Forest cover may also affect sub-canopy shortwave radiation by altering snow-surface albedo (the fraction of incident sunlight that is reflected) through deposition of forest litter on snow (Hardy et al., 2000; Melloh et al., 2002).

Snowmelt rates are higher in open areas in near-freezing temperatures, but when the air warms (i.e., temperatures well above freezing) melt rates are higher under the canopy (Lopez-Moreno and Latron 2008). This switch in melt rates during warm periods is in part due to sensible heat exchange and latent heat of evaporation becoming melt drivers, such that the blocking of incoming solar radiation becomes relatively minor. Additional longwave radiation emitted by the dense vegetation during the warmer periods also amplifies this effect.

Conifer canopies intercept a portion of snowfall, and snow caught in canopies sublimates at higher rates than ground-level snow (Essery et al. 2003). Sublimation rates in areas that have been studied range from 15% to 60% of annual snowfall (Hood et al. 1999, Parviainen and Pomeroy 2000, Montesi et al. 2004, Troendle and King, 1985; Schmidt et al., 1988; Pomeroy and Schmidt, 1993; Lundberg and Halldin,1994; Storck et al., 2002). Higher temperatures, lower humidity, and greater wind speeds can all increase sublimation rates (Montesi et al. 2004).

Box 1. Forest water balance

The water balance for the near surface, or zone of interest for trees and other components of the ecosystem, can be written as precipitation (*P*) being equal to the sum of evapotranspiration (*ET*) plus runoff (*R*), measured as streamflow, plus groundwater recharge (*D*) plus the change is soil water storage (ΔS):

$$P = ET + R + D + \Delta S \qquad (1)$$

In forest catchments, precipitation, runoff, and evapotranspiration typically dominate the water balance. Groundwater recharge is often the smallest term in the water balance equation; soil water storage is expected to balance over the long-term (5-10 years), if not annually. Thus for our analysis, groundwater recharge is assumed to be negligible and net soil water storage is assumed to equal 0. Therefore mean annual water yield is defined as:

$$R = P - ET \qquad (2)$$

Data to evaluate differences in sublimation losses in forests similar to those in the Sierra Nevada are few; however, Ellis et al. (2010) compared accumulation at 4 locations, two of which have trees over 25 m tall (82 ft) and may be somewhat relevant to the Sierra Nevada (Figure 5). Both showed significantly more snow water equivalent (SWE) in the open versus under the canopy, though no differences in melt rates were apparent; differences in melt out date were also inconclusive. However, in the warmer Sierra Nevada, canopy snow unloading should be higher and thus canopy sublimation loss lower than in the two locations shown on Figure 5. In practice, estimating and verifying the effects of changes in canopy in the Sierra Nevada on mass balance of the snowpack involves understanding and predicting sublimation and melt, both on the ground and in the canopy (Box 3).

Box 2. Snowcover energy balance

The energy balance of a snowcover is:

$$\Delta Q = R_n + H + L_vE + G + M \qquad (3)$$

where ΔQ is change in snow cover energy, and R_n, H,L_vE, G and M are net radiative, sensible, latent, conductive, and advective energy fluxes (all terms are in W m^2), respectively; L_v is the latent heat of vaporization, or sublimation (J kg^{-1}) and E is the mass flux by sublimation from or condensation to the snow surface (kg m^2 s^{-1}). In this context, advected energy M is heat lost or gained when mass (precipitation) of a specified temperature is added to the snow cover. In thermal equilibrium $\Delta Q = 0.0$; whereas a negative energy balance will cool the snow cover, increasing its cold content, while a positive energy balance will warm the snowcover. The snow cover cannot be warmer than the melting temperature T_{melt} (0.0°C) and melt cannot occur until the snow, or a layer within the snow cover, has reached this temperature. Once the snow is isothermal at 0.0°C, positive values of ΔQ must result in melt. While the tools are readily available to calculate energy balance both above and beneath the canopy, the necessary data are not widely available. Thus in some cases a simpler temperature-index approach is used, with coefficients developed from snow-index sites in the area. In this approach, daily snowmelt is a linear function of degree days (degrees daily average temperature is above zero) times a degree-day coefficient (T_{index}):

$$\mathrm{Melt} = \mathrm{D}_{\mathrm{day}} \times \mathrm{T}_{\mathrm{index}} \qquad (4)$$

Typically T_{index} increases as the season melt season progresses, reflecting the generally greater net radiation for snowmelt later in the year. While this simpler approach indicates the average snowmelt with warmer temperature, a more-explicit energy-balance approach is needed to describe the effect of forest thinning on snowmelt.

Because of the prevalence of rain at lower elevations and snowfall at higher elevations, the lag between precipitation and discharge depends on elevation. For example, the Kings River Experimental Watersheds (KREW) and associated Southern Sierra Critical Zone Observatory (CZO) are dense, mixed-conifer, headwater forests that show about a two-month lag between precipitation and discharge (Figure 6). Note that only about 50% of the precipitation fell as snow in this catchment. Going up in elevation another 400-500 m (1,300 to 1,640 ft), we find a lag of about three months (Hunsaker et al., 2011). In general, snow melts out about 20 days later for each 300 m (1000 ft) higher in elevation (Rice et al., 2011). Water yield from these catchments varies from as little as 10% of precipitation, in a more rain-dominated catchment in a dry year, to more than 60%, in a snow-dominated catchment in a wet year. Evapotranspiration accounts for most of the precipitation not leaving the catchments as discharge. In the lower-elevation catchments, at least, trees transpire year-round, drawing water from both soil and deeper zones during the dry summer, when evapotranspiration is highest (Bales et al., 2011).

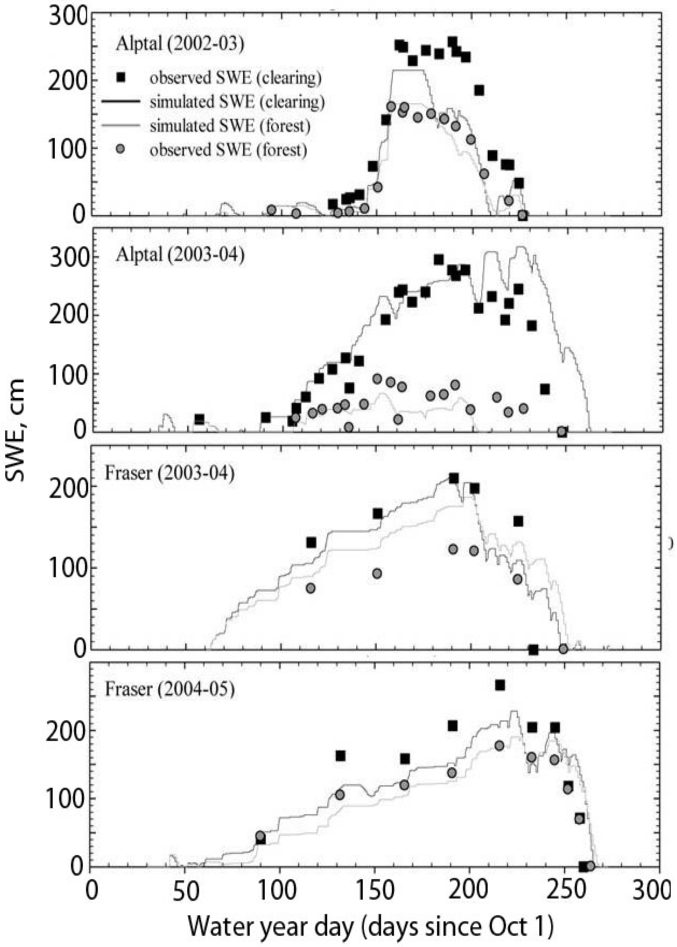

Figure 5. Time series of observed and simulated SWE at paired forest and clearing sites. Aptal is in Switzerland, 1185-1220 m (3887-4002), 47° 3'N, 3-11° slope and 25-m (82 ft.) spruce and fir in forested plot. Fraser is in Colorado, 2820 m (9250 ft.), 39° 53' N, 17° slope and ~27-m (89 ft.) spruce and fir in the forested plot. Adapted from Ellis et al. (2010).

Box 3. Forest snowcover mass

A mass balance on snow in a forest, adapted from Ellis et al (2010), can be expressed as:

$$\Delta SWE = P_s - (I_s - U_l) + P_r - (I_r - R_d) - M - S \qquad (5)$$

where P_s is snowfall, P_r is rainfall, I_s is canopy snowfall interception, U_l is canopy snow unloading, I_r is canopy rainfall interception, R_d is canopy rain drip, M is melt loss and S is sublimation of snow on the ground. The difference $I_s - U_l$ is sublimation loss in the canopy and he difference $I_r - R_d$ is evaporation loss in the canopy. Interception is proportional to LAI. In a non-forested clearing, the balance is:

$$\Delta SWE = P_s + P_r - H_{in} - H_{out} - M - S \qquad (6)$$

where H_{in} and H_{out} are blowing snow into and out of the area of interest.

Data to evaluate these differences are few.

Forest management and water. In principle, vegetation can be managed to meet water-resource goals, particularly in forests where trees create dense canopies. As net primary productivity (i.e., plant growth) increases, evapotranspiration (the primary cause of water loss) also increases. Any manipulation that reduces the productivity (e.g., removes trees, shrubs or grasses) reduces evapotranspiration and thus may increase water availability.

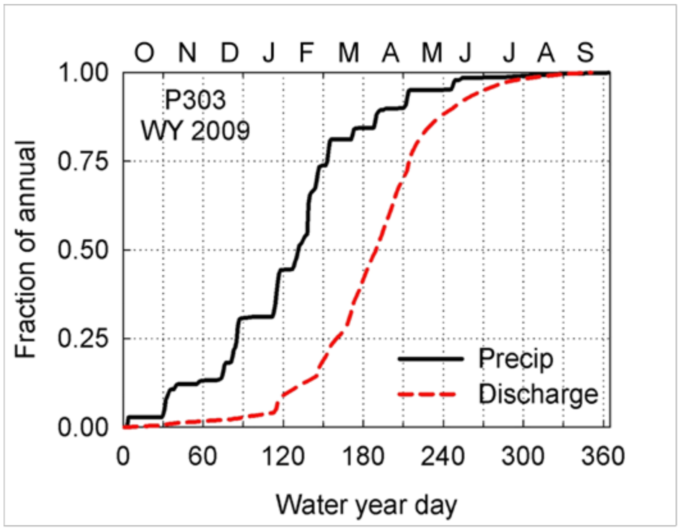

Figure 6. Water year basin-average precipitation and discharge for one headwater catchment at an elevation of 1750-2000 m (5740-6560 ft.). Adapted from Bales et al. (2011).

This well-established link between water and forests suggests that forest ecosystems can be managed to meet water resource priorities. Indeed, there is a long history of research in forest hydrology in which the impacts of various natural and anthropogenic disturbances are evaluated with regard to water quantity and quality (Bosch and Hewlett 1982, Hornbeck et al. 1993, Sahin and Hall 1996, Stednick 1996, Brown et al. 2005).

Paired-watershed experiments provide the bulk of the evidence informing conclusions regarding the effects of vegetation management on forest hydrology. In a paired-watershed study, stream gages are built at the mouth of two or more watersheds. Ideally the watersheds are similar in size, soils, vegetation, and land-use history. Streamflow is monitored for several years to define baseline conditions. Then watersheds are manipulated (e.g., trees cut, shrubs removed, fire introduced). At least one watershed is left untreated to provide a reference. The differences in water yield between experimental watersheds and the reference is the measure of the impact of the treatments. It is an expensive but potentially rigorous approach to watershed science. During the past 60 years, literally hundreds of experiments have been conducted worldwide, and the results have been summarized in a sequence of reviews (e.g., Bosch and Hewlett 1982, Hornbeck et al. 1993, Sahin and Hall 1996, Stednick 1996, Brown et al. 2005). However, no paired-watershed studies have been conducted in the conifer forest that dominates the west side of the Sierra Nevada. Thus, when assessing the potential of forest management to influence hydrology in the Sierra Nevada, inferences must be drawn from an appropriate subset of the literature.

Perhaps the most significant consideration is that most of the paired-watershed studies impose a treatment once and then allow the forest to regrow (Hornbeck et al. 1997). In reporting yield effects, runoff is typically measured for five years following the treatment and the effect reported as the mean during those five years (Brown et al. 2005). However, the recovery of forest vegetation can be rapid. For example, following a whole-tree harvest in a northern hardwood forest in New Hampshire, canopy cover returned to preharvest levels in three years, as did evapotranspiration and stream runoff (Hornbeck et al. 1997). Maintenance of treatment effects is a key consideration in forest management for water.

Generally, paired-catchment studies show immediate on-site increases in water yield, but to propagate the effect far enough downstream to be meaningful for end users requires a large portion of the watershed to be treated. Applying this idea to Coon Creek, a 1,659 ha (4,100-ac) watershed in Wyoming, Troendle and others (2001) found that removing 24% of vegetation led to a significant water yield increase of three inches. Yield increases have been shown to be minimal or negligible during years with drier-than-normal precipitation and maximized during wet years.

Photo 3. Typical meteorological station supporting research in snow-covered southern Sierra Nevada.

A comprehensive project (based at the Fraser Experimental Forest in Colorado) used the Fool Creek Watershed to evaluate the effects of harvesting on water yield, timing, peak discharge, and peak water equivalent over 28 years (Troendle and King 1985). Initial studies following harvest (Hoover and Leaf 1967; Leaf 1975) suggested no change in water balance, attributing changes in water yield to reduced transpiration, with increases in SWE in forest clearings attributed to aerodynamic redistribution of the snowpack. However, when Troendle and King (1985) revisited the issue, analyzing 28 years of data, they were led to the conclusion that increases in water yield (+40%), peak discharge (+23%), and peak water equivalent (+9%) do exist, along with earlier peak flows (-7.5 days). This study highlights the need for long-term monitoring of hydrologic research sites, few of which exist in the Sierra Nevada.

While most of the increase in water yield is concentrated around removal of the trees themselves, additional factors may also affect the water balance. Royce and Barbour (2001) found that per unit of biomass, understory shrubs deplete soil moisture faster and consume more available soil moisture than conifers. This research suggests that understory management may also be an important factor in modifying transpiration effects on water yield.

Generalizations from reviews of paired-catchment studies suggest that the Sierran conifer forest has ecological attributes with a high potential for water-yield gains. First, forest

Photo 4. Snow-depth sensors in Southern Sierra CZO meadow and adjacent forest.

catchments dominated by evergreen, needle-leaved trees consistently show greater per capita gains in water yield relative to fraction of forest cover removed than any other forest type. For example, Bosch and Hewlett (1982) found per capita water yield in temperate conifer forests to be on average 60% greater than in temperate deciduous forests. Changes in water yields depend on the amount of precipitation (Zhang et al. 2001). In extremely dry ecosystems (< 500 mm [<20 in] precipitation annually) and extremely wet ecosystems (> 1500 mm [60 in] precipitation annually), there is limited ability to affect water yield by manipulating the vegetation. In the high Sierra Nevada, total annual precipitation ranges from a low of about 600 mm (24 in) in the south to a high of over 2,000 mm (79 in) in the north (Bales et al. 2006). Thus, in terms of input, the Sierra Nevada spans a range where there is a near-linear increase in water yield with reductions in forest cover (Zhang et al. 2001). In snow-dominated systems like the Sierra Nevada, there is clear seasonality in the water yield response to thinning, with the greatest absolute increases observed during snowmelt (Brown et al. 2005). However, the greatest proportional increases are generally observed during the dry summer months (Brown et al. 2005). Predicted increases in yield from the combination of thinning and storage as snow suggest that upstream forest management can help fill downstream reservoirs in the spring as well as increase crucial flows during the dry summer months.

An indication of the potential water impacts of forest management can be developed using data from the Sierra Nevada and models established in the literature (equation 8 in Zhang et al. 2001). Specifically, we used the range of annual precipitation reported for catchments along the north-south gradient of the Sierra Nevada (Bales et al. 2006). We compared 90% forest cover (i.e., untreated baseline) to 60% and 30% forest cover. Water-yield gain was calculated using a simplified water-balance approach, i.e., the difference in evapotranspiration between treated areas and the untreated baseline for a given precipitation input. There is a steady increase in evapotranspiration with increasing precipitation for the range of inputs (600-2000 mm; 24-79 in) observed in the Sierra Nevada (Figure 7).

However, increases do begin to taper around 1400 mm (55 in) of precipitation, suggesting that in the wettest catchments there is an upper limit to absolute yield gains. On average, treatments that reduce forest cover from 90% to 60% of the potential maximum across a watershed were projected to increase yields by 85 mm (3 in, 9.0%) (Figure 7). Thus both the qualitative and quantitative evidence support our contention that vegetation management can meaningfully modify forest hydrology in the Sierra Nevada.

Forest management and snow. One of the most important impacts that forest management has on water yield in the Sierra Nevada is related to snow accumulation and melt. For example, in a recent study that included sites analogous to Sierra forests there was significantly more snow in the open areas than under the canopy (Ellis et al., 2010). Golding and Swanson (1978) found greatest snow storage in clearing sizes of one tree height in Alberta, Canada. In the Storck and others (2002) study on snowpack in the maritime climate of Oregon, a simple relationship between under-canopy and open SWE was not possible, but in general more snow accumulated in the open areas and snow melted out of open areas one month later compared to snow accumulation and retention under the canopy. The spatial arrangement of trees also affects snow accumulation(Woods et al. 2006).

Studies of forest-management impacts on snow properties in the Sierra Nevada date from the early 1900s (Church 1912, Church 1933). Since that time, the issue has been of interest to the U.S. Forest Service (USFS) and California Department of Water Resources (Kittredge 1953, Colman 1955, Anderson 1963, McGurk and Berg 1987, MacDonald 1987), though forest management for snow retention has

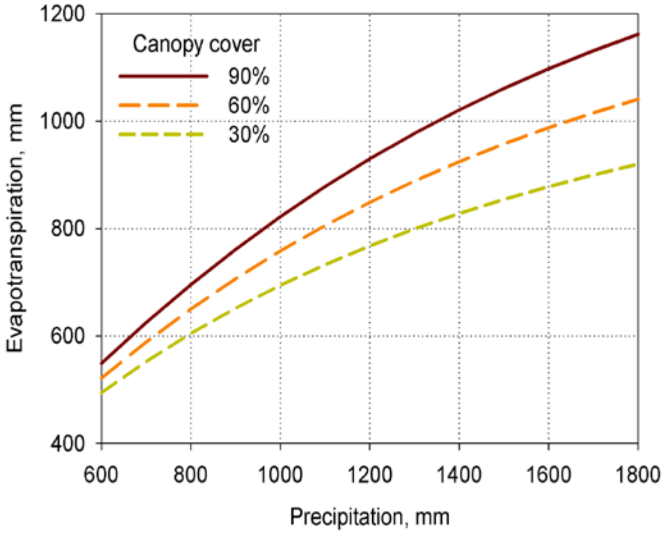

Figure 7. Predicted changes in evapotranspiration for forested watersheds in the Sierra Nevada as a function of precipitation inputs and reductions in forest cover.

Photo 5. Close up of acoustic snow-depth sensors, with up-looking and down-looking radiation measurements on nearest sensor arm, Southern Sierra CZO.

never been implemented on a large scale. Church (1912) suggested a honeycomb pattern of forest clearings, stating, “The ideal forest seems to be one filled with glades whose width bears such proportion to the height of the tress that the wind and the sun cannot reach the bottom.” However, McGurk and Berk (1987) presumed that this pattern of forest treatments would not be as economical as strip-cuts (i.e., cutting a line of trees), which were also recommended by Kittredge (1953). Independent work with group selections from 0.1 to 1 hectares in size (0.25 – 2.5 ac) are increasingly used to increase the regeneration of pines in the Sierra Nevada (York et al. 2004) and could potentially replicate the honeycomb pattern originally suggested by Church. Ultimately, the effectiveness of any treatment depends upon individual stand tree height, slope, and aspect to obtain the right mixture of openings large enough to accumulate additional snow, yet with enough shading to block direct solar radiation for prolonging ablation (the removal of snow by evaporation, sublimation, or wind). Data from sites in the southern Sierra Nevada also show significant differences in snow accumulation between open areas and forest (Figure 8). However, it must be recognized that, because openings were small, some of the snow falling from the canopy may have added to that in the open areas (Bales et al. 2011).

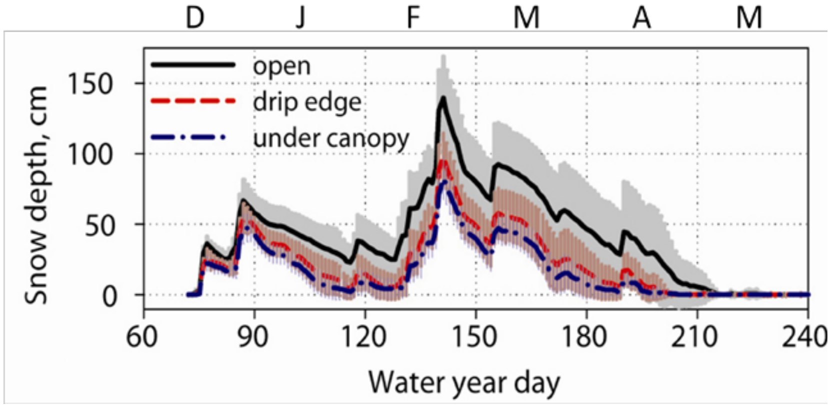

Figure 8. Snow depth relative to canopy, based on 27 continuous sensors at Southern Sierra Critical Zone Observatory, water year 2009 (Bales et al. 2011).

Within the Sierra Nevada, the Central Sierra Snow Lab (CSSL), Onion Creek Experimental Forest, Yuba Pass, and Swain Experimental Forests have all reported on the outcomes of efforts to study forest treatment impacts on snow accumulation (Table 2). The CSSL found the lowest increases in snow accumulation from selective cutting of red fir that reduced crown cover to 50%; this resulted in a 5% increase in SWE (Anderson 1976). The highest percentage increase of SWE, approximately 50%, resulted from strip cuts implemented in Swain Experimental Forest and Yuba Pass. Results from all other types of forest harvesting (block cutting, commercial selection, selective cutting, and clearcutting) increased SWE in the treated areas between 14 and 34% (Table 2). The effects of forest management on snow accumulation can have a lasting impact. McGurk and Berg (1987) revisited the strip-cuts at Yuba Pass 20 years after harvest and found sustained increases in SWE of 25 to 45%.

Increasing temperatures from climate change may actually lead to a decrease in vegetation water use, as snowmelt occurs earlier and less late-summer moisture is available (Tague et al. 2009). Additionally, not removing slash post-harvest has been shown to hasten snow ablation in the spring (Anderson and Gleason 1960), which also affects snowmelt timing.

Table 1. Maximum increases in snow accumulation from different harvest treatments in the Sierra Nevada

Location	Species	Harvest treatment	Increase	
			%	cm
CSSL	Red fir	Selective (crown cover reduced to 50%)	5	5
CSSL	Red fir	Commercial selection cut	14	17
CSSL[a]	Red fir	Selective (Crown cover reduced to 35%)	19	24
Onion Creek EF[b]	Mixed conifer	Commercial selection	20	17
CSSL[a]	Red fir	Clearcut	23	27
CSSL[a]	Red fir	Wall-and-step forest	25	47
CSSL[a]	Red fir	East-west strip, 1H wide	26	30
CSSL[a]	Red fir	Block cutting, 1H wide	34	35
Yuba Pass[c]	Red fir/Lodgepole	Strip-cut 1H (40 m), 2H (80 m) wide	46	22
Swain EF[b,d]	Red/White fir	Strip-cut 2H wide (100 m)	52	24
Swain EF[b,d]	Red/White fir	Strip-cut 4H wide (200 m)	58	21

[a] *from* Anderson *et al.*, 1976

[b] *from* Anderson and Gleason, 1960

[c] *from* McGurk and Berg, 1987

[d] Averaged from multiple measurements

In forest openings, direct solar radiation reaches the ground, causing earlier snowmelt. As a result, water passes through the soil prior to peak transpiration use by vegetation (Troendle and Leaf 1981). This both increases water yield at high flows and augments flow during the period when water resources' economic and ecosystem values are lowest. Therefore, a treatment pattern to not only increase water yield but also extend snow storage by creating forest openings would be best. Modifying the implementation of treatments towards this goal would be beneficial for water management and would also provide a direct complement to fire treatments. Reducing the period of the dry season, when vegetation is extremely susceptible to ignition, is desirable for protecting both property and timberland from devastating fires. With the advent of climate change, this process may be more important to help offset earlier snowmelt (Stewart et al. 2004), as opposed to advancing historical melt-out dates.

4. Why Forest Management Matters for Water

A recent review by the National Research Council (2008) concluded that "Although in principle forest harvest can increase water yield, in practice a number of factors make it impractical to manage forests for increased water." Similarly, a USFS policy analysis echoed this conclusion in evaluating the potentials and limitations of augmenting water yield on forested lands (Sedell et al. 2008): "For a variety of reasons, water yield increases are likely to be undetectable." This conclusion was based in part on work in the Sierra Nevada where Kattelmann et al. (1983) estimated that only a 2 to 6% increase in streamflow could be attained if "National Forest lands were managed almost exclusively for water production while meeting the minimum standards of all applicable laws." The implicit assumption is that limitations on the removal of vegetation due to wildlife habitat and floral retention standards will severely restrict any government action. The perspective that forest management for water supply is not worth the trouble is ingrained in both upstream and downstream resource managers.

The SWEEP team contends that forest management for water supply is worth the trouble for four main reasons. First, previous analyses do not consider changes in the value of the water flow. In the Sierra Nevada, the significant amount of runoff diverted through hydroelectric turbines more than doubles the economic value of the runoff (Stewart 1996). Forest management has the potential to enhance revenue for in-forest and downstream water users and engaging these beneficiaries in paying some of the costs of forest management should be considered. Second, fires are more common in the Sierra Nevada than the nation as a whole and upstream fires can deliver large loads of sediment and debris that impair hydroelectric production. Forest management can mitigate wildfires and lessen sediment loads. That is, forest management actions to mitigate wildfire and to enhance runoff are well aligned. Third, many of the constraints regarding forest management for water yield are operational in nature. In study after study, reductions in tree cover have resulted in measured

Photo 6.Intact forest at Last Chance. View from forest edge (road) looking in. High canopy cover; dense forest.

increases in water yield, but the increases have been short lived because the vegetation has been allowed to regrow. Sustained management of evapotranspiration may be possible. Fourth, climate change is forcing a reconsideration of all options. Not only does a warming climate directly impact water supply and storage, it also aggravates the risks posed by wildfire (Westerling et al. 2006). While concern for the future of the Sierra Nevada is not new—Tom Knudson's Pulitzer-prize winning series, "The Sierra in Peril," was published by the *Sacramento Bee* in 1991—the recent increase in forests impacted by large, catastrophic wildfires has re-focused attention and re-ordered priorities. The latest analysis of land-cover trends by the U.S. Geological Survey (Raumann and Soulard 2007) estimates a nearly tenfold increase during the last decade in the rate at which intact Sierra Nevada forests were converted to an "altered and often unvegetated state" by wildfires. In short, climate change has created an urgent need for managers to intervene in order to continue providing ecosystem services from mountain forests.

Photo 7.Intact forest at Last Chance after tractor thinning to approximately 60% canopy cover.

5. Proposed SWEEP Program and Approach

The SWEEP proposes to increase water yield from forests and extend the retention of snowpack in the spring, both of which will translate into more water at the right time of year for the rest of California. The SWEEP team will test the hypothesis that forest-management strategies that reduce fire risk and maintain the historical "mix" of tree species (e.g. more pines and fewer firs) can also increase water yield and extend the snowpack in the Sierra Nevada. Such a test requires a catchment where experimental treatments can be implemented and effects monitored. The aim is to collect the experimental data needed to support the development of forest treatment and management scenarios through modeling and analysis. Expected outcomes of the experiment are as follows:

- SWEEP will develop the quantitative knowledge base needed to stimulate collaborative forest-management approaches involving land stewards, water beneficiaries and the range of stakeholders with an interest in the ecosystem services provided by Sierra Nevada forests.
- SWEEP will develop a predictive framework for quantitatively assessing the effects of forest management on the mountain water cycle, including snow accumulation and melt, soil water storage, evapotranspiration, and stream discharge. This predictive ability will be based on explicit, measurable characteristics of the forest landscape, including LAI, climate, soils, and physiographic features.
- SWEEP will develop the means to quantitatively measure and value ecosystem services that could support potential public and private investments in forest and watershed management.

In June 2008, the SWEEP team visited several candidate headwater catchments for forest treatments and water-balance studies. The two catchments with the greatest potential, Onion Creek and Rice/Dolly creeks in the upper American River basin, are described here. The American River basin was considered a viable location for the next phase of these investigations in part because of stakeholder interest and in part because of a good base of existing research infrastructure. Figure 9 shows the locations of the Rice/Dolly and Onion Creek catchments, along with other catchments considered. Note that the Frazier and Bear Trap catchments are sites of ongoing forest management and hydrology research.

General watershed features. Geologic characteristics of the upper American River basin show Cenozoic andesite formations in the headwaters of the basin, underlain by mixed sections of metamorphic rocks from a much earlier time when the land was covered by water and granitic bedrock from the subsequent uplift by tectonic forces. Volcanic activity started at the end of the Eocene, with mud and lava flows blocking river channels and changing flow patterns, leading to the landscape and soils present today (USDA 1994). Other specific rock types underlying potential study watersheds include metamorphic argillites, intrusive volcanic granodiorites, intermediate volcanic rock, and glacial drift (Figure 10). Glaciers were active down to 1450-m (4700 ft)during the Pleistocene (USDA 1994), which began about 2 million years ago.

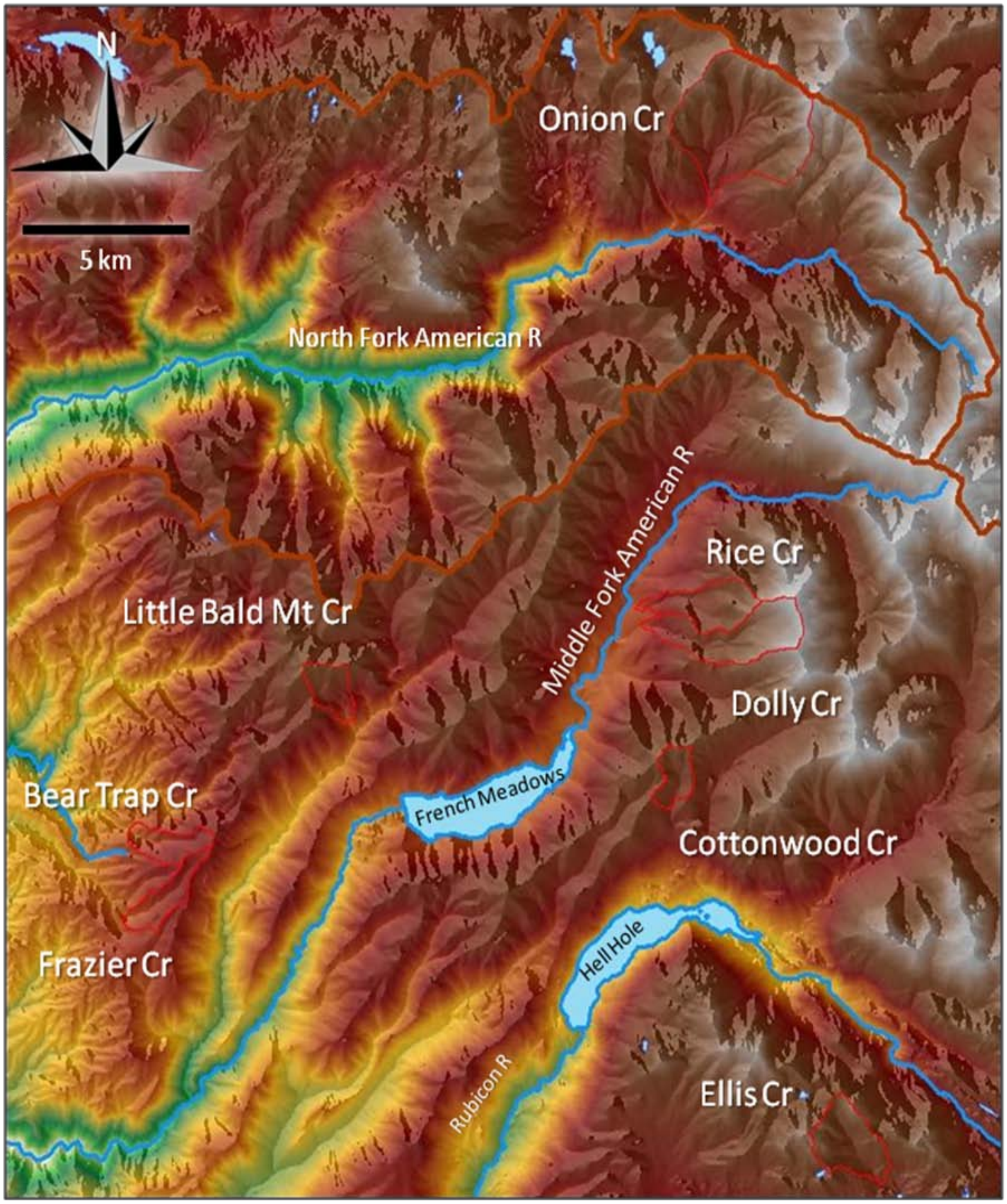

Figure 9.Locations of the potential study watersheds in the headwaters of the North and Middle Forks of the American River. Also shown is the watershed boundary of each fork and two high-elevation reservoirs, French Meadows and Hell Hole. Elevations in this map peak at 2750 m (9020 ft) along the crest of the Sierra in the east, with the major rivers draining towards the west, exiting the region shown at about 700-m (2296 ft), flowing down towards the Sacramento Delta.

Land ownership includes a mix of USFS and private (Figure 11). Two forestry companies (Lone Star and Sierra Pacific Industries) and the North Fork Association own a large portion of the private land in these watersheds.

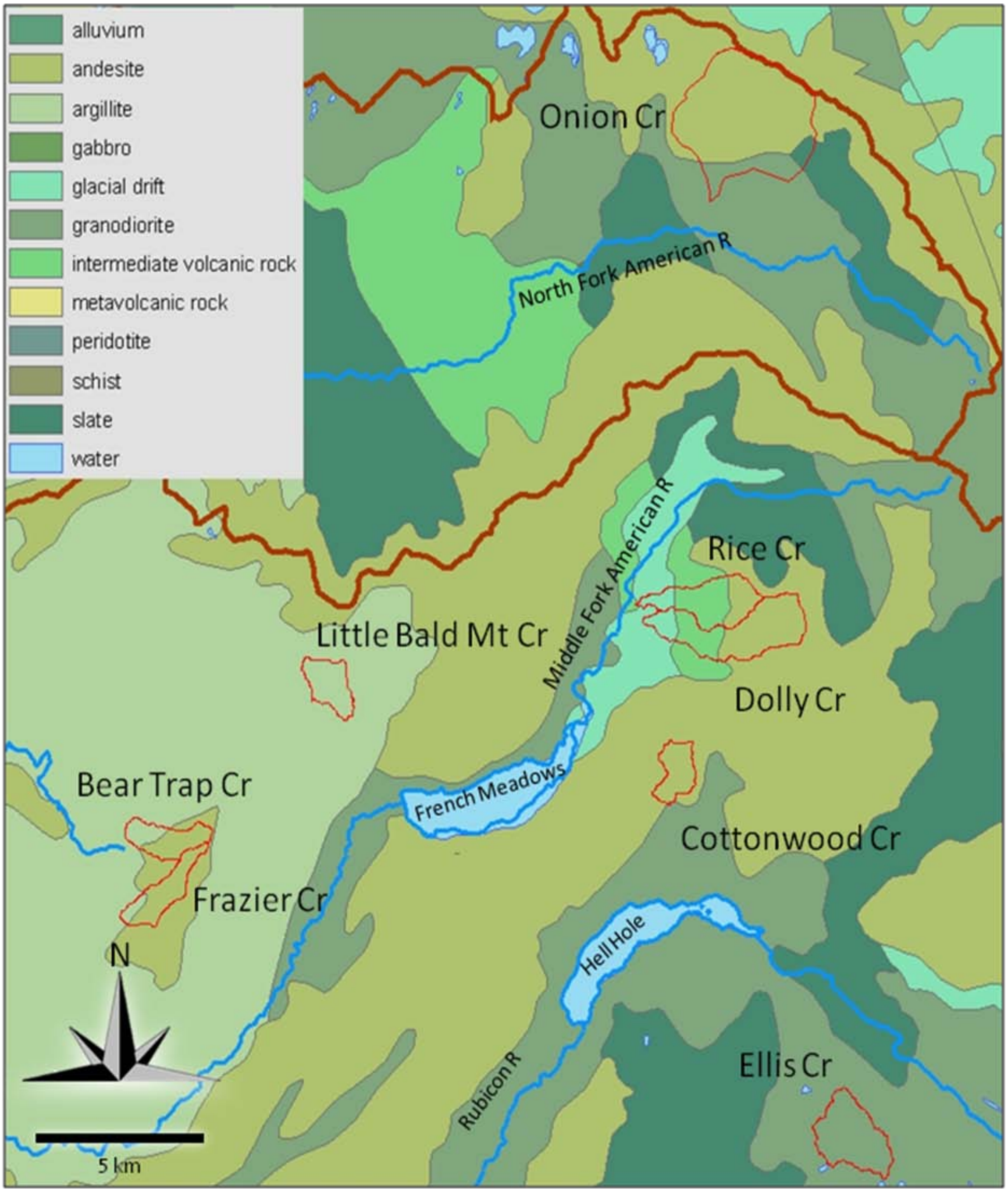

Figure 10. Geologic features in the study region. Andesites (volcanic origin) from the Cenzoic period overlay a mix of older sections of granitic and metamorphic bedrock, with some glacial deposits at the bottom of higher elevation valleys. The volcanic period at the end of the Eocene created much of the landscape and soils present today, with glacial influences above 1450 m.

Soils in the headwaters of the American River are primarily made up of two soil series associations. The Hurlbut-Deadwood-Putt association lies on the ridges and mountainsides of the

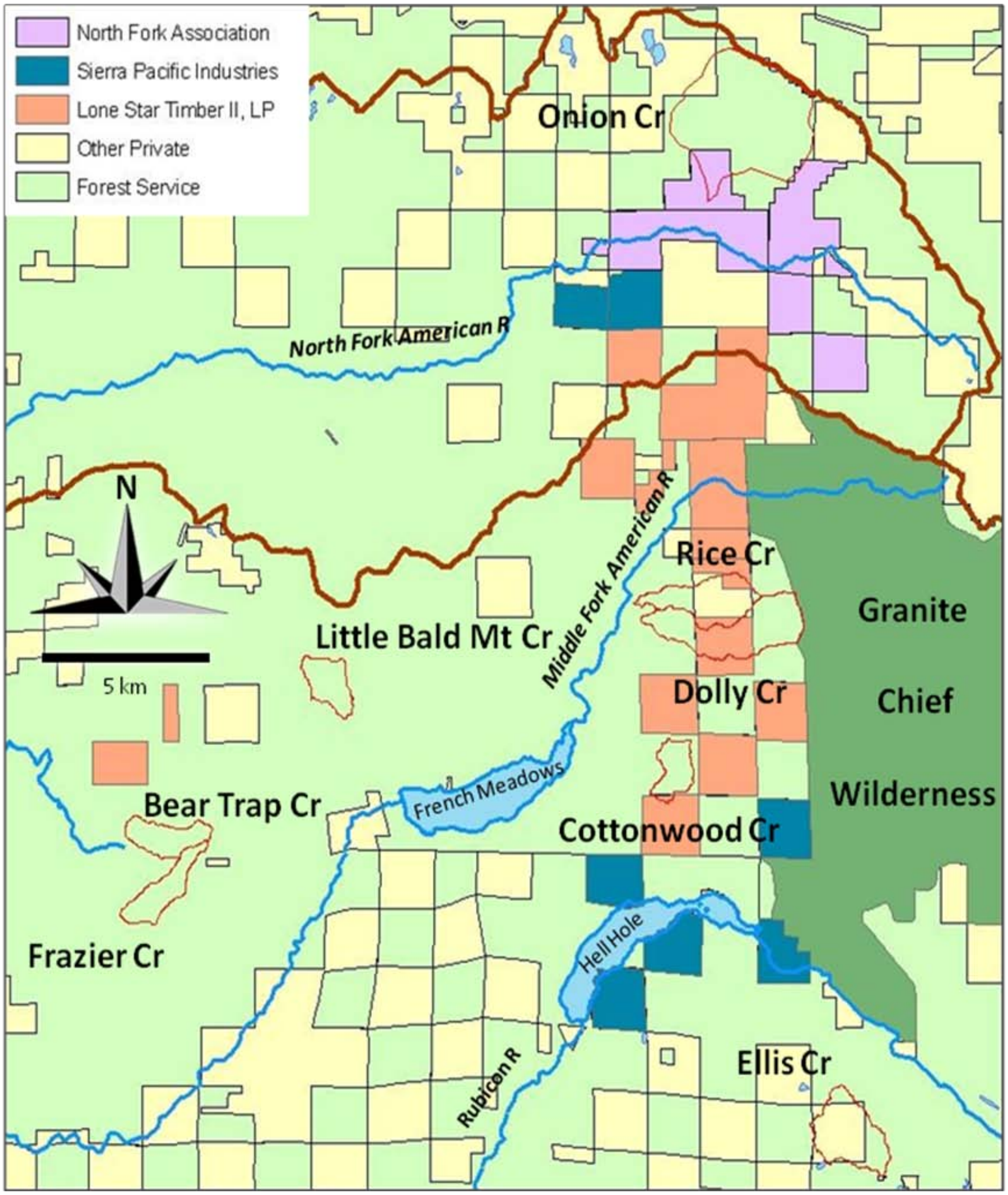

Figure 11.Land ownership in the American River headwaters. Privately held lands of interest around potential study watersheds are displayed.

American River Basin at 600-1830 m (2000-6100 ft). Formed from meta-sedimentary rocks and glacial deposits, surface texture ranges from gravelly loam to cobbly sandy loam.

Characteristics of this series range widely, from moderately deep well-drained soils on almost flat ground, to shallow and extremely well-drained soils on steep slopes. Soils have moderate water holding capacity and are mainly used in this area for timber operations of moderate productivity (USDA, 1994). The Frazier and Bear Trap catchments lie in this soil association. At higher elevations (>1675 m, or 5550 ft), the Tallac-Smokey-Meiss association soils dominate the landscape. These soils have the same characteristics as the lower elevation soils, but may be deeper in some locations. They are not only found on ridges and moraines but also on outwash terraces and in the valleys. Tallac-Smokey-Meiss association soils have lower available-water capacity and may be less productive as timberland. Soils in this association are formed from glacial alluvium, meta-sedimentary rocks, and andesitic tuff breccia. On the surface, the texture is sandy loam to gravelly loam, having increasing gravel content with depth until weathered rock or bedrock. The Rice/Dolly and Onion Creek catchments lie in this soil association. Rock outcroppings are also common in these highest elevations (USDA, 1994). Although these available soil maps give general characteristics of the region, more detailed and site-specific investigations of the candidate study catchments will be required to more-accurately and specifically describe local conditions in the catchments.

Vegetation in this region is dominated by conifer species, giving way to mixed forest and hardwood species alongside large streams, particularly sunny slopes with a south-southeast aspect (Figure12). Shrubs tend to grow in recently harvested areas or in shallow soils, (Note their co-location with barren regions of exposed bedrock on Figure12).

Small holdings of urban and agricultural land use are present in the upper American River but do not play a major role in the use and cycling of water in this region. Onion Creek has a mean canopy closure of about 55%, versus 40 and 45% for Dolly and Rice, respectively. One fourth of Onion Creek has a canopy closure above 65%, versus 55% for Rice/Dolly. These values are based on general USFS regional maps and should be evaluated further in developing thinning prescriptions. While there are steep slopes in the upper parts of Onion Creek, these areas tend to have lower vegetation density. Thus a significant fraction of both Onion Creek and Rice/Dolly could potentially receive a reduction in vegetation.

Onion Creek Experimental Forest. The USFS established the Onion Creek Experimental Forest in 1958 to develop techniques for increasing water yields from forested lands in the snow zone of the Sierra Nevada. Located in the upper reaches of the North Fork of the American River basin, the experimental forest encompasses about 1,200 ha (2,965 ac), organized into five main sub-basins dominated by white fir and red fir. Despite the initial intent, forest harvest impacts on water yield have never been studied at Onion Creek. Thus, harvest disturbance has been minimal (Adams et al. 2004). The University of California Berkeley currently manages the site, in cooperation with the USFS.

In November 2008, members of the SWEEP team conducted a forest survey of seven adjacent watersheds in the upper basin. Three 0.12-ha (0.3-ac) plots were randomly located in each watershed. In each plot, the diameter of all trees greater than 5 cm (2 in) in diameter at breast height (1.37 m or 4.5 ft) were measured and identified to species. The height of each measured tree was estimated. One tree per plot was aged by counting its growth rings.

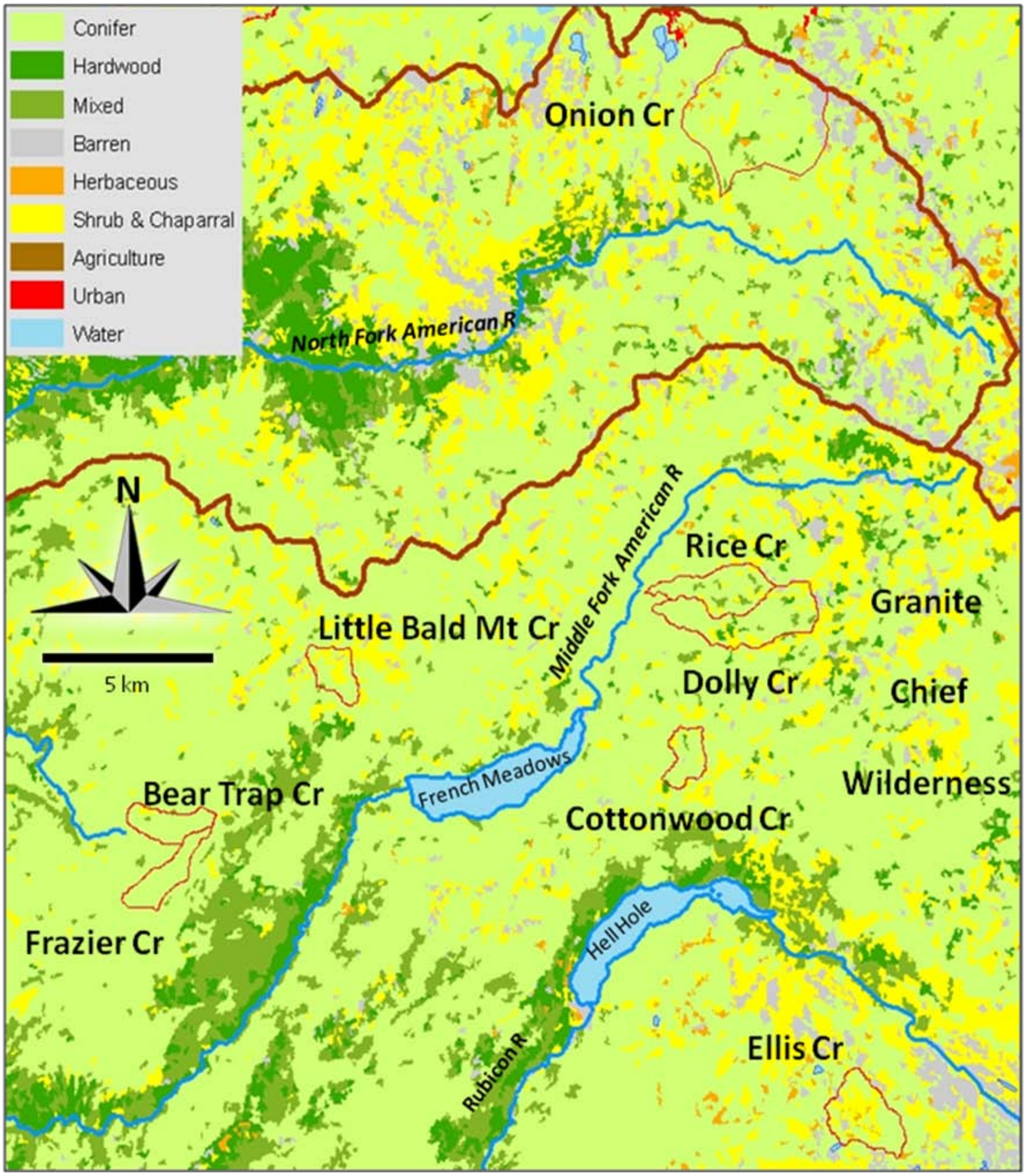

Figure 12.General vegetation map of region.

The upper watersheds at Onion Creek are dominated by red fir (49%) and white fir (29%). The forest is dense, with an average of 500 trees per ha (202 trees per ac) and mean basal area equal to 89 m^2/ha (400 ft^2/ac). Average canopy cover is 51%, but ranges by watershed from a low of 32% to a high of 68%. The average canopy tree height was 18 m (60 ft). The tallest trees in the watershed exceeded 32 m (105 ft) in height. The average age of a canopy-sized tree was 100 years. By every measure, these forests are typical of a naturally regenerated forest that has been protected from wildfire impacts of the northern Sierra Nevada (Gonzalez et al. 2010).

We also estimated LAI, the ratio of cumulative foliage surface area projected downward per unit of ground beneath the canopy. LAI is generally considered a better measure of photosynthetic capacity than canopy closure or canopy cover because it represents total leaf mass that may be arranged in vertical columns above tree stems. LAI is a three-dimensional measure of the canopy. Hence LAI might achieve a maximum for a given site when canopy closure or cover is well below 100%. LAI has the potential to be an integrative tool for a variety of forest management applications. It is a key driver for ecosystem processes, such as light interception, photosynthesis, and hydrologic processes like interception (precipitation caught by leaves or needles) and evapotranspiration. A management strategy based on LAI allocation to determine stocking and design stand structures in multi-aged stands shows promise for Sierra Nevada forests (O'Hara and Valappil 1999, North et al. 2009). LAIs were estimated using plot data and equations for leaf area prediction from individual trees (Gersonde 2003). The variation in LAI between watersheds was quite high, with a range from 5.4 to 14.7 (Figure 13). Some of this variation may be due to differences in species composition, disturbance history, or site productivity.

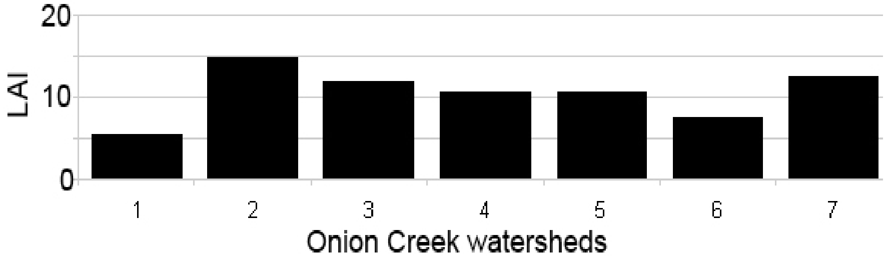

Figure 13. Leaf Area Index for watersheds within the Onion Creek catchment.

For comparison, LAI in managed forests at the University of California's Blodgett Forest, which is also located in the American River Basin, approaches 8 or 9, depending on site quality, species composition, and management history. Compartments that received thinning or single-tree-selection treatments had post-treatment recovery rates that ranged from approximately 1.5 to 2.0 LAI per decade. The compartments that were not harvested had rates of LAI increase of approximately 0.75 to 1.0 per decade. This difference was largely due to the lower LAI and higher vigor of residual trees in the harvest treatments as compared to the untreated stands, which are assumed to be approaching a maximum LAI level. Recovery following timber harvest likely follows a logistic growth, where the increase is slow immediately after harvest and slow late in development as the stand approaches a maximum. In between these extremes, LAI recovery is probably very rapid. From these preliminary LAI estimates, we may assume that a treatment in a similar uncut stand that reduced LAI from 12 to 8 might take approximately 25 years to recover. A treatment that reduced LAI from 12 to 4 might require more than 50 years. The LAI at Blodgett reflects above-average sites in second-growth stands.

The high LAIs in Onion Creek and Rice/Dolly creeks watersheds are likely due to the prevalence of shade-tolerant conifers, which typically have high LAIs. For example, all the plots had large amounts of red and white fir. The low LAI in watershed 1 may simply represent a more recent disturbance history and earlier stage of recovery. Another possibility is that LAI is being over-predicted in these higher elevation stands. A prerequisite to work in Onion Creek would be calibrating these equations for this site and for all species present.

Photo 8. Dense forests at Onion Creek (approximately 90% canopy cover. Photo taken from forest edge on trail.

Treatment Plan. Three treatments are proposed: restoration, partial, and control. These would create stand structures that encompass the desired range of characteristics. First, the restoration treatment would create a low-density forest resembling pre-European stand structures. The restoration treatment would result in approximately 30% canopy cover, with a corresponding reduction in LAI; marking would favor shade-intolerant pines and the largest trees for retention. Compared to the current condition, the treatment would enhance water yield, achieve the greatest reductions in fire hazard while maintaining wildlife habitat, and possibly sequester significant amounts of carbon. Prescribed burning, grazing or herbicides would be used to control understory in the future. Second, a partial treatment would achieve some of the hydrologic, fire, and restoration objectives. It would result in approximately 60% canopy cover and maintain about 70% of the LAI. The treatment would favor retention of shade-intolerant pines and the largest trees over shade-tolerant fir and smaller trees.

The partial treatment would result in greater retention of shade-tolerant species than the restoration treatment. The 40% reduction in canopy cover, basal area, and trees per acre would

Photo 9. Onion Creek: View of multiple leaf layers contributing to high LAI.

result in a smaller decrease in LAI because of retention of a higher proportion of shade-tolerant species as compared to the restoration treatment. Understory control would be possible with future use of prescribed burning, although prescribed burning poses greater risks in this treatment because of the residual density. Third, the control would have no treatment and maintain baseline conditions for comparison, i.e., up to 90% canopy cover in the densest stands.

At a first level of analysis we used Zhang curves (Zhang et al. 2001) to project the impact on water yield of the treatments. Annual precipitation at Onion Creek is 1060 mm (42 in) per year at 1,830 m (6000 ft) in elevation with 80-90% falling as snow during the winter (Adams et al. 2004). In the control watershed (90% canopy cover), the estimated water yield is 204 mm (8 in, estimated from Equation 2). The partial treatment (60% target canopy cover) is projected to increase this yield by 69 mm (2.7 in, 8.1%). For the restoration treatment (30% target canopy cover), the projected increase is 139 mm (5.5 in, 16%). Both of these treatments would dramatically modify the fire behavior. Results from fire simulation models conducted for similar forests surrounding Bear Trap Creek (Collins et al. 2011) suggest that the canopy thinning would greatly reduce the risks of catastrophic crown fires for approximately 20 years. However, the gains in water yield would likely require more frequent entries. At this point, we do not have enough preliminary data to evaluate how these treatments would affect snowpack patterns.

Recognizing that this simple analysis gives only an approximation of the impact of treatments on the mountains water cycle, i.e. the partitioning of water between runoff and evapotranspiration, a program of field measurements and hydrologic/ecosystem modeling is absolutely essential to establish quantitative effects of forest treatments. A quantitative predictive ability is also necessary to plan for broader treatments across the landscape and secure financing for forest management.

Field measurements would complement those made by other programs in progress and focus on measurements (such as evapotranspiration and LAI) that are largely absent from other programs. Two other programs are of particular interest, the Kings River Experimental Watersheds, an uneven-aged treatment prescription being carried out by the Pacific Southwest Research Station, U.S. Forest Service; and the Sierra Nevada Adaptive Management Project, being carried out by the University of California in cooperation with Region 5 of the U.S. Forest Service and the State of California Resources Agency. Measurements would follow the protocols already in use at five instrumented locations and would include snow depth using ultrasonic sensors placed under the canopy, at the drip edge, and in the open. Stream stage would be measured using a pressure transducer, and evapotranspiration would be measured using sap flow. These methods are described in Bales et al. (2011). Self-logging pressure transducers would be placed in catchment streams. Sap flow would be measured in the dominant species at 10 nodes, with snow-depth and soil moisture sensors placed to sample physiographic variability at 20 nodes. All installations would be on solar power, with the nodes in each catchment connected with wireless radios to a base station.

Hydrologic modeling would use a process-based coupled model of eco-hydrologic interactions such as RHESSys (Tague and Band, 2004). RHESSys has been successfully used to estimate climate-related changes in streamflow, snow and vegetation water use, and carbon flux for a variety of watersheds in the western U.S. and European Alps (Tague and Grant, 2009; Zierl et al., 2007). We are using it at our previously instrumented catchments in the Sierra Nevada; those parameterizations will be directly relevant for this project. Our approach to modeling the response of soil water, evapotranspiration, and streamflow to vegetation and climate variation/change would account for complex heterogeneity in snow accumulation and melt, evapotranspiration, and soil drainage. Assimilation of satellite-derived snow products into RHESSys would support this analysis and link simulations of snowmelt with changes in land cover and soil-water storage. Model parameterization would build on data for these previously instrumented catchments.

Evaluation of full range of ecosystem services would begin with data collection on the actual costs and revenues from the forest-management project activities as well as an extrapolation of the potential costs and revenues for treatments applied at a commercial scale of operation. The economic value of the estimated increased late-season flow would be calculated from the marginal value of the water as it runs through sequential hydroelectric turbines and is then available for diversion to agricultural or urban water districts. The value of the increased late season in-stream flow would be estimated by the implicit price of contractual obligations as well as through sets of structured interviews with water managers and environmental consultants engaged in monitoring in-stream flows. The project data would then be used to parameterize a more generic model to estimate the benefits and costs on systems with different-sized treatment areas, number of turbines, and lengths of streams with improved conditions.

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