University of California
Agriculture and Natural Resources | California Institute for Water Resources

Effect of Forest Management on Water Yields and other Ecosystem Services in Sierra Nevada forests

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Project Summary

This project is a long-term effort to gain a detailed and comprehensive understanding of the interactions between forest stand structure and forest management on the hydrologic processes of mid- and upper elevation forests in the Sierra Nevada. This project, commonly referred to as SWEEP for Sierra Nevada Watershed Ecosystem Enhancement Project, was initiated in 2007 and will continue for a minimum of several years beyond the end of this ANR grant.

The length of this study is due to:
1) the complexity of a project involving large areas, hydrologic responses that require expensive instrumentation for monitoring, and years of data to remove annual variations in climate; 2) the California drought which delayed initial instrumentation; and 3) delays in finding a suitable cooperating landowner and the subsequent delays related to planning large-scale projects on a National Forest. We are working cooperatively with the Stanislaus National Forest and treatments are already planned and being implemented. Our efforts may lead to a second installation on the Tahoe National Forest.

Our results are described in greater detail in the appendices which follow this report. To summarize these results we have:

1) Developed a robust set of leaf area prediction models for individual species that allow us to estimate leaf area of individual trees and sum to estimates of stand-level leaf area index (LAI). Additionally, we collaborated with Martin Ritchie of the Pacific Southwest Research Station of the US Forest Service and a graduate student at Oregon State University to develop prediction equations for shrub species in California.

2) These estimates of LAI provide the critical information necessary to predict hydrologic processes such as interception, evaporation, and transpiration in Sierra Nevada forests.

3) Determined using alternative methodology that differences in water use efficiency (WUE) of Sierran conifers do exist. This indicates that management to favor certain species can improve WUE and potentially water runoff.

4) Modeled results from existing data indicate that reductions in stand density or stocking result in significant reductions in evapotranspiration supporting our contention that restoration treatments that reduce density can result in reduce evapotranspiration and potentially increased water runoff.

5) Additional modeling results indicate that water runoff will be positively affected when precipitation exceeds evaporation. This supports our contention that these treatments can increase water yield. Additionally, canopy cover may be a better predictor of site water balance than leaf area index, but that both variables are important.

6) Proposed treatments to Sierran mixed-conifer forests will also result in ecosystem services that are both directly and indirectly related to potential increases in water yield. For example, light thinning treatments on US Forest Service lands should increase forest productivity over current values and generate sellable commodities. An additional benefit is the reduction in risk of insects and pathogens. Heavier restoration treatments will probably increase water yields but at a direct cost of significant reductions in timber yields. There is a potential to increase stand-level water yields in treated areas but increased water usage from downstream forests may negate gains.

7) Outreach has been effective in reaching and involving stakeholders through presentations, newsletters, and website usage. However, this should continue in the future as critical results become available from this long-term study.

Research Program

ORIGINAL OBJECTIVES (Detailed results for each objective are provided in appendices): Because this study's objectives involved measurement of various hydrologic processes, California's historic drought (2011-2016) prevented our planned establishment of monitoring stations and delayed initial modeling efforts. We requested, and received, a one-year no-cost extension in 2014. A second six-month extension was requested in 2016 for UC Merced to complete financial transactions.

Determine rates of Evapotranspiration in Sierran mixed-conifer/true fir forests. It has recently become apparent that ET estimates based on ecological modeling versus those based on field measurements of hydrologic water balance differ by 50% or more. It is also apparent that the ET and net primary productivity (NPP) values for Sierran forests do not correspond to the well-established near-linear relationships between NPP and ET.

Determine water use efficiency of trees and shrubs in Sierran mixed-conifer and true fir forests. The carbon gained per unit of water transpired (i.e., water use efficiency) is an overarching silvicultural question. We need to learn how to protect species diversity and maintain a healthy forest given climate change, while also minimizing the use of in-forest water use and maximizing water yield. Essential to this task is quantifying differences in water use efficiency among the common forest species.

Determine the potential for forest management to delay snowmelt in Sierran forests. Storage of water in the snowpack attenuates streamflow. Delaying runoff later into the summer drought season has value to multiple ecosystem services. While it is well known that changes in the magnitude and distribution of LAI influence the forest energy balance and thus snowmelt, prescriptions specific to the heterogeneous landscape of the Sierra Nevada and their impact have yet to be quantitatively assessed with hydrologic modeling.

Determine potential economic tradeoffs of forest management treatments to affect water yield and ecosystem services. Forest management interventions designed to increase late season runoff and related environmental benefits will need to be substantial enough to produce measurable and predictable changes to justify the development and enforcement of contracts for the additional services. In addition to estimating the on-site costs and benefits, the contractual arrangements between the producers and willing buyers of variable quantities of goods and services will be characterized.

Involve stakeholders in decision-making regarding forest management and watershed effects. Over the past 2-4 years, stakeholders concerned with Sierra Nevada ecosystem services (primarily water- and wildlife-related services(, have become sensitized to the potential synergies and conflicts between these services, and the potentially large economic benefits to be gained from better information to support decision-making. For example, the investigators on this project have collectively given talks and attended meetings to address these issues an average of at least twice monthly and often several times a month over the past 2-4 years.

Information Transfer/Outreach Program

Demonstrated relevance and likelihood of impact on significant agricultural, economic, environmental, and social issues in California:

Our broad SWEEP project will continue for a minimum of several years. Once the field installations are established, we will monitor results for several years and through multiple seasons and, hopefully, wet and dry years. The primary results will be those that come from this monitoring of field experiments. Changes in learning, practice, and policy are therefore in the future of this project.

Encouraged collaboration:

This project began with the as a collaborative project involving UC Berkeley, UC Extension personnel, and UC Merced. These collaborations have continued and expanded through the period of this ANR grant. Current personnel/collaborations include:

UC Berkeley: Professors Kevin L. O'Hara (PI), John J. Battles (co-PI), Cooperative Extension Specialist William Stewart (co-PI); and various graduate students

UC Merced and Sierra Nevada Research Institute: Professors Roger Bales (co-PI), Martha Conklin, Post-doctoral Researchers/Staff: Yinsu Chen, Phil Saksa,

UC Cooperative Extension Advisor: Susan Kocher (co-PI) Environmental Defense Fund: Eric Holst

US Forest Service: Eric Knapp, Martin Ritchie Nature Conservancy: Ed Smith

Oregon State University: S. Huff, graduate student

Partnerships:

Stanislaus National Forest: the Stanislaus has revised their Hemlock project to accommodate our student needs to form a long-term collaborative arrangement.

Tahoe National Forest: The Tahoe also has a large restoration project in the planning stages (French Meadows) that may result in long-term collaborations.

Strengthened the research-extension network:

Our network involved two UC faculty (O'Hara and Battles), one Cooperative Extension Specialist (Stewart), and one local Advisor (Kocher).

Because our project is ongoing, and will last a minimum of several more years, there have been limited results and limited potential for teaching and outreach. However many graduate students have been involved in this work at both UC Berkeley and UC Merced.

Additional resources leveraged:

This project began with seed money from the Sierra Nevada Conservancy and the Bella Vista Fund. The Environmental Defense Fund was a key collaborator in the early stages of this project. We have also developed cooperative relationships with the U.S. Forest Service, Stanislaus National Forest to treat a group of sub-basins in conjunction with our instrumentation of these watersheds. This large Forest Service project, the "Hemlock Project"
(https://eng.ucmerced.edu/people/rbales/americanriver/Hemlock_catchments).

This long-term cooperation will ultimately provide the empirical evidence to answer the central questions in this project. Other cooperative projects include the French Meadows Restoration Project on the Tahoe National Forest which includes public and private land. We also have been in discussions about working with Sierra Pacific Industries to monitor managed sub-basins on their property. We have recently received support from Pacific Gas & Electric, The Nature Conservancy, Placer County Water Agency, Agricultural Research Service, and US Bureau of Reclamation. We continue to seek additional support for this long-term project.

Notable Achievements

LAY SUMMARY OF ACCOMPLISHMENTS
UC Delivers impact story format:

The Issue
California is emerging from a historic multiyear drought. The potential for climate change may further exacerbate future water shortages. California's mixed-conifer forests in the Sierra Nevada have too many trees and are in danger of burning. This research attempts to determine if restoration treatments to reduce the number of trees in these forests may also delay snowmelt and increase water supplies to the state.
What Has ANR Done?

A long-term research project has been established to answer questions about the potential of restoration treatments to increase water supplies. Our research team has been laying the foundation for a large field trial by installing instrumentation in key watersheds and developing important hydrologic relationships for these forests. Future studies will monitor the effects of actual forest management activities on snow retention, water yield, and timing of water yield.

The Payoff
This project should provide a clearer picture of the interactions between forest stand structure and the timing and amount of water yield in the Sierra Nevada. If the future results of this project indicate that we could either increase water yields, or delay snow melt, they may provide future justification to more restoration treatments in the Sierra Nevada. This would provide multiple benefits to Californians through healthier forests, reduced fire dangers, improved wildlife habitat, and increased water yields.

Supporting Unit
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Include a photo.

This photo shows a desirable low-density forest structure in the foreground and the over-stocked forests typical of the Sierra Nevada in the background (photo by Eric Knapp).

Appendix: Objectives 1 and 2:
Determine rates of evapotranspiration in Sierran mixed-conifer/true fir forests; and Determine water use efficiency of trees and shrubs in Sierran mixed-conifer and true fir forests

These two objectives were similar and overlapping in their intent and how they were approached in study. The processes of evapotranspiration and water use efficiency are dependent on the amount of total foliage area present, and how it is arranged in a stand. In this project, we have represented foliage area with leaf area index (LAI). This required more precise tools for estimating LAI in forest stands in the Sierra Nevada. We developed prediction models for the primary species in the Sierra (Jones et al. 2015). These models allow us to either collect standard inventory data, or use existing inventory data, to predict stand-level LAI. In contrast to approaches that rely on remote sensing, our approach allows us to estimate leaf area of individual trees by species, and sum to get LAI at the stand-level. This provides estimates of LAI by species, and allows us to model the effects of removing some species in treatments while still estimating the LAI of the stands in question.

Our proposed treatments will also stimulate a shrub response. We have cooperated with a study at Oregon State University to predict shrub LAI. A master's thesis by Huff (2016) predicted foliage biomass. We worked with the US Forest Service Pacific Southwest Research Station and Huff to college foliage samples of the same species. We used these samples to estimate specific leaf area and thereby to develop leaf area prediction equations for shrubs from Huff's foliage biomass equations. The processes of evaporation and transpiration in forest stands are strongly related to LAI. Intercepted precipitation is related to surface areas of which foliage is often the most exposed leading to evaporation. Transpiration is a leaf process that varies with the amount of foliage or leaf area.

However, tree species vary in their interception and transpiration even when LAI is held constant. Hence our approach to estimating LAI of individual trees provides more robust estimates of these processes than would be obtained by more generalized stand-level estimates. Water use efficiency (WUE) is a plant functional trait that has a major influence on the hydrology of forest catchments. WUE is defined as the ratio between carbon fixation and water loss. This trait varies among species but the general expectation is that the more drought-tolerant species achieve this tolerance through higher WUE (Field et al. 1983). To estimate WUE for the dominant species in the SWEEP watersheds, we used two inferential methods: eddy covariance measures of carbon and water flux from sites along a climate and vegetation gradient and tree-level estimates of sapwood and leaf area.

Methods

We relied on measurements at two sites from the Southern Sierra Critical Zone Observatory (CZO). These sites are part of a gradient of four eddy covariance towers the spans the western slope of the Sierra Nevada Mountains (Sierra National Forest). The sites are located at approximately 800 m elevation intervals, spanning 65 km east to west (Table 1). Field measurements of forest composition and structure were conducted in a 200 m by 50 m (1 ha) plot located in the "footprint" of each flux tower.

Eddy covariance measurements began between September 2008 and July 2010. WUE was calculated as the ratio of gross primary productivity divided by annual evapotranspiration and was expressed as mmole of CO2/mole H2O (Kelly 2014). Kelly (2014) reported a decline in WUE associated with increasing water demand. To account for this meteorological influence on WUE, we adjusted WUE for a site by the weighted vapor pressure deficit (VPD) at a site. Specifically, we calculated linear regressions with WUE as the dependent variable and VPD as the independent variable for each site and then quantified site-level differences in WUE with the intercepts of the linear regressions.

At two adjacent sites, the forest was dominated by ponderosa pine (Pinus ponderosa) at Soaproot (Table 1) and white fir (Abies concolor) at P301 (Table 1). These two species co-occur across the broad swaths of the Sierran conifer forest but have distinct life-history strategies. Ponderosa pine is considered a light-demanding but drought tolerant species while white fire is more tolerant of shade but less tolerant of drought (Niinemets and Valladares 2006). We assumed that any differences in ecosystem WUE at the two sites could be largely attributed to differences in WUE between the two dominant species.

For the tree-level estimate of WUE, we used results from Jones et al.'s (2015) estimates of leaf area for the dominant tree species in the SWEEP watersheds. For the 103 trees included in the study, Jones et al. (2015) measured sapwood area and leaf area. Theoretically, there should be a strong functional dependency between sapwood area and leaf area. Sapwood provides the conductive tissue necessary to support leaf function (Shinozaki et al. 1964). While this general relationship holds and follows a power law scaling curve (Niklas and Enquist 2011), the slope of the relationship varies among species. As Williams has recently noted (In review), a larger leaf area to sapwood area ratio represents a hydraulic architecture that can increase WUE.

Following this logic, species in the Sierran conifer forest that maintain more leaf area for a given unit of sapwood area have a greater capacity for efficiency. To quantify differences among species, we modeled leaf area as a function of sapwood area using a power law equation (Williams, In Review). We used the data collected by Jones et al. (2015). For each species, we linearized the variables by taking their natural logs and then calculated the slope of the relationship using linear regression. We interpreted the slope as an indicator of WUE potential with a steeper slope (i.e., leaf area increases faster than sapwood area as a tree grows), indicating higher potential.

Results
The lower elevation ponderosa pine forest was more productive and experienced higher vapor pressure deficits. Between 2010-2013, gross primary productivity averaged 14.7 MgC ha-1 yr-1 at Soaproot compared to 12.9 MgC ha-1 yr-1 at P301 (Kelly 2014, Table 2.5). For the same interval, the mean VPD at Soaproot was 1.64 kPA (standard error = 0.03) and 1.23 kPA (standard error = 0.04) at P301. This increased productivity at Soaproot coincided with greater ecosystem WUE. WUE in the ponderosa pine forests 23% greater on average than in the white fir forest. At the intercept WUE at Soaproot was 4.2 mmole of CO_2/mole H_2O; at P301 it was 3.4 mmole of CO_2/mole H_2O. However while the annual variability in WUE was low (9% coefficient of variation at both sites), there was considerable uncertainty in the estimate of the intercept.

The increase in leaf area with sapwood area was well-described by a power function (Fig. 1). For all species in the analysis the regressions were significant and explained the vast majority of the variation (Table 2). However there were distinct differences with the rate of increase in leaf area. For species that were considered more drought-tolerant, more leaf area was added per unit increase in sapwood area.

Discussion
The results of both inferential analyses suggest important differences in WUE among the tree species in the Sierran conifer forests. At the ecosystem scale, the ponderosa pine dominated forest consumed approximately 20% less water per unit carbon fixed than the white fir dominated forests. While other species were present in the footprint of the eddy covariance tower, pine or fir accounted for 58% or more of the live tree biomass (Table 1). The allometric analysis also supported the contention that pine had higher WUE than fir.

The ration of leaf area to sapwood area increased much faster in ponderosa pine compared to white fir (Table 2). Moreover the slopes of the leaf area- sapwood area curves closely tracked independent assessments of drought tolerance. There was a 0.77 correlation between the slope of the curve and the drought tolerance rank. Given these results, we contend that as a viable first approximation, the WUE for ponderosa pine and the closely related Jeffrey pine could be increased by 20% relative to associated species in modelling applications.

Table 1. Forest composition in the footprint of two flux towers along the E-W transect of the Southern Sierra CZO. Forest composition data from Kelly (2014). AGL = aboveground live tree biomass; RelDom = relative dominance calculated from contribution to AGL. Location map from flux tower tansects: http://criticalzone.org/sierra/infrastructure/field-areas-sierra/.

Site	Species	AGL (Mg/ha)	RelDom (%)
Soaproot	Total	119.8	
	Ponderosa pine	69.6	58.1
	Incense-cedar	16.8	14.0
	Black oak	15.4	12.9
	Other	18	15.0
P301	Total	181.8	
	White fir	133.4	73.4
	Incense-cedar	16.6	9.1
	Sugar pine	16.6	9.1
	Other	15.2	8.4

Table 2. Results from the linear regression of leaf area as a function of sapwood area for the common conifer species in the Sierran conifer forests. The variables were log-transformed prior to analysis. Data from Jones et al. (2015). Drought tolerance ranked on a scale of 0-5 (Niinemets and Valladares 2006).

Species	Spp Code	Drought tolerance rank	Intercept	Slope	R2	P
Douglas-fir	DF	2.6	-0.34	0.91	0.94	<0.0001
Incense-cedar	IC	3.8	-1.02	0.98	0.91	<0.0001
Jeffrey pine	JP	4.2	-2.98	1.24	0.98	0.0008
Ponderosa pine	PP	4.3	-2.65	1.09	0.95	<0.0001
Red fir	RF	0.7	-0.69	0.84	0.97	0.001
Sugar pine	SP	2.7	-0.63	0.86	0.98	<0.0001
White fir	WF	1.9	-0.94	0.96	0.95	<0.0001

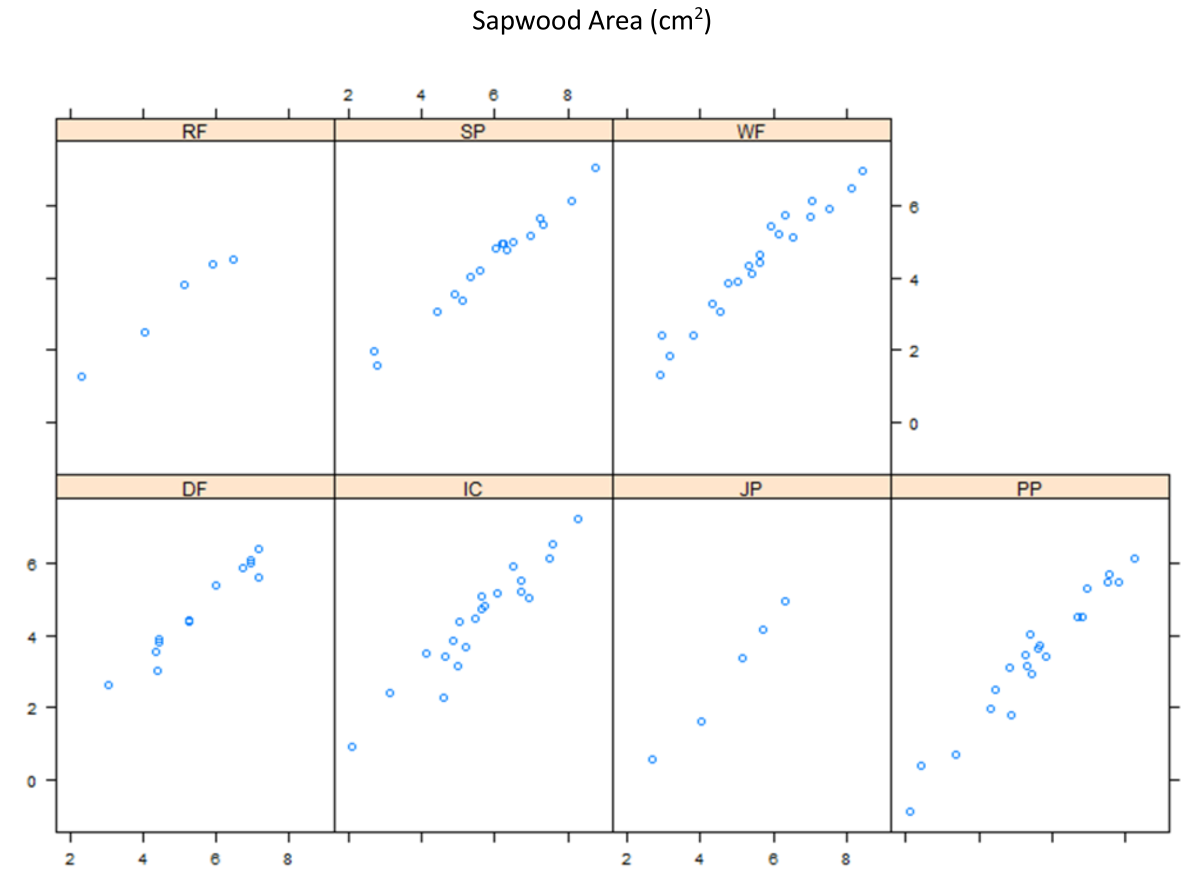

Figure 1. Summary of the increases in leaf area as a function of sapwood area for the seven most abundant conifer. Species codes in Table 2. Note that the scale is logarithmic.

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Appendix: Objective 3

Determine the potential for forest management to delay snowmelt in Sierran forests.

We investigated the water-balance changes from forest thinning in the central and southern Sierra Nevada. Our focus was on the partitioning of water between forest evapotranspiration and runoff, given the precipitation levels over time between the two areas. We used this information to design field studies for Phase III of the SWEEP project, involving on-the-ground measurement and evaluation of the water-cycle changes from forest management. We also initiated rigorous economic analyses. Both the changes in water balance and economics of forest management are very site specific, and generalization across the Sierra Nevada will lead to results that do little more than reflect assumptions. Thus a major product of our work under this grant was the initiation of more-rigorous research, in partnership with landowners who are undertaking restoration-type forest treatments.

Observed changes in forest biomass and evapotranspiration. We investigated the potential magnitude and duration of forest evapotranspiration (ET) decreases resulting from forest-thinning treatments and wildfire using a robust empirical relation between Landsat-derived mean-annual normalized difference vegetation index (NDVI) and ET measured at flux towers. Among forest treatments, the minimum observed NDVI change required to produce a significant departure from control plots with NDVI of about 0.70 was -0.07 units (a basal area reduction of 3.1 m2 ha-1), equivalent to an estimated ET reduction of -102 mm yr-1. Intensive thinning that approached pre-fire- exclusion forest densities reduced basal area by 40-50%, generating estimated ET reductions of 152- 216 mm yr-1 over the first five years following treatment.

Peak estimated pre-fire ET was 830 mm yr-1 at 950 m elevation and 650 mm yr-1 at 1450 m elevation in the American and Kings watersheds, respectively. ET reduction due to a 50% reduction in basal area following fire was 320 and 200 mm yr- 1 at 1000 m elevation in the respective basins. Five-year post-fire ET reduction per unit area was in the Central Sierra was double that in southern Sierra watersheds in 1990-2008. Achieving basin-wide thinning similar to that produced by fires in 1990-2008 could result in ET reduction that approaches 10% of the full natural flows for drought years in the American River watershed. Net annual ET reduction due to forest fires in 1990-2008 was 65 and 14 million m3 yr-1 in the American and Kings River watersheds, respectively.

Scaling modeled changes in forest biomass and evapotranspiration. We applied an eco-hydrologic model (RHESSys), previously constrained with spatially distributed field measurements, to assess the impacts of forest-fuels treatments and wildfire on hydrologic fluxes in two Sierra Nevada firesheds.

Strategically placed fuels treatments were implemented during 2011-2012 in the North Fork of the Middle Fork of the American River in the central Sierra Nevada (43 km2) and in the Lewis Fork of the Fresno River in the southern Sierra Nevada (24 km2). This study used the measured vegetation changes from mechanical treatments and modeled vegetation change from wildfire to determine impacts on catchment water balance. The well-constrained headwater models were applied to larger watersheds, based on geologic and hydrologic similarities, to evaluate how hydrologic fluxes respond to vegetation changes from treatments and wildfire. In the American catchment fuels treatments were implemented in 18% of the watershed, and in the Lewis catchment fuels treatments were completed in 29% of the watershed.

Treatments in the wetter central Sierra Nevada resulted in a spatially averaged vegetation decrease of 8% over the entire catchment, leading to a 12% runoff increase, averaged over wet and dry years. Wildfire events simulated with and without forest treatments reduced vegetation by 38% and 50%, and increased runoff by 55% and 67%, respectively. Treatments in the drier southern Sierra Nevada also reduced the spatially-averaged vegetation by 8%, but the runoff response was limited to an increase of less than 3% compared to no treatment. Simulated wildfire with and without treatments reduced vegetation by 40% and 43%, increasing runoff by 13% and 15% respectively. The results point to forest vegetation in the southern Sierra Nevada being more water-limited than in the central

Sierra Nevada, where treatments had a greater impact on the water balance. Changes to catchment- scale water-balance simulations were more sensitive to canopy cover than to leaf area index, indicating the structure of vegetation treatment is important to consider when evaluating hydrologic response. Overall, results show that fuels treatments on a portion of a watershed can increase runoff at the catchment-scale where precipitation exceeds evapotranspiration. The metric used to assess forest biomass reduction will influence results. Simulated forest treatments are more sensitive to changes in canopy cover than leaf area index.

For future research and verification of water-balance changes, we found that headwater models calibrated with spatially distributed measurements can be scaled to assess hydrologic response in larger watersheds.

Phase 3 assessments of water-balance changes from forest thinning. We have initiated 2 headwater-catchment scale investigations, the French Meadows project in in the Tahoe National Forest and the Hemlock project in the Stanislaus National Forest.

A diverse partnership is working to advance the French Meadows Forest Restoration Project on public and private lands in the headwaters of the American River, west of Lake Tahoe. The partnership includes the Tahoe National Forest, which manages part of the project area; American River Conservancy, which owns over 10,000 acres adjacent to Forest Service lands; Placer County Water Agency, which manages two reservoirs downstream of the project for municipal water and hydropower; The Nature Conservancy; Placer County; and the Sierra Nevada Research Institute (SNRI) at the University of California, Merced. These partners also in consultation with the Sierra Nevada Conservancy. The partners have developed a memorandum of understanding to advance ecologically based forest management in the American River headwaters. The overall aim of the work in this proposal is to measure and assess the effects of restoration treatments on year-round streamflow in source-water watersheds, including drought resiliency, and on downstream water supplies.

Additional aims of the partnership include restoring forest health, reducing the likelihood of high-intensity wildfire, and its associated risks to habitat and infrastructure. Forest conditions in the area are unhealthy and at risk of uncharacteristic, high-severity wildfire due to past management, fire suppression, five years of drought, warmer temperatures, and a rapidly expanding bark beetle infestation resulting in millions of dead trees. Nearby severe wildfires in recent years, just downstream of the project area, have caused hundreds of thousands of tons of topsoil to erode into the river system, clogging infrastructure and degrading wildlife habitat and watershed health. The French Meadows Project aims to “get ahead of the curve” by accelerating ecologically based forest management to enhance streamflow, reduce wildfire risk, and promote more resilient forest conditions.

The partners have made significant progress to date in advancing the project. The partnership funded and launched wildlife and botanical surveys, along with fire modeling required for planning and permitting this project and has raised the money for implementing forest restoration on both the private and public areas of the French Meadows project. The Forest Service recently issued a public scoping notice for the project, initiating the required public review and analysis under the National Environmental Policy Act. The funding we are requesting from the Wildlife Conservation Board (WCB) in this proposal would build on the existing large investment on the baseline hydrologic measurement, assessment and research that are needed to accurately establish the connection between watershed restoration and streamflow enhancement. In order to quantify the potential impacts of proposed forest fuels management activities on forest health and water quantity, we have initiated detailed measurements of streamflow, soil moisture, snow depth, evapotranspiration, forest health, and tree growth in both treated and untreated watersheds. This project fills a critical gap in our knowledge base around water, climate and forest management; and is aimed at being transformative in bringing the dialog and inter- agency, multi-stakeholder cooperation to a new level.

The Hemlock Forest Restoration Project is the first comprehensive, quantitative assessment of the water-cycle consequences (both positive and negative) of forest restoration following GTR 220 (North et al. 2009) in a Sierra Nevada mixed-conifer forest. The 12,000-acre landscape-restoration project is located in the Stanislaus National Forest and Mokelumne River basin. The Stanislaus National Forest expects that their restoration actions will restore watershed functions by creating different forest-stand structures and densities; reducing the forest's susceptibility to insect, disease, and drought-related mortality; reducing surface fuels, increasing the height to canopy, and decreasing crown density; retaining large, fire-resistant trees; maintaining and enhancing wildlife habitat; enhancing the extent and connectivity of aspen stands; and improving resource and watershed conditions.

These actions will also enhance water-supply reliability by restoring the fraction of precipitation that leaves the basin as runoff versus evapotranspiration; guard against erosion, water-quality problems and snowpack losses associated with wildfire; and maintain water and forest health as the climate warms and evaporative demand increases. The overall aim of the project is to quantitatively evaluate the effects of differences in stand structure on wildfire resilience, water yield and the water cycle in the snow-rain transition zone by a program of field measurements, integration of data using hydrologic modeling, and assessment. Our research is currently in the instrumentation-placement and hydrologic-baseline- data acquisition phase. We are scheduled to install two complete weather stations, three soil moisture, metric potential, and snow monitoring clusters, and four water-stage recorders this summer/fall.

The Forest Service has completed the Environmental Assessment (EA) in compliance with the National Environmental Policy Act (NEPA) and other relevant Federal and State laws and regulations.

Economic analyses of water-related benefits from forest treatments. In collaboration with Blue Forest Conservation, we have initiated two projects involving economic and financial analyses of the water-related benefits of forest restoration.

First is a Healthy Watershed grant for the Hemlock Landscape Restoration Site Specific Scientific and Economic Analysis. In collaboration with the World Resources Institute we are evaluating the hydrologic and economic impacts resulting from the 13,000 acre Hemlock Landscape Restoration Project in the Stanislaus National Forest. Project outcomes will be methods to measure the water quantity and economic impacts from restoration to make the business case for utility investment in the Sierras.

Second is a project supported by a USDA SBIR Phase I grant for Remote Sensing Water-Yield Evaluation. This project seeks to develop an easily scalable framework for calculating water yield changes following forest restoration to allow for the distribution of restoration costs across all beneficiaries, including downstream hydroelectric utilities and water districts. Proper allocation of these costs will enable forest restoration to occur at the landscape scale, while reducing direct costs to the U.S. Forest Service.

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Appendix: Objective 4

Determine potential economic tradeoffs of forest management treatments to affect water yield and ecosystem services.

The original challenge

“The Sierra Nevada Watershed Ecosystem Enhancement Project (SWEEP) was launched to examine the potential to optimize snowpack retention through forest management while also quantifying the economic value of snowpack retention, water storage, and flow attenuation. The proposition underlying this research is that water users that benefit from these services might be

willing to pay upstream landowners to provide these services providing powerful financial incentives to landowners to invest in beneficial management practices.
In addition, SWEEP seeks to ultimately develop policy and institutional mechanisms for facilitating such transactions in ways that maximize benefits to water users, forest landowners, and forest resources. "Original proposal

Key themes for estimating the potential tradeoff –$$ into forest management v $$ out in additional water yield
1. Alter evapotranspiration from forest stands to increase water runoff
2. Alter evaporation and sublimation from snow to increase water runoff
3. Arrange water right holders to pay more for what rights they already own

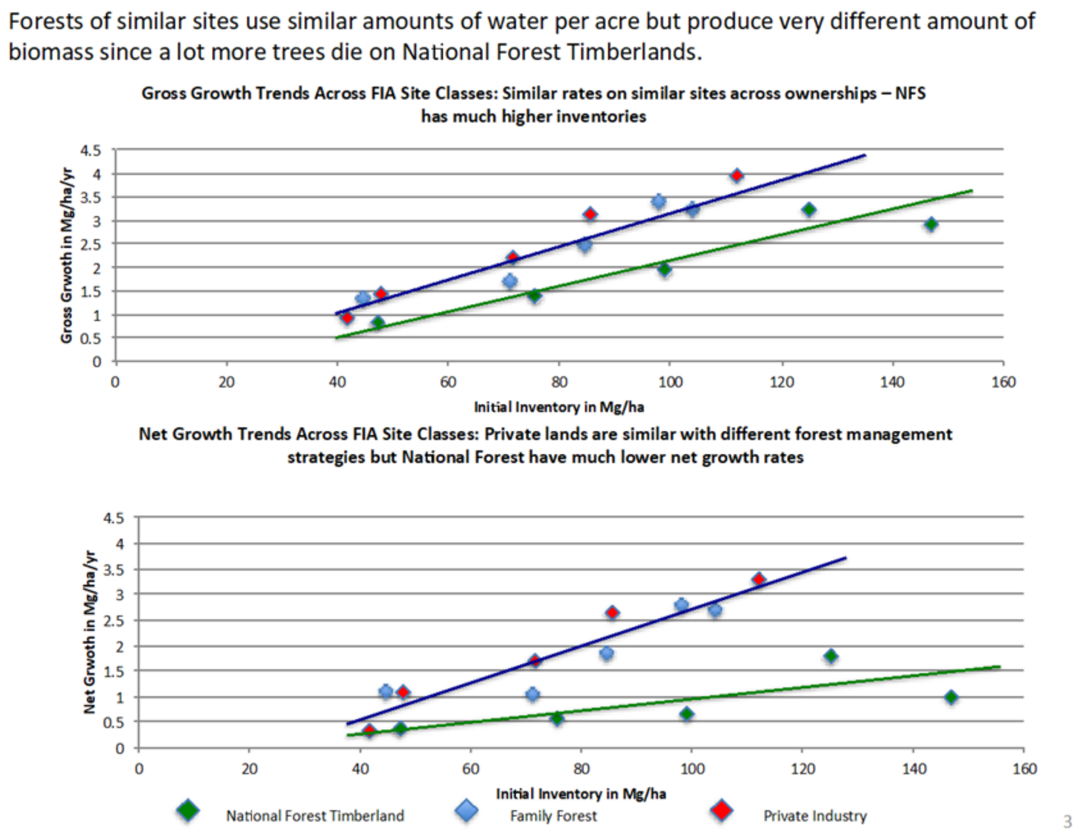
It has long been documented that one of the most financially valuable resources of the Sierra Nevada is the water runoff as it is put to a wide variety of financially valuable uses (Stewart 1996). It is therefore not surprising that there has been policy interest in the potential to increase runoff, if it could be done and could be done at a cost that was less than the additional revenue. I will address the three key issues below.

1. *Alter evapotranspiration from forest stands to increase water runoff*

The largest consumer of water in the Sierra Nevada occurs via the stomata on conifer needles as they open to capture carbon dioxide and by necessity also release water pulled up from the soil (Chapin et al. 2011). Approximately half the carbon is involved in respiration and half in new plant growth with limited variation in this allocation ratio across a wide range of ecological conditions (Chapin et al. 2011). Of the total plant growth, much of the new carbon will go into leaves, reproductive parts, and roots. While the exact ratio varies, in forests it is common to use the easily measured biomass in the bole of the tree as proportional to total plant biomass growth. By extension, we can assume that gross biomass growth also scales linearly with water transpiration. Recent improvements in the statistical format of U.S. Forest Service Forest Inventory and Analysis (FIA) plots provides more accurate estimates of annual gross biomass growth for different types of forests.

Assuming annual water use is proportional to annual gross biomass growth, it is possible to estimate how thinning stands or forest landscapes (multiple stands) could affect water use and water runoff. Using statewide averages separated by FIA sites class (a composite metric that should capture variations in soil resources, water availability and growing days) , and using ownership as a proxy for different forest management regimes, we can get some insights into estimate forest water use per hectare of different forest management regimes.

The following two figures compare annual gross and net growth over the past decade with initial inventory levels for three major types of owners and across FIA site classes 2,3,4, and 5.



The symbols with the higher initial inventories and annual growth rates are those with higher FIA sites. Higher quality sites have forests that grow more biomass and use more water per hectare. National Forest timberlands carry much higher inventories than private timberlands with similar site quality, but all three ownership types have roughly similar gross growth rates and assumed water use rates. One implication is that even if the National Forest timberland sites where thinned so that their average stocking was permanently reduced by 1/3, the thinned National Forest sites would still use roughly the same amount of water. It would appear that Sierra Nevada forests are more similar to the water limited forests on the Southwest US rather than the water unlimited forests of the US Southwest as summarized in the summary of the summary of the (National Research Council 2008) results in (Chapin et al. 2011).

Well-designed selection thinning with associated fuels reduction would most probably reduce fire/insect/disease risk factors but are often not done on National Forest lands as they are contrained by assumed ‘wildlife population * inventory’ assumptions that are written into their guidelines.

The net growth figure illustrates why such a change in forest management could have benefits other than increased water runoff. Even if water use and carbon capture of the thinned and unthinned ownership types is estimated to be similar, a large fraction of the initial carbon capture (and water use) essentially goes into snags that will slowly decompose. The snags and eventual down logs will have various associated habitat benefits, but the efficiency of generating snags in terms of carbon capture and water use may be lower in the unthinned forest.

Based on inventory per hectare data, we see a pattern that the stronger the financial incentives to produce sellable biomass (> 12” sawlogs have high value per ton, 8-12” sawlogs have less value per ton, <8” logs and tops currently have a negative value per ton), the lower the inventories maintained across ownerships. Private industry harvests more than family forest owners who harvest more than the National Forests.

Higher elevation sites in the Sierra Nevada generally have lower site class due to mainly to fewer degree-days and thinner soils, so it is important to consider the site quality when comparing results from field plots. NFS Reserved and National Park Service (NPS) lands can not legally harvest timber solely for their commodity value. In some areas, they can harvest trees for public safety or ecological goals, but only if mechanized equipment is allowed (ie not in designated Wilderness areas).

Andrea Hardlund’s “Silvicultural Prescriptions and Opportunities for Forest Management of Western Sierra Nevada Mixed Conifer for Timber, Water, and Fire Objectives” project for her Master of Forestry project. (Hardlund 2014) tested variants of these strategies on both federal and private lands over a 40 year period.

The take home messages with respect to thinning to enhance the total basket of forest goods and services produced per hectare are:
1. Thinning up to 1/3 of inventories across National Forest lands should generate considerable initial sellable commodities and would result in forests in forests with roughly double the productivity in terms of net primary productivity per hectare per year, mainly by substantially reduce fire/insect/disease risk.
2. Such an extensive thinning program would probably not increase water yield as water limited trees downslope of any area with locally reduced evapotranspiration would capture the ‘extra’ water before it entered the stream channel.

3. Thinning to even lower levels of inventories would probably increase water yields but at a direct cost of significant reductions in timber yields.
4. National Forest regulations based on wildlife habitat, aesthetics, and erosion from vehicle based restrictions are significant in preventing the National Forests from changing from their current management regime.

2. *Alter evaporation and sublimation from snow to increase water runoff*

In addition to altering transpiration from the trees, altering the evaporation from wet canopies, and sublimation and evaporation from long term snow storage is another potential avenue where forest management could play a positive role in increasing water yields. This topic was also addressed extensively in Andrea Hardlund's Masters of Forestry project paper (Hardlund, 2014). A key insight is that the regions where we would assume that forests capture most of their precipitation as snow and are cold enough for the snow to not be washed away with winter and spring rains is also the region where 75% of the area in Public reserve status where no mechanical equipment for tree harvesting is allowed.

There are minimal exceptions for public safety, but for most of the forests with high snow the only management tool that can be used to increase water yields is managed wildland fire. Unmanaged wildfire has a much higher probability on federal lands than on private lands, but any increased localized water yields are often accompanied by increased sediment deliveries.

References

Chapin, F.S. III, P.A. Matson, P.M. Vitousek. 2011. Principles of Terrestrial Ecosystem Ecology. 2nd Ed. Springer, New York. 529 p.

Hardlund, A.M., 2014. Silvicultural prescriptions and opportunities for forest management of western Sierra Nevada mixed conifer for timber, water, and fire objectives. University of California – Berkeley, Department of Environmental Science, Policy and Management. Master of Forestry Professional Paper. 83 p.

National Research Council. 2008. Hydrologic Effects of a Changing Forest Landscape. National Academies Press, Washington, D.C. 163 p.

Appendix: Objective 5

Involve stakeholders in decision-making regarding forest management and watershed effects.

We were largely successful at achieving this objective, although the California drought worked both for and against us. California's severe drought affected the entire state and focused attention on conservation and means to improve water supplies. Hence this added focus to our project which began before the drought. However, the drought also delayed our study forcing us to extend the study an extra 1.5 years. Funding limitations affected our outreach activities towards the end of our study.

We published four newsletters during the project that were included on our website: http://ucanr.edu/sites/cff/Research/Sierra_Nevada_Watershed_Ecosystem_Enhancement_Project/ We used these newsletters to describe the project, key concepts related to the research, and the people involved. We also produced a poster that was included under "newsletters" that was available to describe the project and be used by stakeholders such as the landowners or agencies interested in communicating concepts about the project.

Whereas there is general support for producing more water and changing the timing of water delivery in the Sierra Nevada, stakeholders are more reluctant to accept our proposals for changing forest structure by removing trees in these forests. We proposed three treatments in our treatment areas: a "restoration" treatment, a "light" treatment, and an untreated control. It is important that we communicate that the restoration treatment attempts to return stand structures to a state that was more similar to presettlement structures than their present condition. By favoring the development of more natural stand structures, this treatment also benefits wildlife, reduces fuels and fire danger, as well as potentially enhancing snow retention and water yield. The light treatment was intermediate between the restoration and the control treatments. The control treatment will essentially leave the stands untreated. The critical selling point for stakeholders was the restoration treatment and its potential multiple benefits.

The investigators in this project have given many presentations on this project and will continue to do so as it moves forward in future years. Some of these are listed above under "Extension activities". These have be delivered to audiences that vary from lay groups, local planning commissions, government agencies, and professional groups.

Publications from prior projects

Articles/papers:

Jones, D.A., K.L. O'Hara, J.J. Battles, and R.F. Gersonde. 2015. Leaf area prediction using three alternative sampling methods for seven Sierra Nevada conifer species. Forests 6, 2631-2654; doi:10.3390/f6082631

James W. Roche, Michael L. Goulden, and Roger C. Bales, Estimating evapotranspiration change due to forest treatment and wildfire at the basin scale in the Sierra Nevada, California, paper to be submitted Fall 2017.

Saksa, P.C., R.C. Bales, C.L. Tague, J.J. Battles, B.W. Tobin, and M. H. Conklin. (in prep). Forest fuel treatments and wildfire effects on Sierra Nevada mixed-conifer runoff. paper to be submitted Fall 2017.

Saksa, P. C, M. H. Conklin, J. J. Battles, C. L. Tague, and R. C. Bales. 2017. Forest thinning impacts on the water balance of Sierra Nevada mixed conifer headwater basins. Water Resources Research 53(7): 5364-5381; doi: 10.1002/2016WR019240

Website/Web Portal:

Website developed on UC Berkeley Center for Forestry website:
http://ucanr.edu/sites/cff/Research/Sierra_Nevada_Watershed_Ecosystem_Enhancement_Project/

New tool/method/model/technology (such as decision support tool, app):

We made major advances in the prediction of stand-level leaf area index (LAI) for Sierra Nevada conifers that are described in the published paper listed above (Jones et al. 2015).

Poster:
http://ucanr.edu/sites/cff/newsletters/SWEEP_Newsletters46835.pdf

Extension activities/Presentations:

Bales, R.C. (2016) Observations from drought in the Sierra Nevada: evapotranspiration, climate & regolith weathering, Caltech James J. Morgan Symposium. Pasadena CA. September 23, 2016.
Bales, R.C. (2016) Water, forests & climate in the Sierra Nevada, Alpine Biomass Committee.

Markleville, CA. September 6, 2016.

Bales, R.C. (2017) Observations from drought in the Sierra Nevada: evapotranspiration, climate & regolith weathering. University of California Berkeley Environmental Engineering Seminar. Berkeley, CA. February 17, 2017.

Bales, R. (2016). Water & carbon balances in the Southern Sierra: measurements, drought and scaling. Presented at NASA Jet Propulsion Laboratory, Jan 13, 2016, Pasadena CA.

Other:

UC Berkeley Master of Forestry: Hardlund, A.M., 2014. Silvicultural prescriptions and opportunities for forest management of western Sierra Nevada mixed conifer for timber, water, and fire objectives. University of California – Berkeley, Department of Environmental Science, Policy and Management. Master of Forestry Professional Paper. 83 p.