1. Introduction

The forested mountain watersheds that comprise 25% of the land area of California, and provide more than 60% of the state's developed water supply are, fundamentally, fire prone ecosystems [1-6]. Fires pose significant risks to water supply, as evidenced by the 2013 Rim Fire, which threatened water quality and infrastructure in the Tuolomne and Hetch Hetchy watersheds, critical to water supply in San Francisco and for the 8 million residents of the Bay Area [7-10]. Contemporary drought, and projected future climate change simultaneously exacerbate fire risks in the Sierra Nevada, and threaten the sustainability of the State's water supply [11-15]. Similar challenges face the Western USA in general, where 75% of all streamflow derives from snowpack [16], and dramatic future increases in fire frequency and severity are projected as climates warm [17]. There is thus an urgent need to re-evaluate the contemporary management paradigm for forested mountain watersheds (e.g. [12]), recognizing the intrinsic connections between land cover composition, fire management and water balance (Figure 1).

Contemporary fire management features a paradigm of fire suppression, under which small fires are extinguished upon detection. This paradigm has greatly reduced fire frequency in forested basins relative to a pre-management baseline, as revealed by fire scar records and other proxies [18, 19]. The fire suppression paradigm is dominant across the US as a whole. By the end of the 20th Century, over 250,000 km^2 of federal lands were completely fire-suppressed, and a further 560,000 km^2 experienced significant anthropogenic modification of the fire-regime, leading to reduced fire frequency [20]. It is now recognized that many ecosystems managed via fire suppression, including the Sierra Nevada [21], are ecologically adapted to frequent fires. Removing fire from these ecosystems represents a century-long, massive, and poorly-understood ecological experiment, altering the composition, demography, allometry and succession dynamics of forests [22], with presumed (although largely unquantified) effects on biogeochemistry, hydrology and ecosystem function [3, 18, 23-25].

This research will develop a probabilistic (stochastic) modeling framework describing the coupled dynamics of fire, water and forests in the Sierra Nevada, allowing a rapid assessment of the watershed-scale effects of re-introducing fire to Sierra Nevada forests.

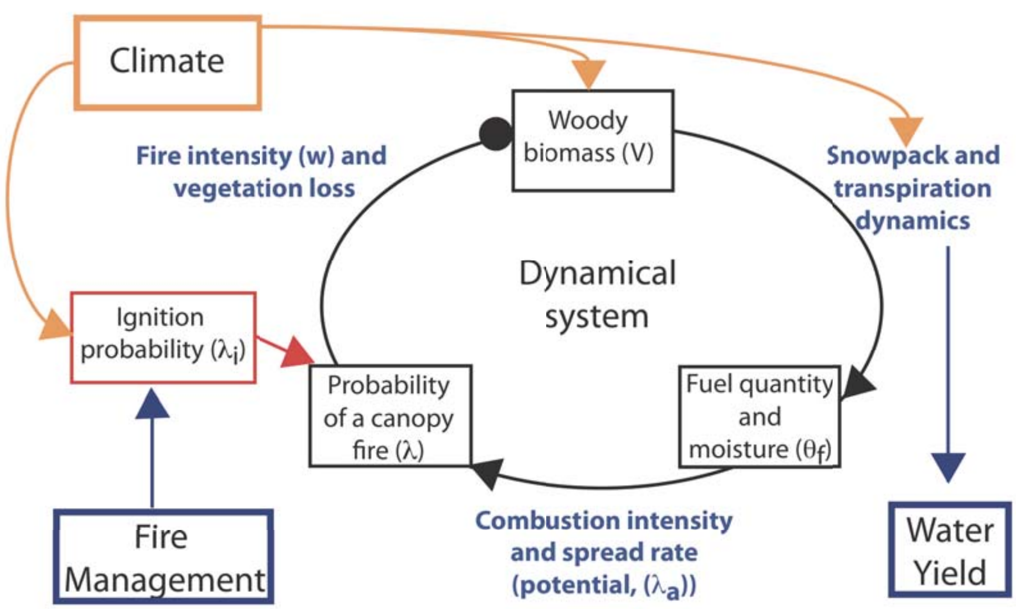

Figure 1: Hypothesized fire, water and vegetation interactions in the Sierra Nevada. Higher canopy area increases snow sublimation and transpiration, reducing fuel moisture and increasing the risk of canopy fires. Higher fire frequency lowers woody biomass, a negative feedback (closed circle). Climate and human fire management are exogenous drivers; and changes in water yield arise co-incidentally from vegetation change.

No such rapid assessment framework is currently available. The development of such a tool has been impeded to date by the ubiquity of fire-suppression: the only fires that occur within a fire-suppressed regime are those that are too extensive or dangerous to suppress. Catastrophic wildfires have well-known hydrological outcomes, in terms of increased flood and erosion risks, caused by loss of ground cover, post-fire soil hydrophobicity and ash-clogging of soil pores [26-34]. Little is known, however, about the potential hydrological response to alleviation of fire suppression, when the resulting fires are smaller, more frequent, and lower-intensity [19, 25, 35]. My research will address this knowledge gap by focusing on two basins in the Sierra Nevada mountains where a natural fire regime has been maintained for the past 40 years: the Illilouette Creek Basin (ICB) in Yosemite National Park and the Sugarloaf Creek Basin (SCB) in Sequoia-Kings Canyon National Park [2, 18, 35, 36]. Remote sensing and aerial photography will be used to evaluate the changes in watershed-scale vegetation structure in response to the shifting fire regime. Continuous measurements of rainfall, snowpack, soil moisture and the drivers of potential evaporation (solar radiation, surface temperature, wind speed and relative humidity) will provide critical information about how fire-induced changes in vegetation and land surface properties alter point-scale hydrological fluxes. A targeted laboratory study will explore how cycles of freeze-thaw and wetting-drying (typical of Sierra Nevada winters) degrade post-fire soil hydrophocity. Distributed measurements of surface soil water content, fuel moisture, and plant water potential, including data collected by middle-school students in a citizen science campaign, will provide a basis for upscaling. Detailed analysis of hydrological sensitivity to the changing vegetation in the study basins will be made using the RHESSys ecohydrological model [37]. The field, remotely-sensed and model-derived data will provide a comprehensive test-bed with which to confront the predictions of the probabilistic model.

The developed model will be used in a regional analysis to **identify watersheds where restoring the fire regime creates the potential for a "win-win-win"** – a reduced risk of catastrophic fire, an increase in water yield, and an increase in landscape diversity. These basins are high priority targets for management intervention. I will work with the California Fire Science Consortium (CFSC, headed by collaborator Prof Scott Stephens) on an outreach effort to share the results with land and water managers. The model will be incorporated into my education plan, which will train 30 PhD students in science communication (targeting modeling), and offer ~500 middle-school students/year an opportunity to participate in learning modules that incorporate modeling into an outdoor environmental education experience.

2. Theoretical Development

The model development recognizes that fire, water and vegetation are coupled by the effects of fire on vegetation structure, the effects of vegetation structure on point-scale hydrological dynamics, and the effects of changing hydrology on fire risk (Figure 1). Thus, the model will link three existing components: (i) fire-vegetation probabilistic models (developed for savanna ecosystems, e.g. [38-43]), (ii) the "moisture-damping" concept, a standard component of fire modeling that describes how increased moisture content in fuels reduces the heat released during a fire [44], and (iii) probabilistic soil moisture models, predicting the probability density function (PDF, denoted p) of soil moisture (and related fluxes such as transpiration) from climate, vegetation and soils information [45-47]. The approach differs from other attempts to link fire, water and vegetation dynamics in (i) its probabilistic representation of climate and fire, and (ii) its mechanistic treatment of fire-soil moisture links (c.f. [43, 48, 49]).

Fire-Vegetation Dynamical Systems Models

The model builds on a probabilistic fire-vegetation model proposed by D'Odorico [40]. Recognizing a separation in timescale between fire occurrence (fast) and the growth-response of woody vegetation (slow), fires are treated as an Poisson random process, with an (exponential) rate of occurrence that depends on the vegetation cover in the system. The model describes the growth of woody biomass in a spatially implicit fashion, ranging from 0 to 100% of land cover. Mean fire frequency (λ, $[T^{-1}]$) is proportional to the fractional land cover of woody biomass (V, where $0 \leq V \leq 1$):

$$\frac{dV}{dt} = \alpha V(1-V) - F(V,t)V \tag{1}$$

$$F = (1-\omega/2)/(1+\omega/2), \quad p(\omega) = \frac{e^{-\omega/\omega_0}}{\omega_0\left(1-e^{-2/\omega_0}\right)}, \quad 0 \le \omega \le 2 \tag{2}$$

$$\lambda = \lambda_0 + \beta V \tag{3}$$

Here α is the rate of woody biomass expansion [T^{-1}]. Perturbations due to fire at time t, $F(V,t)$ are parameterized in terms of fire severity, ω, which is random and exponentially distributed between 0 (no woody biomass destroyed) and 2 (all standing woody biomass destroyed), according to equation (2). (The convoluted relationship between F and ω reflects the convention used to solve the equations, see [40]). The likelihood of fire of a given severity occurring is adjusted by parameter ω_0 [40]. Woody cover loss in a fire is proportional to the fuel available to burn (i.e. F multiplies V in equation 1). Equation 3 modifies fire frequency from a baseline rate in the absence of woody biomass (λ_0), by parameter β. In savanna ecosystems $\beta<0$, as grass burns more readily than trees. Analyses of fire occurrence in mountain forests, however, suggest that fire risk is primarily determined by weather conditions (exogenous to this model), and fuel moisture [50-52]. That is, Equation 2 should be replaced with a functional relationship for λ that accounts for fuel moisture. The need to find such a relationship motivates the first hypothesis, explored further in the next section: **Hypothesis 1.1 Fuel moisture co-varies with soil moisture.**

Fuel moisture

The frequency at which a stand-replacing fire (i.e. a fire that can induce a change in V by burning the forest canopy) occurs can be decomposed into the frequency of ignition events λ_i [T^{-1}], and the probability that an ignition event leads to a canopy fire, λ_a []. The frequency of ignition events is **exogenous**: weather, lightning, human activity and the fire management regime (i.e. suppression) change this frequency. Conversely, the probability that ignition events lead to canopy fires is **endogenous**, depending on the availability and nature of fuels and vegetation. The frequency of canopy fires is then:

$$\lambda = \lambda_i \lambda_a \tag{2a}$$

The probability that a canopy fire occurs can be estimated from the intensity I [kWm^{-1}] of combustion (i.e. the heat released by a fire). If the intensity exceeds a threshold (denoted I_a, and varying with forest cover), then canopy fires occur. Existing fire models, such as the widely-used Rothermel fire energy intensity model [44] predict I as a function of weather conditions and fuel moisture θ_f [L^3L^{-3}]. For fixed weather conditions, λ_a is obtained from this model as $\lambda_a = \theta_f|T,RH,u,$ where T is temperature, RH relative humidity and u wind speed. Fuel moisture is assessed for live fuels (i.e. canopies), coarse fuels (i.e. coarse woody debris), and fine fuels (i.e. duff and litter). Live fuel moisture depends on plant type and water availability. For example, in chapparal shrub species, live fuel moisture is a linear function of root zone soil moisture content, declining as soils dry [53]. Soil moisture controls fine fuel moisture by diffusion and evaporation/condensation at the soil surface [54]. Coarse fuel moisture is correlated to soil moisture because they are controlled by common climatic drivers [55]. These relationships remain poorly characterized for Sierra Nevada forests (but see [56]). I hypothesize a co-variance between soil moisture and fuel moisture: $\theta_f = f_1(\theta)$. The functional form, strength and variability in this relationship (f_1) will be evaluated empirically. In addition to field campaigns in the ICB and SCB, middle-school students will participate in field studies in Yosemite National Park targeting θ_f and θ (see **Education Plan**)

Probabilistic soil moisture model

Fire-suppressed forests in the Sierras have high canopy densities and transpiration demands [12, 57-59]. Thinning or loss of forest cover (i.e. declines in V), are thus anticipated to increase soil moisture. The soil moisture PDF can be predicted as a function of the (stationary) mean depth of daily rainfall γ [L] (exponentially distributed); the (stationary) mean frequency of storms λ_p [day^{-1}], the peak evaporative demand E_{max} [L/day], the rooting depth Z_r [L], and soil properties drawn from the water retention curve:

$$p(\theta) = f_2\left(\gamma, \lambda_p, E_{max}, Z_r, \text{ soil properties}\right), \tag{4}$$

Climate change impacts the rainfall statistics and E_{max} estimates. Vegetation physiology and canopy structure also influence these properties, leading to the second patch-scale hypothesis:

Hypothesis 1.2 Transpiration increases with canopy density and root depth. Mature forests will transpire more than shrubland, which will transpire more than burned forests/meadows.

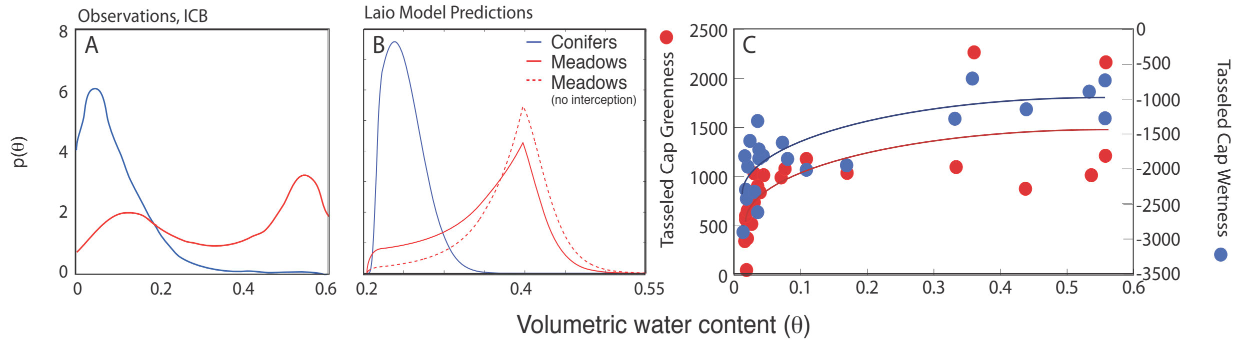

Figure 2: Surface soil moisture (A, summer 2013-2015), and Laio model predictsion (B), for conifers (200cm root zone, 140cm/year E_{max}) and meadows (20cm root zone, 70cm E_{max}). Model assumes rainfall of 50 cm/ growing season. Dashed lines in (B) show effects of reduced interception in meadows. (C) Shows relationship between satellite wetness indices (Tassled Cap Greenness and Wetness) and meadow soil moisture, suggesting a basis for upscaling. Lines show best power-law fits.

As shown in Figure 2 (A), large differences in soil moisture do in fact arise between forests and meadows in the ICB. The Laio model reproduces these qualitative differences (Figure 2 (B)). These observations and preliminary modeling results motivate the next patch-scale hypothesis:

Hypothesis 1.3 Summer soil moisture decreases with increasing transpiration and decreasing snow sublimation. Mature forests will exhibit drier soils than shrublands, which will exhibit drier soils than burned forests / meadows.

These predictions neglect (i) lateral transfer of water through subsurface flow between sites, which is likely responsible for the very high soil moisture measurements made in some meadows [58, 60, 61], and (ii) the influence of snow on summer soil moisture. While the former is an intrinsic limitation of the 1D Laio model, the latter can be accommodated using a recent elaboration [62], accounting for carry-over of water storage from wet to dry season. By linking the Laio model with an empirical description for Equation 3, the Rothermal fire model, and the D'Odorico fire-vegetation model, a probabilistic-dynamic framework that synthesizes point-scale water balance, disturbance and fire frequency modeling can be formulated. Figure 3 illustrates this synthesis for the ICB, by (1) scaling observed summer soil moisture values across the basin using vegetation cover, (2) estimating fuel moisture from the soil moisture, using an empirical relationship found in [53], and (3) classifying regions as "low" or "high" fire risk based on a sensitive "wet" fuel moisture value of 110 identified in an inter-model comparison [63]. Figure 3 is only illustrative (relationships between soil moisture, fuel moisture and fire risk are yet to be quantified for the ICB), but demonstrates how hydrological feedbacks could reduce fire risk in Sierra Nevada settings.

Probabilistic point-scale water balance

The Laio framework also provides an avenue to estimate runoff. The soil moisture PDF can be transformed into a PDF of evapotranspiration E (e.g. [46, 47]), which, given rainfall statistics λ_p and γ allows estimation of the growing season runoff (Q) as $Q = T_{season}\, \gamma\, \lambda_p - E$, where T_{season} is the length of the growing season [days]. This framework assumes that all rainfall infiltrates into the soil, implicitly neglecting the potential formation of post-fire soil hydrophobicity [26, 30, 64]. However, Sierran late-summer fires are followed by winter snows, subjecting hydrophobic soils to repeated cycles of freeze, thaw, wetting and drying – potentially degrading hydrophobicity [65]. This motivates the next hypothesis:

Hypothesis 1.4 Fire-induced soil hydrophobicity does not persist through a winter snow season (and can be omitted from the modeling framework).

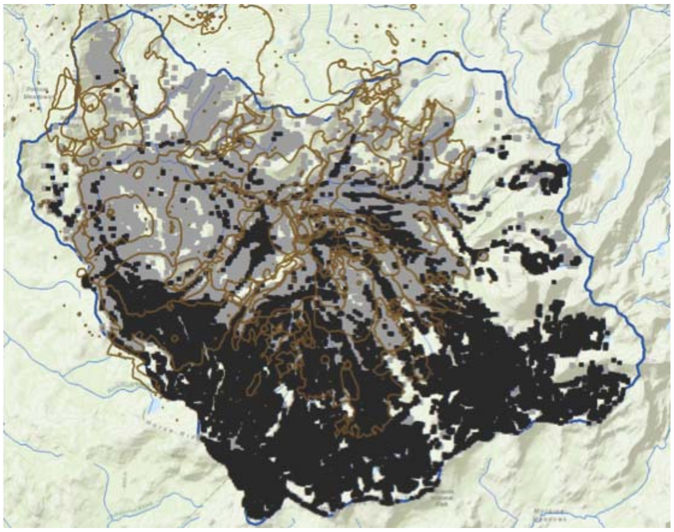

Figure 3. Effects of changed fire regime on fire risk due to fuel moisture. Grey areas switched from "at risk" to "low risk" of burning, based on estimated fuel moisture values due to past fires (outlined in brown). Black areas have unchanged risk.

Although the probabilistic model is an appropriate tool to explore growing season hydrological dynamics (those that govern fire occurrence), most runoff from Sierran basins is snow-melt. Snow-pack accumulated through winter determines this runoff volume, and varies with local climate and burn history / vegetation type [59, 66-72]. Treating climate as an exogenous variable (local weather measurements will be made in the field, and long-term records are available from the National Park System near both sites), snow pack dynamics – especially differences in canopy interception, sublimation and melt timing under different vegetation types and burn histories – will be measured for the ICB and SCB, and used to parameterize a simple snowpack model [73]. The model will be used to estimate water availability for runoff generation as a function of each vegetation type. This motivates the next hypothesis:

Hypothesis 1.5 Snow interception and sublimation will decrease with canopy density. Mature forests will intercept and sublimate more snow than shrubland, which intercepts and sublimates more snow than burned forests / meadows.

Qualitative predictions at the Basin Scale

The model development links fire risk to fuel moisture, and thus to vegetation cover, climate and water yields. The qualitative effects of these dependencies can be explored by solving Equations 1-3 (following [40]) with $\beta>0$, assuming that higher V leads to drier conditions and increases fire frequency. Figure 4 shows a phase space for two model realizations– one without a hydrological feedback on fire frequency ($\beta=0$, left panel) and one where the hydrological feedback causes $\beta=0.8$ (right panel). The qualitative predictions shown in Figure 4 motivate three watershed-scale hypotheses:

Hypothesis 2.1 Increasing fire frequency (e.g. natural versus fire suppressed) will increase the fraction of meadows in the watershed, and reduce the fraction of woody cover, proportional to λ/α.

Hypothesis 2.2 Basins with higher fire frequency will yield more runoff, relative to the fire-suppressed state (and this will remain valid under warmer, drier climatic conditions).

Hypothesis 2.3 Basins with higher fire frequency will experience reduced fire risk (measured by the PDF of woody biomass consumed on a per fire basis, i.e. the PDF of FV in Equation 1).

Once developed, the model will be used to test a final, regional-scale hypothesis:

Hypothesis 3. Sierra Nevada watersheds can be identified where restoring a natural fire regime is (a) feasible (i.e. basins are sufficient remote from human habitation/sensitive areas) and (b) will reduce fire risk, increase water yields, and diversify land cover composition.

Hypothesis testing

Field data, remote sensing, laboratory experiments, detailed modeling and synthesis of existing data will be used to test the hypotheses. Tests of the probabilsitic model focus primarily on the ICB and SCB study sites (see Section 4), using the pre- and post-1970 conditions as different treatments (c.f. [74]). This maximizes the ability to control for variable geology, topography and forest use histories. It also reflects the absence of other watersheds with λ_i>>0 in the Sierra Nevada (due to ubiquitous fire-suppression). Model tests in fire-suppressed watersheds to explore the effects of climate and predictions of the lumped water balance are feasible, and will be conducted for a set of basins with known fire history where long-term streamflow and climate data are available (at least 6 such basins have been identified). Existing land cover, vegetation, habitation, and climate datasets will be used to test Hypothesis 3.

The research will identify priority watersheds across the Sierra Nevada where manipulation of the fire regime holds the greatest promise for securing water supplies and averting the risk of catastrophic fires, both under contemporary and future climate conditions. The identity of these watersheds and the potential gains in water and fire security will be shared with federal agencies, state and water utility managers through a targeted outreach program coordinated through the CFSC (see Broader Impacts).

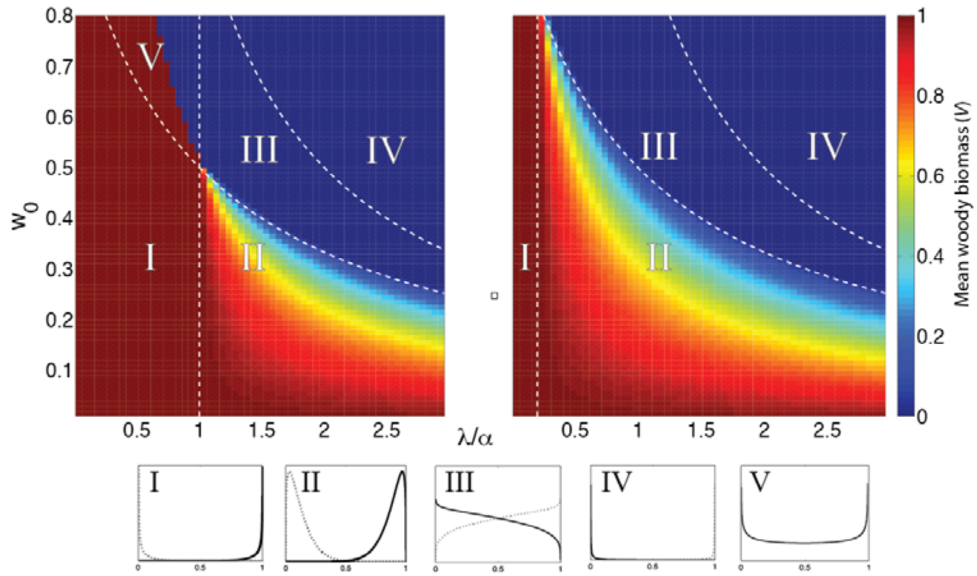

Figure 4: Phase space showing modal woody biomass (*V*) as a function of the fire intensity (w_0) and the ratio of fire frequency to biomass growth rate. Five regimes exist – forest cover (I), grassland with tree cover (III), grassland without tree cover (IV), co-existence (I), and bimodal tree-grass cover (i.e. bistability) – (V). Incorporating a hydrologic feedback (right panel, β=0.8) expands the co-existence regime (III) at the expense of forest cover and bi-modal regimes. Insets show woody cover PDFs i.e. *p(V)*.

4. Study sites and Preliminary Results

The study focuses on two exceptional watersheds in the Sierra Nevada: the Illilouette Creek Basin (ICB) in Yosemite National Park, and the Sugarloaf Creek Basin (SCB) in Sequoia-Kings Canyon National Park. Fire exclusion in these basins ended in the 1970s – making them the only watersheds in the Sierra Nevada with a "natural" fire regime. The post 1970 fires have been mapped and classified, providing a 40-year fire history [36]. Since 1970, ICB experienced 22 fires exceeding 40ha, and Sugarloaf Creek has experienced 12 fires of this size. The current fire regime in the ICB is consistent with the pre-European fire regime (documented by fire scars) – a fire return period of 6.8 years (c.f. 6.3 years prior to 1920). In SCB, the fire return period is now 12 years, compared to 9 years. The pre- and post- 1970 conditions in the basins allow an evaluation of three fire regimes, characterized by different fire return intervals. The two sites are otherwise comparable: ~15,000 ha in area, 1400 m to ~3000 m elevation range, a Mediterranean climate with annual temperatures ranging from -5°C to 32°C (observations from Yosemite and Sequoia/Kings Canyon National Park weather stations, 1948-2006). Precipitation is 100cm, dominated by snow. Forests comprise Jeffrey pine (*Pinus jeffreyi*), red fir (*Abies magnifica*), white fir (*Abies concolor*), lodgepole pine (*Pinus contorta*), interspersed with rocks, meadows and shrublands.

In 2013, I initiated a program of hydrological field and remote sensing studies in ICB, focused on reconstructing the changing vegetation cover from 1969 – 2015, and relating these vegetation changes to hydrologic response. This work is performed in close association with the Berkeley Fire Ecology Lab (lead by Prof. Scott Stephens), who are committed to sharing their 15-years of fuel and vegetation assessments at these sites. We assembled high-resolution (<1m) aerial photography records from 1969, 1987, 1997 – 2015, and are currently developing a geospatial analysis protocol to interpret key vegetation types (forest, wetland, grassland, shrubs) from these images, via object-oriented classification in the eCognition suite (Trimble, Figure 5 c). The resulting classification is validated against contemporary Yosemite vegetation maps, field data, and, in historical images, vegetation cover in unburned sites. Inspired by observations (e.g. [75, 76]) suggesting that vegetation type may serve as a proxy for soil moisture, we made over 3280 measurements of surface soil moisture (in over 70 sites) characterizing the associations between mean soil moisture and its summer trajectory, and vegetation type (e.g. Figure 2 A). Cognizant of the difficulties associated with the interpretation of surface soil moisture (e.g. [77, 78]), we also measured predawn and midday plant water potentials, verifying that these metrics (representative of moisture conditions throughout plants' root zones) were linearly related to the surface soil moisture. Similarly, remotely sensed wetness indices (specifically Tassled Cap Wetness and Greenness indices, Figure 2 C), are correlated to surface soil moisture in meadows, providing a basis for upscaling.

We applied the RHESSys ecohydrological model to the ICB, and are currently re-calibrating it to historical vegetation conditions. RHESSys is widely used to study ecohydrology in the Sierra Nevada, and has already been applied to the Upper Merced Basin (surrounding the ICB) [68]. Vegetation cover history (from the imagery analysis) will be used in a model experiment to assess the sensitivity of the hydrological regime to the changes induced by fire. Preliminary results (comparing historical vegetation cover to a synthetic condition in which all vegetation and litter was removed from the fire areas) are suggestive of increases in snowpack (approximately 200 mm on average) and decreases in summer transpiration (a decline of >80mm or about 50%) in response to burning. In summer 2015, weather stations will be installed in the ICB covering three different vegetation and fire conditions (burned conifer forest regenerating with wetland plants, un-burned conifer forest, and shrubland) to characterize the one-dimensional water and surface energy balance. Rain and snow gauges, and solar radiation sensors, are co-located with three TDRs spanning the top meter of soil. Multiple temperature, humidity and solar radiation sensors are installed in surrounding trees. Time-lapse cameras mounted in trees will report snowpack depth, calibrated against multiple visual targets in their viewfield. While this measurement approach is somewhat unorthodox, it represents the negotiated "minimum requirement " for wilderness permitting and research approvals in the ICB (granted for 2015-2019). Flow measurements and rating curves are also being developed for the Illlilouette Creek above its confluence with the Upper Merced River (presently IC is gauged after the confluence, with approximately 100 years of flow data available).

To date, no hydrologic work has been undertaken in Sugarloaf Creek, but initial discussions with Sequoia-Kings Canyon NP indicate support for exploring fire-vegetation-water dynamics in this basin.

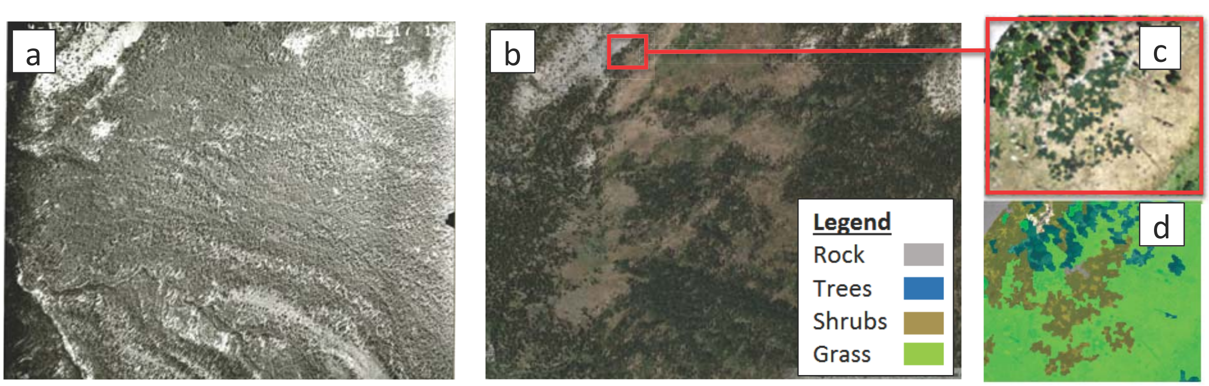

Figure 5: Changes in woody vegetation cover (*V*) over time in the ICB. In 1969, this 4 x 4 km region was near-homogeneous forest (a). Following 40 years of restored fire regime, extensive new grassland (meadow)

environments opened up (b). The eCognition suite is used to classify the aerial photography into major vegetation types (rock, trees (conifers), shrubs and grass (meadows), c and d).

5. Project Tasks

To address the hypotheses, I propose four project tasks to be completed over a 5-year interval. These tasks link remotely sensed observations, model development and predictions and the continuation and augmentation of existing field campaigns at ICB and SCB.

Task 1: One-dimensional water balance components and field observations

Field installations will be maintained in the ICB and replicated at SCB to provide information about the vertical water balance under different vegetation and fire history conditions. In each basin, I will target a mature conifer forest, a burned conifer forest regenerating with wetland vegetation, and shrubland. Climatic forcing, snowpack depth and soil moisture dynamics will be measured for at least three years at each site. At winter snow courses/year will be made at each site to measure snow density. Differences in snowpack accumulation and spring ablation rates under closed versus burned canopies will be determined, allowing me to test **Hypothesis 1.5** in these intensively locations. Differences in summer soil moisture will be measured via TDRs and used to infer evaporation/ transpiration rates, allowing me to test **Hypothesis 1.2**. Spatially extensive soil moisture measurements made in ICB will be repeated there (at least once) and extended to SCB (for at least three summers) to evaluate the $\theta=\theta(V)$ relationship, allowing me to test **Hypothesis 1.3** over multiple sites (over 70 locations have been measured to date in the ICB). Plant water potential measurements (dawn and midday) will be made at a subset of these sites for comparison with TDR observations (allowing me to relate surface soil moisture observations to root-zone water content, and assisting in testing **Hypothesis 1.3**). Porometry and LAI measurements will be made for different cover types as input to the RHESSys model. Vegetation communities associated with the soil moisture measurements will be mapped, providing a ground-truth dataset for air-photo analysis (see Tasks 2 and 3). Fuel samples (for the fine, coarse and live fuel fractions in the basin) will be made at a subset of sites in ICB and SCB, spanning the observed range of soil moisture conditions. Fuel moisture measurements will be undertaken following the protocols used by the Berkeley Fire Science Group. As part of the education plan, students from NatureBridge will also make coupled fuel moisture and soil moisture measurements for different vegetation types and fire histories around Yosemite National Park, extending the dataset. The soil moisture and fuel moisture datasets will be coupled to test **Hypothesis 1.1**. A stratified sample of soil types from ICB and SCB will also be made, brought to campus, and heated (following the protocols in [79]) to replicate fire effects on hydrophobicity. Treated soils will be subjected to cycles of wetting, drying, freezing and thawing that approximate post-fire winter soil surface conditions in the Sierra Nevada. Water and ethanol drop penetration tests [64] will be used to evaluate hydrophobicity and test **Hypothesis 1.4**. Finally, stilling wells and pressure tranducers will be installed in three streams in the SCB (draining areas with different burn histories), and rating curves developed. These installations are a top priority, as they will represent the first hydrological data available for the basin, which will be necessary to support the RHESSys modeling in Task 3. Field-work will be lead by the graduate student researcher, supported year-round by a technician (research specialist) at 10% time, and in summer by 2 undergraduate researchers, who will be required to develop and present on independent projects based on their work (see **Education Plan**). Field studies linking soil moisture and fuel moisture will be greatly augmented (in time, space and number of replicates) by a citizen science program engaging 500-1000 middle-school students/year in Yosemite and implemented through collaboration with NatureBridge, an outdoor education organization (see **Education Plan**).

Task 2: Remote sensing

Remote sensing imagery acquisition will focus on SCB, as imagery is already available in ICB (Figure 5). At SCB, 1m resolution aerial photography is available from 1999 -2015; LandSat imagery (30-80m) will be used to analyze vegetation cover change from 1970-1998. Protocols developed for ICB will be used to classify images in eCognition as: pine forest, shrubs, meadow/grassland, rock or water. Contemporary images will be validated against ground observations in SCB. Classified images will form a timeseries of vegetation cover, which will be aggregated to analyze patch-scale dynamics, the spatial correlation of vegetation structure, the probabilistic composition of vegetation cover over time, and the vegetation transitions induced by fire. These data will be used to test **Hypothesis 2.1** for ICB and SCB. Woody biomass spread rates will be determined and used to estimate the growth parameter α in Equation 1. The LandTrendr algorithm developed by Kennedy et al. [80] for NASA and USGS, and Landsat data from 1982 to 2013, will be used to analyze trends in the Tasseled Cap wetness and greenness indices in SCB meadows. This task will be lead by the graduate student researcher, supported in summer by 2 undergraduate researchers, who will develop and present on their research projects (see **Education Plan**).

Task 3: Watershed modeling

The Regional Hydro-Ecologic Simulation System (RHESSys, [37]) was designed to simulate climate and land use change impacts on coupled ecosystem carbon and nutrient cycling and spatially distributed hydrology. RHESSys explicitly models two-way feedbacks between hydrologic variables such as soil moisture and vegetation water use and growth and resulting impacts on streamflow. RHESSys has been applied to examine climate and land use change in a variety of snow dominated mountain environments and evaluated using both hydrologic and carbon cycling data [60, 81, 82]. RHESSys will be applied to both the ICB and the SCB to estimate the hydrological changes generated by fires. Modeling of ICB with RHESSys is in progress (see Section 4), with the model being calibrated for the pre-1970 period using the 1969 vegetation cover, obtained from the aerial imagery. Due to the lack of long-term flow gauging of the SCB, data gathered during the field campaigns will form the basis for calibration. The calibrated models will be run using observed climatic forcing in each basin (obtained from interpolated datasets, e.g. ClimSurf [83]). For each model run, a different vegetation cover will be used. Five cover types will be used for the ICB: 1969 (fire suppressed), 1987, 1997, 2005 and 2015. A similar chronology will be developed for SCB based on image quality and fire occurrence. Differences in total runoff, runoff ratio, the snow-melt fraction of runoff, and changes in soil moisture and snowpack across the basins will be determined, and used to test **Hypothesis 2.2** (and to provide further insight into results obtained when testing **Hypotheses 1.2, 1.3** and **1.5**). RHESSys modeling will be lead by the postdoctoral scholar starting in the third year of the project. I intend to employ a postdoctoral scholar with RHESSys expertise who will devote 50% of their time to the project over 2 years, sufficient to complete this modeling.

Task 4: Theoretical development and model synthesis

This task executes the theoretical development outlined in Section 3 of this proposal, with two elaborations. The first addresses the spatial patterns of fire (Figure 6, A,B). The extent of fires in the ICB and SCB within previous fire boundaries is now limited by low fuel availability, so that the landscape consists of patches with distinct fire histories [8]. To capture this effect, I will modify the probabilistic model to include a deterministic spatial neighborhood function (based on [84]) – and implement it in a cellular automata framework (Figure 6 C shows illustrative output). I will assess the effects of spatial dynamics on the domain-averaged model behavior, seeking re-scalings of the patch-scale metrics ω_0 and $\lambda(V)$ that describe the emergent behavior (c.f. [85]). The second elaboration addresses the representation of land cover types. I will experiment with dividing woody biomass into shrubs and conifers, which have different growth rates and fire risks. I will implement numerical schema with these multiple cover types, and explore the potential of *n-species* stochastic analytical models (e.g. [86, 87]) to describe the system. I will seek a semi-empirical relationship to estimate lumped model parameters for the 2 species model that approximate results from the 3 species model. The final probabilistic model will be parameterized for the Sierra Nevada under current and future climate scenarios (e.g. those available via the CalAdapt portal, or from USGS [88]), at the HUC-12 watershed scale, to explore the joint effects of changing fire management (i.e. changing λ) and climate (i.e. changing λ_p, γ and E_{max}, e.g. [89]) on forest, water and fire risk. The feasibility of restoring a natural fire regime will be primarily evaluated on proximity to dwellings: unmanaged fire regimes are only feasible in isolated areas. Results will be used to evaluate **Hypothesis 3**, and will form the basis for CFSC outreach. I will lead this research and outreach effort, allowing me to use the model as the basis for case studies and teaching examples in a Graduate Seminar, and incorporating the model into modeling teaching modules to be implemented in collaboration with the NatureBridge outdoor education organization (see the **Education Plan**).

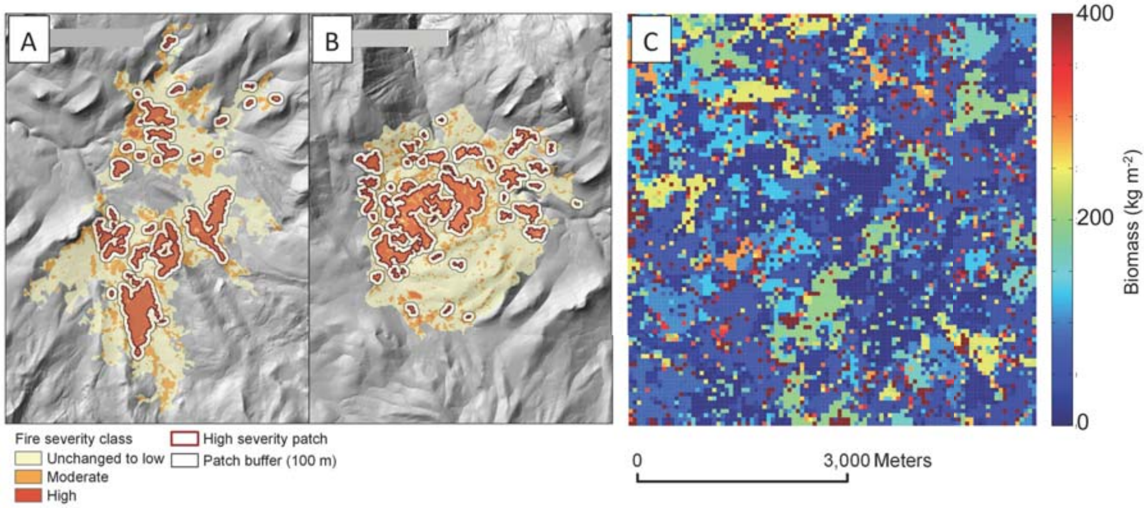

Figure 6: Spatial properties of fire, and resulting biomass spatial distribution in a simple cellular automata (CA) model. Panels (A) and (B) show the Hoover and Meadow Fires in the ICB respectively. Panel C shows model output of local woody biomass density after 3000 annual timesteps.

6. Education Program

Probabilistic models, as developed in the research component of this proposal, have a 30-year history in hydrology and ecohydrology [90-92], and many attractive features (including low data requirements, robustness, scalability and representation of key random processes). Yet their uptake for management applications remains almost negligible. Bridging the gap between the formulation and testing of such models, and their use to make management and development- relevant predictions is a major theme in my recent research (e.g. [89, 93-97]). The education program proposed here aims to address another set of roadblocks that impede the widespread use of probabilistic models – lack of familiarity, credibility and acceptance amongst users. I aim to address this issue by (i) equipping researchers (PhD students) to become credible educators and communicators *about* these kinds of models and (ii) by familiarizing middle-school students with modeling as an integrated component of science education and practice.

In designing an educational platform to achieve these goals, I will also address two more general issues. Firstly, I want to generate positive, meaningful science education experiences at the middle-school level, broadening student participation in STEM. Secondly, I want to address a gap in the existing graduate curriculum in the UC Berkeley Environmental Engineering program, by creating a course that explicitly targets "Twenty-First Century Skills" for scientists – e.g. education, communication, participation in inter-generational teams etc. [98, 99] - to improve students' preparation as future faculty and environmental leaders. No such program exists in the Environmental Engineering graduate curriculum at UC Berkeley presently.

Figure 2: NatureBridge participants in an outdoor classroom at Yosemite National Park.

The education program will link the outdoor education organization, NatureBridge, with my research and teaching at UC Berkeley. Based in Yosemite National Park, in proximity to the ICB, NatureBridge delivers outdoor-based environmental science education (see Figure 7). Targeting **middle-school students**, NatureBridge aims to create engaged students, healthy communities and a sustainable future through one- to five-day residential environmental education programs. 13,000 students, a large proportion (56%) coming from under-represented and under-served minorities in STEM, participate in NatureBridge activities each year. NatureBridge is well positioned to incorporate data collection supporting my proposed research activities into its ongoing outdoor education programs. At the same time, my expertise and interest in modeling environmental systems is synergistic with current educational needs at NatureBridge. Specifically, NatureBridge is working to align its educational philosophy with the Next Generation Science Standards (NGSS). The NGSS were developed by The National Research Council, the National Science Teachers Association, and the American Association for the Advancement of Science. They address content knowledge, cross-cutting concepts, and science practices. Students are responsible for content knowledge, but are asked to make connections (i.e. cross-cutting concepts), while engaging in the same habits of mind – or science practices - employed by working scientists. NatureBridge is working to incorporate all eight NGSS science practices into their curriculum. My education plan will connect graduate students and NatureBridge in support of a NGSS science practice that has posed some challenges for this outdoor education organization - developing and using models.

Education plan components.

The education plan has three major components: (i) Augmenting existing outdoor education and data collection activities at NatureBridge, (ii) Creating a new graduate seminar course: "**Numerics to Nature: Teaching and communicating environmental models**," offered within the Civil and Environmental Engineering graduate curriculum at UC Berkeley and incorporating practical mentoring and implementation of learning modules with NatureBridge educators. The third component of the education plan (iii) focuses on developing a vertically-integrated research team in my laboratory, spanning undergraduate to postdoctoral researchers. In forming this team, I will capitalize on an existing Undergraduate Research Opportunity Program (UROP) in the Department of Civil and Environmental Engineering at UC Berkeley to engage undergraduate students in the research effort.

(i) Augmenting existing outdoor education and data collection activities at NatureBridge

NatureBridge offers **informal educational programs**. Informal (non-classroom) settings represent an important avenue to promote scientific learning [100], improving STEM literacy [101]. According to the National Academy, there is "mounting evidence that structured, non-school science programs can feed or stimulate science-specific interests… positively influence academic achievement for students, and may expand the sense of future science careers" [100]. Linking informal scientific activities with "real" scientific research is often foundational to the success of such programs [100, 102]. I will augment an existing outdoor activity at NatureBridge that measures fuel moisture, by providing NatureBridge with access to and training in the use of a surface soil moisture mobile TDR (the Campbell Hydrosense II), and the use of a citizen science portal (e.g. CitSci.org or CrowdCrafting.org). Students will measure soil moisture and fuel moisture in different locations and forest types, compiling their data in the citizen science portal, and use the portal to explore emerging trends across seasons and locations. This program will greatly expand the number of measurements and range of conditions in which fuel and soil measurements can be made, providing a valuable dataset to the project, and enriching the content and value of NatureBridge's existing fuel-moisture learning activity. 500-1000 students are anticipated to participate in this activity in each year of the project.

(ii) Graduate seminar course and delivery of learning modules at NatureBridge

Motivation: This component of my education plan addresses teaching, communicating and learning about mathematical models, with the model developed in the research component of the proposal acting as a case study. Classroom teaching about models is traditionally abstract, technically detailed, and daunting [103-106]. Incorporating modeling into informal science education can circumvent these challenges. Successful informal education has three characteristics: juxtaposition, interaction, and multiple-modes of engagement [100, 102]. The key elements of working with models – summarizing process understanding, making and testing predictions and evaluating the results – are well aligned with these characteristics. Incorporating modeling in NatureBridge's curriculum could thus be highly effective for student learning, as well as supporting NatureBridge in meeting the NGSS goals.

The capability of traditional graduate education to equip PhDs as future faculty has been challenged [107], with the Graduate Schools Council (GSC) noting that "teaching and professional service are frequently not components of doctoral education [107]." As reflected by increasing calls to improve graduates' "Twenty-First Century competencies", there is also a broad need to develop skills in communication and interpersonal competency [98, 99]. At UC Berkeley, undergraduate courses must be taught by faculty, limiting graduates' opportunities for undertaking meaningful teaching roles (a major obstacle noted by the GSC [107]). The proposed course would fill this gap, educating participants in the latest thinking about education and communication of science, and providing them with a meaningful teaching role at NatureBridge. The course curriculum will be based on the highly successful "Communicating Science" courses developed at the Lawrence Hall of Science (http://www.lawrencehallofscience.org/comsci/session_all.html), with content tailored towards educational and communication challenges associated with the use of mathematical models. The modeling framework developed in the research component of this proposal will provide a case study. The capstone requirement for the course is the design and implementation of a learning module at NatureBridge that combines mathematical modeling with outdoor education. E.g. this integration might be achieved by students gathering field data as input to a model; or by making a prediction with a model that are then tested in a field setting. Professional educators from NatureBridge will mentor, guide and assist students teams in designing and implementing these modules. Each year, the most successful module will be integrated into the NatureBridge curriculum, through an "educating the educators" event that I will run at the conclusion of the semester. A curriculum and schedule for the course is available online (http://tinyurl.com/CurriculumThompson).

Learning Goals: Learning goals are proposed for the graduate and middle-school students.

At the end of the "Numerics to Nature" course, **graduate students** should be able to:
1. Identify key features of content knowledge around the use, interpretation and limitations of mathematical modeling of environmental systems.
2. Link these features to potential teaching strategies relevant to mathematical modeling of environmental systems, drawing on best-practice and research.
3. Critically assess educational experiences (as learners or as instructors) based on personal observations, peer, mentor and student feedback, and plan improvements.

Specific learning goals for the **middle-school students** at NatureBridge will vary with the learning modules. All modules will be developed with the goal that at their conclusion, students should be able to:
1. Explain why scientists use environmental models, and critique this use;
2. Develop a plan of inquiry that combines the use of field observations and models;
3. Meet selected goals as articulated in the Common Core Mathematics Standards (http://www.corestandards.org/Math/Practice/) and Next Generation Science Standards Practice 2 – Developing and Using Models (http://www.nextgenscience.org/next-generation-science-standards), as appropriate to the learning module design.

Implementation: I will act as the director and facilitator of the course, but I will lean heavily on the expertise of educational specialists from NatureBridge, the Lawrence Hall of Science (LHS), and the Center for Teaching and Learning at UC Berkeley. NatureBridge will engage 4-5 educators from their Yosemite program to work directly with small teams of students in the design and implementation of the learning modules. Experts from the Lawrence Hall of Science will be engaged in three ways. Firstly, I will communicate extensively with LHS Deputy Director Craig Strang, designer of the award-winning "Communicating Science" course, as I finalize design of the graduate seminar. Secondly, I will invite educators from the BEETLES program (which trains field instructors for outdoor education, http://beetlesproject.org/index.html) to deliver a guest lecture to the seminar class, addressing the design of outdoor education activities. Finally, The LHS Research Group will work directly with the class regarding the assessment of student learning and evaluation of the learning modules they design. Dr. Rena Dorph, The Director of the Research Group (and Lecturer at the Graduate School of Education at UC Berkeley), will mentor and guide the students through the design of a tailored evaluation instrument. Independently, the LHS Evaluation Program will conduct a **formal evaluation** of the effectiveness of the graduate seminar in meeting the learning goals. Evaluation efforts will include the collection and analysis of data regarding the experience of the participants in the seminar. The evaluation team will conduct selected observations of seminar sessions and activities, interviews with seminar participants and instructor, and review of participant classwork and projects. Data will be coded and analyzed to detect patterns and themes related to seminar participants' learning, and the influence that the seminar experience had on participating graduate students. Valeria Romero, Associate Evaluator, will serve as the evaluator. Valeria is the lead researcher for several programs, including two UC Berkeley projects funded by NIH under the Initiative for Maximizing Student Development (previously known as Initiative for Maximizing Student Diversity) and the Minority Access to Research Careers programs.

Incorporation into NatureBridge's Curriculum / Continuous Improvement: I will initiate the graduate seminar during years 2-4 of the project, allowing a year of "spin-up" to refine the curriculum, complete necessary administration required to list the course as part of the CEE Graduate Curriculum, and to develop class materials. I will run the course for three years and engage evaluators in each year. This gives me an opportunity to improve the offering, and to guide students towards improved educational module design. Following the first implementation of the teaching modules at NatureBridge, I will identify the most successful, based on feedback from NatureBridge educators. I will run an educator training session for this module, targeting **20 NatureBridge** educators (ensuring the module is taught to at least **500 middle-school students/year**). I will carry this refined module forward into subsequent graduate seminars as a target for continuous improvement and experimentation in teaching design by the graduate students. In the last year of the project I will, if appropriate, work with LHS collaborators to publish course materials and a description of the educational activities in an educational journal.

(iii) Diverse and vertically integrated research group
The final component of education program involves forming a **gender-balanced and vertically integrated** research group. At present, my lab contains 6 PhD students (three female), 1 female postdoctoral scholar, and 8 undergraduate researchers (four female). PhD students in my lab undertake extensive mentoring of undergraduates via a variety of on-campus programs (e.g. SMART http://smart.berkeley.edu/, and the Energy Corps http://vcresearch.berkeley.edu/energy/welcome-cal-energy-corps). I will sustain this vertical integration by incorporating researchers at all levels into the project team. I am particularly keen to "open the pipeline" to research for undergraduates, and will do so by recruiting 2 students a year from the Undergraduate Research Opportunities (UROP) initiative in the Department of Civil and Environmental Engineering. This program offers undergraduates research training and sponsorship to undertake individual research projects. Results are presented at a poster session during "CalDay" – UC Berkeley's annual open house event (attracting 30-40,000 people). 4 - 8 UROP students would obtain research experience and mentoring through this project.

7. Intellectual Merit

The **intellectual merit** of the proposed research lies in making three contributions to hydrological science and the practice of probabilistic modeling. Firstly, it will **contribute new process understanding** regarding the interaction of fire and hydrology in snow dominated landscapes. Specifically it will address existing knowledge gaps regarding the effects of fire on snowpack dynamics (including interception, sublimation and melt timing), and the effects of freeze-thaw processes on post-fire soil hydrophobicity, which have received little attention, but are increasingly important as fire risks increase in montane areas. Secondly, it will provide **unique spatial, temporal and historical datasets** that address the consequences of fire suppression and its alleviation in montane forests on vegetation and hydrology jointly. The unique history of the study basins relative to the uniform practice of fire suppression in the remainder of the Sierra Nevada mean that these datasets offer insight into the effects of fire suppression and the potential impacts of reversing fire exclusion policies: these are critical questions as fire risks grow with climate change and the build up of fuels in fire-suppressed forests. Finally, the project will offer an excellent opportunity to **develop and test a probabilistic, dynamical systems model linking fire, vegetation and water dynamics**. Such models have not been well formulated or tested outside of savanna ecosystems, and the data gathered here create an excellent opportunity to undertake such tests. The research project represents one of relatively few attempts to use stochastic process models to inform management, continuing this major theme in my research [89, 93-97].

8. Broader Impacts of the Proposed Work

The **broader impacts** of the work arise in two areas: (1) **motivating new fire management in the Sierra Nevada**, simultaneously reducing the risk of catastrophic fire, and enhancing the security of water supplies in a region that supplies 60% of the water used by a state with over 38 million residents, and (2) **educational outcomes** including improved STEM education, educator development, and enhanced participation of women and under-represented minorities in STEM and STEM education. Firstly, the research will provide evidence-based evaluation of the effects of restored fire regimes on hydrology, and identify basins where similar management treatments are both viable and beneficial. This information will be shared with State and Federal agencies, including water utilities, with land and water management responsibilities. The US Forest Service and the National Park Service are revising forest management plans for all western US National Forests, the first such revision to be made in 20-30 years, making the provision of this information timely. To maximize outreach to these agencies I will partner closely with the CFSC (http://www.cafiresci.org/), headed by collaborator Prof. Scott Stephens. The CFSC's mission is to transfer fire science information from researchers to agencies and community groups to enhance management decisions. I will partner with an outreach specialist at the CFSC to develop a portfolio of outreach options that will maximize the impact of my research. Strategies include webinars, writing research briefings and syntheses, and articles in a monthly newsletter reaching 1800 readers. Outreach through the CFSC will parallel traditional scientific activities, including participation in national and international conferences, and publication of results in the peer reviewed literature. Through the planned educational activities, I will train approximately 30 graduate students in improved science education and communication strategies, engage 500 middle school students/year at NatureBridge in learning about environmental modeling, and another 500-1000 per year in a citizen science project. NatureBridge students are primarily Latino (51%), with significant participation from African American (5%) and Indigenous (1%) students, and there is also an active outreach program to bring students from under-served schools in California's Central Valley to NatureBridge. Collaboration with NatureBridge will therefore enhance scientific learning opportunities for a large number of students from under-represented and under-serviced backgrounds. It will also enable me to educate ~20 NatureBridge educators about environmental modeling per year, enhancing the overall curriculum and expertise of these educators (who together teach ~13,000 students/year). I will engage 4-8 undergraduate students in meaningful research experiences and research preparation activities through the CEE UROP program. I will also provide opportunities for mentoring and research development for a graduate student researcher and a postdoctoral scholar within a vertically integrated and gender-balanced research group.

9. Project Management

Thompson has authored 37 peer-reviewed manuscripts covering hydrological and ecological sciences, non-linear dynamics, and field and modeling studies. She will lead a research team consisting of a graduate student researcher, a postdoctoral scholar at 50% time, a field technician (10% time, supporting field deployment) and 2 undergraduate researchers/summer (for 4 summers). Project tasks and timeline are shown below. Symbols indicate the team-members working on each task.

Task	Year														
	1			2			3			4			5		
	F	Sp	Su	F	Sp	Su	F	Sp	Su	F	Sp	Su	F	Sp	Su
Fieldwork - ICB	☐	☐	☐✗	☐✗	☐✗	☐✗★									
- SCB	☐	☐	☐✗★	☐✗	☐✗	☐✗★	☐✗	☐✗	☐✗★	☐✗	☐✗	☐✗★			
Rem Sensing -SCB			✗	✗	✗	✗	✗								
- Analysis			✗	✗	✗	✗	✗	✗	✗						
RHESSys							O	O	O	O	O	O			
Theory	•	•	•	•	•	•	O•	O•	O•	O•	O•	O•	•	•	•
Synthesis							✗	✗	✗	✗	✗	✗	✗	•	•
Class			•	•		•	•		•	•					

• Thompson	☐ Field Tech.	O Postdoc	✗ Graduate Researcher	★UROP students

10. Results from Prior NSF Support

NSF IIA-1427420: '*Collaborative Proposal: US-India planning visit: Linking remote sensing, citizen-science and robotics to address critical environmental problems in data-sparse regions*.' (Awarded $38,733.00 Peschel and Thompson, PIs; May – December 2015).

Intellectual Merit: Novel robot-based (UAV) measurements of cascading tank rainwater harvesting systems were made in two locations in the Arkavathy watershed, Karnataka, South India, addressing data-scarcity in the region. Measurements were linked with (i) satellite observations of peak annual surface water levels (1970-2015) to reconstruct hydrologic change, (ii) in-situ daily tank depth measurements to infer contemporary runoff dynamics and water balance (iii) kite-photography to validate this low-cost measurement technique. Robot-based (robotic boat) water samples and in-situ water quality sensing (pH, temperature, conductivity) were made in one urban lake to provide spatially-resolved images of variation in scalar fields around sewage inflows. Feasibility of the data fusion and new measurement techniques has been verified. Results were shared with 25 sensor, water science, remote sensing, and citizen-science specialists who participated in a joint workshop on June 12 entitled: *Linking Robotics, Citizen Science and Remote Sensing to Advance Water Science in Data-Scarce Regions*, held at the Ashoka Trust for Research in Ecology and the Environment in Bangalore, India (Minutes available: http://tinyurl.com/ockn297). Five manuscripts are currently proposed drawing on this work. The first, *Penny G., S. Young, V. Srinivasan, J. Peschel and S. Thompson, "Augmenting satellite and ground-based hydrological analyses with UAV bathymetry in a data-sparse region in Southern India"* will be submitted to a Special Issue of *Water Journal* entitled: "New Developments in Methods for Hydrological Process Understanding " in August 2015.

Broader Impacts: The project builds on existing research foci held by ATREE (e.g., evaluation of impacts of urbanization in Bangalore on water demand, water use, and water quality in the city and its hinterland), UIUC (human-robot interfaces for environmental observations) and UCB (satellite remote sensing for reconstruction of water histories in south India). The pilot data collection thus supports wider research aims. ATREE's involvement connects the work to policy formation in south India. Data collected are currently available to ATREE. Once quality assurance and control are completed, data will be shared through the ATREE project portal and the India Water Data Portal. The proposal currently supports one PhD student and one project masters student conducting field research with ATREE in Bangalore. Broader impacts from the June 12 workshop included identification of four immediate technical opportunities to develop new, low-cost groundwater, weather, and lake water quality monitoring, and development of a low-cost automatic water sampler. ATREE is working with local technical partners in Bangalore, and the PIs, to realize these opportunities and integrate them into ongoing environmental research and citizen science in Bangalore.