

Project title: Developing fuels treatments for balancing fuel reduction, soil exposure, and potential for erosion in the Tahoe Basin

Theme and sub-theme addressed by proposal: Theme 2, Forest Management, Fuels Reduction, and Stream and Meadow Restoration, Fire and Fuels sub-theme

I. Project Team and Contact Information:

Andrew P. Stubblefield, Department of Forestry and Wildland Resources, Humboldt State University, One Harpst St., Arcata, CA 95521; Phone: (707) 826-3258, FAX: (707) 826-5634, email: aps14@humboldt.edu

J. Morgan Varner, Department of Forestry and Wildland Resources, Humboldt State University, One Harpst St., Arcata, CA 95521; Phone: (707) 826-5622, FAX: (707) 826-5634, email: jmvarner@humboldt.edu

Eric E. Knapp, U.S. Forest Service, Pacific Southwest Research Station, 3644 Avtech Parkway, Redding, CA 96002; Phone: (530) 226-2555, FAX: (530) 226-5091, email: eknapp@fs.fed.us

Mark E. Grismer, Department of Hydrologic Science, University of California, Davis. One Shields Ave. Davis, CA 95616. Phone: (530) 752-3243, FAX: (530) 752-5262, email: megrismer@ucdavis.edu

Grants Contact: Julie Davy (Lead Grants Analyst), Humboldt State University Sponsored Programs Foundation, One Harpst St., Arcata, CA 95521. Phone: (530) 826-5203, email: jms49@humboldt.edu

Total funding requested: \$262,434

Total value of in-kind and financial contributions: \$74,715

II. Proposal Narrative

- a. **Justification Statement:** With clarity of Lake Tahoe the dominant concern in the Basin, protecting soil resources and reducing erosion currently dictate how many forest and fuel management activities are carried out. Concurrently, reduction of wildfire hazards looms large in land management decisions over the recent past, particularly following major wildfires in 2007. Balancing these two often opposing concerns is a major challenge for land managers and policymakers in the Lake Tahoe Basin. While fuels treatments may meet soil erosion and fire behavior reduction objectives in the short term, these same treatments may exacerbate the same issues in the long-term in the event of a wildfire. Both the amount and continuity of organic material on the forest floor may result in high fire severity and more homogenous burns. As an example, the Little Washoe Fire near Tahoe City during the summer of 2007 burned into an area where thinning had been conducted and small trees and slash masticated, producing a compact but continuous fuel bed. Fire managers commented that the compacted fuel bed appeared to slow rates of spread and moderate flame lengths, making fire control easier. Because of the large amount of organic material on the forest floor, however, the heat generated was still sufficient to kill all or most overstory trees, and the fuel continuity resulted in a complete burn. To reduce the potential for erosion, considerable rehabilitation expense will be required, and stand replacement will result in succession to shrubs and small trees that will increase fire hazard within the critical wildland-urban interface for many decades. Fire suppression policies throughout the Basin have resulted in a similar conundrum. The excess litter and woody fuel that is now on the forest floor and the greater continuity of this organic material may indeed protect the soil, but when this material burns, either through wildfire or prescribed fire, the result is a burn that is much more continuous than historical fires were likely to be (for example, the Angora Fire of 2007), leaving the system more prone to erosion. As a result, expensive rehabilitation is required. Research is urgently needed to understand how best to balance erosion and fire hazard reduction objectives using forest and fuel management activities in the Lake Tahoe Basin.
- b. **Background and Problem Statement:** Prior to Euroamerican settlement, low to moderate severity fires burned through forests in the Lake Tahoe Basin at an average return interval of 11 years (Taylor 2004). After fire, litter and other fine fuels necessary to sustain surface fire require time to accumulate to the point where they propagate fire. Because of the spatial heterogeneity of Basin forests, litter accumulation can be quite variable. Historically, the mixture of areas with and without sufficient fuels to carry fire led to patchy burn patterns (Knapp and Keeley 2006), but the way fire now burns may be fundamentally different. In forests that have experienced many decades of fire suppression, forest densification, and fuel accumulation, most areas currently contain sufficient fine fuels to carry fire. This increased connectivity (Miller and Urban 2000) has implications for how much fuel is consumed, the amount of mineral soil exposed, and with wildfires – the total fire size.
- All of these factors can influence erosion and sedimentation rates. Understanding relationships between fuels management, erosion and sedimentation is of central importance for ecosystem health of the Lake Tahoe Basin. The clarity of Lake Tahoe has declined dramatically in 40 years of measurement. Research suggests that the origins of this decline are linked to watershed sources of suspended sediment and total phosphorus (Jassby et al. 1994, 1999). A documented shift towards earlier snowmelt and increased rainfall relative to snowfall in the mountainous west (Knowles et al. 2006, Westerling et al. 2006) is likely to increase the probability of high-severity fire and the erosivity of precipitation (Beeson et al., 2001).
- Burn patchiness may have played an important role historically, with unburned islands at multiple scales creating barriers to erosion. Research suggests that there may be thresholds of bare mineral soil exposure that when exceeded result in exponential increases in sediment yield (Campbell et al. 1977, Johansen et al. 2001). Using rainfall simulation experiments, Johansen et

al. (2001) found sediment yield to be highly correlated with the amount of bare mineral soil exposed. Compiling data across multiple studies in different ecosystems, Johansen et al. (2001) determined that the relationship between sediment yield and bare soil is non-linear; sedimentation rates were low at low to moderate levels of soil exposure, but once a threshold of approximately 60-70% of the ground surface was exposed, erosion increased exponentially. They proposed that as the percentage of area exposed increases, the connectedness of burned patches increases, reducing sediment capture and infiltration.

As shown by the Angora Fire, the Little Washoe Fire, and other recent fires within and outside of the Basin, it is clear that the amount and continuity of surface fuel currently found in many contemporary forests leads to undesirable outcomes when burned in a wildfire. Wildfires occurring in the driest conditions of summer and early fall frequently burn a high proportion of the available fuel and cover a large proportion of the ground surface. In addition, high surface fuel loads increase the probability of torching and crown fire (Agee and Skinner 2005, Ritchie et al. 2007). Fires that consume tree crowns eliminate needle cast, which can rapidly cover the ground after less severe fires and reduce post-fire erosion (Pannkuk and Robichaud 2003). Treating/ removing this surface fuel through prescribed burning would reduce the probability of such high severity fire. However, the Tahoe Basin has its own unique constraints to fire management because of erosion concerns with soil exposure, the extensive wildland-urban interface, and air quality issues. Where prescribed fire is not an option, mechanical treatments may be used instead, but how much fuel/ organic matter is it necessary to leave on the forest floor and in what spatial arrangement should it be left to minimize the threat of erosion while also reducing the chance of forest loss in a wildfire? Where prescribed fire is an option for reducing these fuel loads, is it possible to develop burning prescriptions that lead to patchy burns with enough unburned islands to capture sediments but also consume enough fuel to reduce the probability of high fire severity?

It is well known that fuel consumption is strongly associated with fuel moisture at the time of burning (Van Wagner 1972, Hille and Stephens 2005), with consumption constrained at higher fuel moisture values because of the high specific heat of water (Frandsen 1987). How fuel moisture influences the spatial patchiness of burns is one aspect of fire severity that has only more recently been addressed (Miller and Urban 2000, Hille and Stephens 2005, Knapp et al. 2005, Knapp and Keeley 2006). Knapp et al. (2005) found that early season burns conducted under higher fuel moisture conditions were patchier and left more than twice as much ground unburned compared to late season burns (27% vs. 12%, respectively). This burn patchiness, in surface fuels similar to those found in the Tahoe Basin, occurred at many spatial scales, ranging from centimeters to 10's of meters (Rocca 2004; Fig. 1).

Burn patchiness may be explained by fuel moisture variation across the forest floor and influenced by shading and rainfall interception by the forest canopy (Miyanishi and Johnson 2002, Hille and Stephens 2005). With prescribed burning, managers can time ignition for particular fuel moisture levels and thus control the amount of spatial patchiness in burn pattern. Prescribed burns conducted when duff is still relatively moist can lead to burn patterns with patchiness closer to historical norms (Knapp et al. 2005). Patchy burns may be especially desirable for the initial restoration burn after long periods of fire suppression. Once the first burn restores some heterogeneity in forest fuels, patchiness in subsequent burns is easier to attain. A tradeoff is that less fuel is consumed and more follow-up burns may be required to meet fuel reduction objectives, but by reducing fuel gradually and leaving more unburned patches, the potential for erosion may be reduced.

Perhaps nowhere else is this conflict between fuel reduction objectives and erosion control objectives clearer than in the Tahoe Basin. Threat of high severity wildfire is minimized by reducing surface fuel loads; however, this exposure of bare mineral soil may lead to erosion and sedimentation concerns. Research linking the amount and arrangement of surface fuels to erosion and sedimentation and determining erosion thresholds will help managers design mechanical and

prescribed fire treatments that balance fire hazard reduction objectives with ecological and hydrological realities unique to the Tahoe Basin. Furthermore, research on how fuel moisture influences prescribed fire burn pattern in different litter types under contemporary conditions of high fuel loading and high fuel continuity may allow burn prescriptions to be developed that better meet both fire hazard reduction and water quality goals.

- c. ***Goals, Objectives, and Hypothesis to be Tested:*** Our goal is to understand erosion thresholds in order to determine the optimal levels of surface fuel retention with mechanical mastication and prescribed fire treatments that maximize fire hazard/ fire severity reduction goals while minimizing the threat of erosion and sedimentation. Secondly, we seek to understand the mechanisms by which burn patchiness (including sediment capture in islands of unburned fuel) can be created even under the current high fuel loading and fuel continuity in Tahoe Basin forests by linking fuel moisture with timing of prescribed fire, and the pattern of the resulting burn. We propose to 1) determine how much organic material is required on the forest floor to buffer against erosion and whether erosion thresholds exist for the Basin's soils by using on-site overland-flow simulation, 2) evaluate the role of spatial arrangement of organic material (evenly dispersed vs. patchy) on erosion rates, and 3) determine the extent to which heterogeneity in prescribed burn severity (including percentage of ground surface burned) is generated by fuel moisture heterogeneity and how this changes with season.

Specific hypothesis to be tested include:

- Differences in post-treatment percentage of ground surface exposed will result in quantifiable differences in erosion rate as measured with on site runoff simulators.
- Patchily distributed and evenly dispersed surface fuels will result in equivalent erosion rates while the former will be superior in reducing the risk of high severity fire and rate of fire spread.
- As a result of greater fuel moisture heterogeneity, prescribed burns conducted earlier in the season will have increased post-burn patchiness and thus reduced erosion rates. Forest floor fuel moisture content will differ based on vegetation and fuel composition and structure and this variation will decrease over the dry season.

d. ***Approach, Methodology, and Location of Research***

i. Geographic location

The experiments will be performed in forested areas within the Lake Tahoe Basin where mastication treatments have recently been completed and other sites where prescribed fires are planned. Communication with the Lake Tahoe Basin Management Unit (LTBMU) Fire Management Officer (Kit Bailey, November 2007) indicates that four to eight understory prescribed burns are planned for each of the summers of 2008 and 2009, over a range of forested environments. Permission to perform pre- and post- mastication and burn fuels and forest litter studies, and rainfall simulation measurements will be obtained from the LTBMU, California State Parks, California Tahoe Conservancy, or the relevant land owner. Sites will be selected to capture the Basin's dominant soils, forest floor types, and slopes.

i. Approach and methodology

In collaboration with the LTBMU (letters of support filed in Appendix), we will select sites within the Basin with either planned 2008-2009 prescribed fires or recent (1-2 yrs) fuel mastication treatments. Within this list of burn projects, we will select sites from fir-dominated

and pine-dominated stands on volcanic and granitic soils, where possible. At each site, we will estimate downed woody fuel loading using modifications of standard methods (Brown 1974) with supplementary collections of forest floor mass. Vegetation (overstory, midstory and understory) composition and structure at each site will be sampled along the same transects as the fuels. After site characterization, we will conduct experiments designed to evaluate sediment yield response to specific fuel treatments or prescribed burn patchiness.

Pre and post fuel characterization (amount and spatial arrangement) for prescribed burns and wildfires

For all prescribed fires and any wildfires that may occur in 2008 and 2009, we will intensively characterize forest floor fuels. In all prescribed fire units, we will establish 20 linear transects along hillslope contours that capture the variability in fuels and vegetation (lengths will be at least 50m long, but vary based on burn unit size and the scale of burn heterogeneity). Prior to burns, we will survey woody fuel loading along each transect, and install twenty 30cm duff pins flush with the forest floor at equal intervals along the transect (dependent on transect length) to evaluate forest floor depth by horizon. Following the prescribed burns we will re-measure fuel along each transect, quantifying changes in depth and mass of each fuel category and note the start and end point of unburned or partially burned patches. In Basin stands burned by wildfire over the study period, we will follow the same methods as in the prescribed burn units by randomly establishing twenty 50 m linear transects following hillslope contours to capture post-fire variation in forest floor fuels. If no wildfires occur within the Basin during these 3 years, we will sample wildfires on adjacent forest lands with similar vegetation and soils. Along each burned transect we will record frequency and cover (distance) of mineral soil exposure and depth of residual forest floor (by horizon). These fuel consumption data will be analyzed using two-way ANOVA comparing forest type (fir vs. pine) and fire type (prescribed vs. wildfire) effects on mineral soil exposure, depths of residual forest floor, unburned patch area, and unburned patch size. Metrics that encompass the amount of variance among sites for each fuel consumption parameter will be similarly analyzed

To determine within-ecosystem drivers of fuel consumption and mineral soil exposure, we will use multiple regression analysis with fuel consumption (litter, duff, 1-, 10-, 100-hr timelag fuels) and % of the length of the transect with mineral soil exposed as response variables and day-of-burn fuel moisture content and fuel loading as predictors.

Characterization of fuel moisture patterns over the season

To characterize forest floor moisture content variation, we will establish intensive forest floor mapping arrays at each selected site. Arrays will consist of 30 cm X 30 cm subplots placed across a range of overstory cover (from closed-canopy to openings) representing a range in forest floor depth. In each subplot, we will describe pre-fire fuels by horizon (litter and duff) depth and bulk density. We will characterize woody and forest floor fuel moisture in two ways: using fuel moisture sensors and periodic destructive sampling. We will collect surface fuel moisture at each site within the arrays using Campbell Scientific CS505 fuel moisture sensors attached to CS1000 dataloggers. We will couple these continuous measurements with collections of surface fuels at monthly intervals throughout the 2008 and 2009 fire seasons, beginning shortly before surface fuels are dry enough for a prescribed burn and ending in the fall, when fuels are too moist to burn. All collected fuels will be sealed in polyethylene bags and oven-dried at 60°C for 72 h to determine moisture content. All fuel moisture values will be compared between ecosystems (fir vs. pine) in a repeated measures ANCOVA incorporating position beneath the canopy or distance from the nearest tree as a covariate. The amount of variance among samples for each fuel moisture parameter will be similarly analyzed.

Response of Treatments to Simulated Overland Flow

Rainfall simulation (RS) experiments have been widely used to obtain site-specific erosion rates for field treatments that are difficult to replicate accurately in the laboratory. The standard for rainfall simulation experiments is to use 3.03 m X 10.7 m erosion plots with a 16 m rotating boom rainfall simulator (e.g. Johansen et al. 2001). This large size limits the number of treatments and replications that can be examined feasibly in diverse terrain with dense forest stands, steep slopes, and where access to water is limited. A smaller rainfall simulator (0.8 m X 0.8 m plots), such as the type used by project team member M. Grismer in the Lake Tahoe Basin to evaluate revegetation/mulch erosion control of disturbed soils associated with ski-runs, road cuts and fills (Grismer and Hogan 2004, 2005) provides one alternative. However the small RS size does not allow for the measurement of hillslope-scale erosional processes and the impacts of fuel treatments and burn patchiness we wish to capture with this proposed work. Another alternative is to simulate overland flow directly. Robichaud et al. have successfully used runoff simulators to evaluate post fire erosion effects in Idaho for 2, 4, and 9 meter plot lengths (2002, 2006). Field observations in the Lake Tahoe Basin indicate that raindrop impact has little effect on surface aggregate breakdown and subsequent sediment movement; rather erosion is largely controlled by available “stream power”. Furthermore, with its subalpine elevation (1897-3320 m) the bulk of precipitation in the Lake Tahoe Basin falls as snow. The dominant overland erosional process results from snowmelt and resulting runoff rather than rainfall impact. For this study, project team member Grismer will build a portable runoff simulator using his own design or using the template of Robichaud et al. (2002, 2006).

After selecting and characterizing fuel loading and patchiness at eight prescribed burn and eight fuel mastication sites, we will locate plots for runoff simulation. Treatments will follow the block design outlined below (Table 1). The different sites will represent blocks. For masticated fuel treatment sites we will use a control and seven treatments (Experiment 1 in Table 1). Four of these treatments will involve removing 25, 50, 75 and 100% of surface fuels. This will be done by removing all fuels, dividing by the desired amount and redistributing a proportion back on the plot. The amount of fuel will be lessened but fuel continuity retained. The final three treatments will be 25%, 50% and 75% removal, with the remainder patchily rather than evenly distributed so that the fuel complex is broken up. For these three treatments, fuels will be removed from the upper 25%, 50% and 75% of the plots, respectively, exposing bare mineral soil. The lower portions of the plot will be left untouched. Any fuels removed to create the treatments will be dried and weighed to provide a second estimate of site fuel loading.

For the prescribed burn erosion rate study we will utilize a control and 5 treatments (Experiment 2 in Table 1). The control will be placed in an area protected from burning by a constructed line, so that all surface fuel remains intact. Fuel reduction treatments will be placed at locations where fire has passed over 0-25%, 25-50%, 50-75% and 75-100% of the plot, exposing bare soil. Actual amount of bare mineral soil exposed will be estimated by survey and measured by GIS post-processing of digital photography.

After the forest litter/surface fuels treatments have been conducted or burn plot locations identified, erosion plot boundaries will be delimited by sheet metal plates. Plot size will be 2 meters X 5 meters. The size of the plot may be adjusted depending slopes and burn patchiness observed in the field. A sheet metal apron and collection pipe will be mounted at the bottom of the plot, and sealed flush to the soil surface. The runoff simulator will be installed at the top of the plot. Multiple 12-minute periods of concentrated flow will be released at 15 L/min. Multiple periods are necessary to evaluate armoring – the extent to which erosion rates are reduced as available fine material is flushed away. All runoff will be captured in sample bottles and collection basins. Measurements of travel time (m/sec), infiltration rate (cm/s), runoff amount (l), sediment concentration versus time, average sediment concentration (mg/l), and sediment yield (g) will be obtained. Particle size distributions will be characterized for suspended sediment samples using laser particle size analysis (Spectrex PC-2200, Redwood City, CA, owned by HSU).

The six burn patchiness treatments (Experiment 2, Table 1) will be replicated eight times in separate blocks. Combined with eight treatments on each of eight blocks for fuel mastication sites, we will perform a total of 112 runoff simulations over the course of two field seasons. We will use ANOVA to evaluate the significance of treatment effects. We will then use a regression framework to look for threshold effects.

Integrating fire hazard and erosion risk

The goal of the study is to provide managers with the information they need to design prescribed burn and fuel mastication treatments that will optimize the reduction of fire hazard while minimizing erosion rates, as illustrated by functional response curves (Figure 2). In this example, bare soil coverage of 40-50% would optimize fire hazard and erosion yield. Our proposed work would directly provide the data needed to delineate the erosion-fire hazard relationship of Figure 2 for Lake Tahoe conditions. The fire hazard and fuel load/ fuel patchiness relationships will be developed using standard fire behavior and fire spread models such as BehavePlus (Andrews et al. 2005) and FARSITE (Finney 2004), the latter to compare spread rates across simulated landscapes with random patches containing different fuel loading conditions such as those tested by the treatments in the erosion rate experiments. This component of the work will be conducted by a postdoctoral researcher working with co-P.I. Knapp.

The final integration of the experiment will consist of a) estimating erosion yields for surveyed study sites using the relationships defined in the runoff simulations between burn parameters or mastication treatments and erosion, and b) evaluating how fuel moisture affected burn severity and patchiness.

e. *Strategy for engaging with managers*

We will establish these study plots in collaboration with managers in the Basin. Each rainfall simulation experiment is blocked eight times, and therefore can be conducted in eight different locations, enabling us to work with lands of varying ownership, as well as multiple agencies and managers. This will allow the flow of information to go both ways (managers ensuring that the study design directly addresses management issues in the Basin, and researchers ensuring that results are rapidly and widely reported). We have already discussed our ideas with personnel from the LTBMU and others in the Basin, and will plan field visits with LTBMU, local NF personnel, and other manager contacts such as the California Tahoe Conservancy as soon as funding is gained, in order to pin down the location of study sites. Please find attached a letter of support from the California Tahoe Conservancy. At or near the conclusion of the project, data will be presented at meetings attended by Basin managers. Final results will be disseminated as published papers, workshop summaries, and management summaries to regional staff. A project website will be created, with visually rich content geared toward diverse audiences. The more scientific/ technical papers will be linked to the site so that they can be referenced and read by those who require the extra detail.

f. *Deliverables /products*

Workshop with Lake Tahoe Basin resource managers: Balancing fuels, restoration, and erosion potential in the Lake Tahoe Basin (field tour and presentations).

Workshop or Symposium at a National Meeting: Linking fire severity and erosion potential.

Management Summary. Fuel treatment prescriptions for balancing fuel reduction, soil exposure, and potential for erosion in the Tahoe Basin

Project Website: Balancing wildfire risk and erosion risk in the Sierra-Nevada

Manuscript: Identifying the sources of variation in forest floor moisture content in fir- and pine-dominated forests in the Lake Tahoe Basin

Manuscript: Burn heterogeneity in prescribed fires: linking season, forest floor composition, and moisture content variation

Manuscript: Developing fuels treatments for balancing fuel reduction, soil exposure, and potential for erosion in the Tahoe Basin

Manuscript: Consequences of fire and fuels treatments for erosion in the Tahoe Basin

g. Schedule of Milestones/Deliverables

The schedule of events is listed below (Table 2). Preliminary site selection, meetings with cooperating agencies and obtaining permissions will take place in the spring and early summer of 2008. Pre and post burn sampling of fuels, soils, sediment yield, and fire effects will take place during the summers of 2008 and 2009. Sample processing will take place in the Fall of 2008 and 2009. Data analysis and writing will take place in Winter and Spring of 2009 and 2010. Writing, publication of results and conference presentations will take place throughout 2010. Brief updates on project accomplishments and invoices will be submitted quarterly on the 1st of September, December, March and June.

III. Figures

Table 1. Block Design for Runoff Simulation Experiments.

Experiment 1: Masticated Fuel Treatment Sites								
Plot #	1	2	3	4	5	6	7	8
	<i>Patchy removal</i>				<i>Even removal</i>			
Treatment	<i>Bare soil</i>	<i>Top 75% of plot-bare soil</i>	<i>Top 50% bare</i>	<i>Top 25% bare</i>	<i>25% reduction of fuel load</i>	<i>50% reduction of fuel load</i>	<i>75% reduction of fuel load</i>	<i>Control-100% fuel load</i>
Experiment 2: Prescribed Burn Sites								
Plot #	1	2	3	4	5	6		
Treatment	<i>Bare soil</i>	<i>0-25% surface area covered</i>	<i>25-50% cover</i>	<i>50-75% cover</i>	<i>75-100% cover</i>	<i>Control-100% cover</i>		

Table 2. Timeline of research activities.

Time Period	Activity					
	Site selection. Meet with Basin Contacts	Pre burn transects	Post burn transects. Erosion simulation	Runoff sample, duff, & soil processing	Progress report Issued	Data analysis, writing, publication, & conferences
Spr 08	*					
Sum 08	*	*	*	*	*	
Fall 08				*	*	
Win 09					*	*
Spr 09					*	*
Sum 09		*	*	*	*	
Fall 09				*	*	*
Win 10					*	*
Spr 10					*	*
Sum 10						*
Fall 10						*



Figure 1. Forest floor after early season prescribed burn in mixed conifer forest in Sequoia National Park (Elev. 6,500ft), showing patchiness of burn at multiple spatial scales.

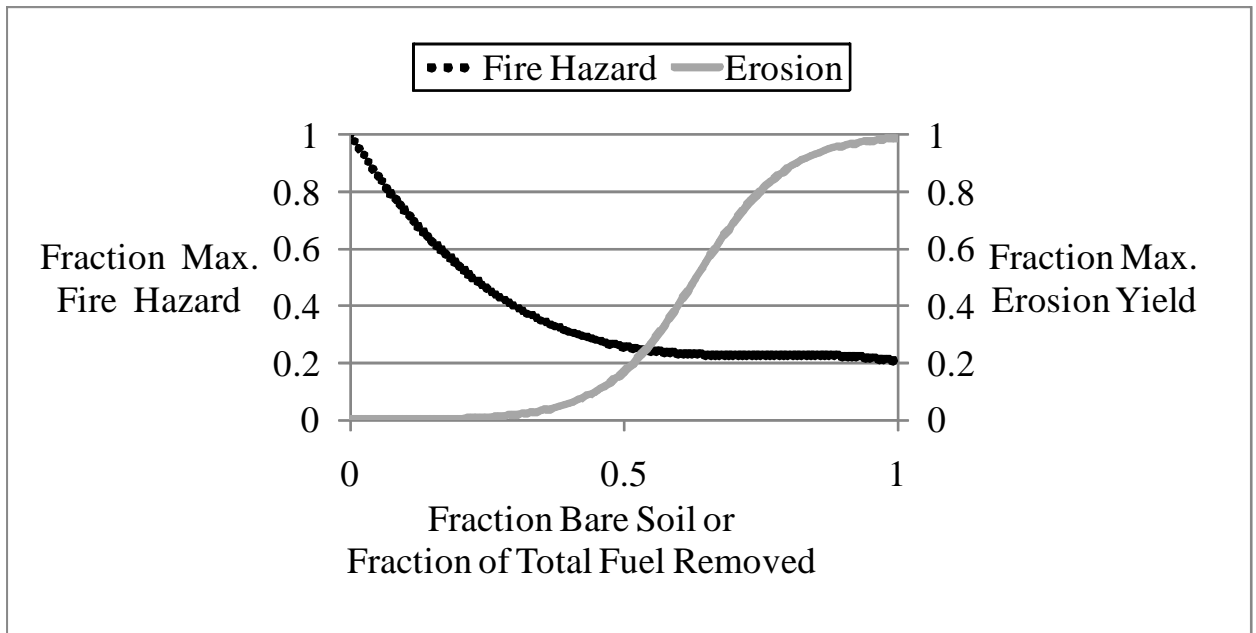


Figure 2. Balancing fuel reduction, soil exposure, and potential for erosion in the Tahoe Basin.

Literature Cited

- Andrews, P.L., C.D. Bevins, and R.C. Seli. 2005. BehavePlus fire modeling system, Version 3.0: USDA Forest Service General Technical Report RMRS-GTR-106WWW. Ogden, UT.
- Battany, M.C. and M.E. Grismer. 2000. Development of a portable field rainfall simulator system for use in hillside vineyard runoff and erosion studies. *Hydrologic Processes* 14:1119-1129.
- Beeson, P.C., S.N. Martens, D.D. Breshears. 2001. Simulating overland flow following wildfire: mapping vulnerability to landscape disturbance. *Hydrologic Processes*. 15:2917-2930.
- Agee, J. K., and C. N. Skinner. 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**:83-96.
- Campbell, R. E., M. B. Baker Jr., P. F. Ffolliott, F. R. Larson, and C. C. Avery. 1977. Wildfire effects on a ponderosa pine ecosystem: an Arizona case study. USDA Rocky Mountain Research Station, General Technical Report RM-191.
- Finney, M.A. 2004. FARSITE: Fire Area Simulator - Model Development and Evaluation. USDA Forest Service General Technical Report RMRS-RP-4Rev. Ogden, UT.
- Frandsen, W. H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Canadian Journal of Forest Research* **17**:1540-1544.
- Hille, M. G., and S. L. Stephens. 2005. Mixed conifer forest duff consumption during prescribed fires: tree crown impacts. *Forest Science* **51**:417-424.
- Johansen, M. P., T. E. Hakonson, and D. D. Breshears. 2001. Post-fire runoff and erosion from rainfall simulations: contrasting forests with shrublands and grasslands. *Hydrological Processes* **15**:2953-2965.
- Knapp, E. E., and J. E. Keeley. 2006. Heterogeneity in fire severity within early season and late season prescribed burns in a mixed-conifer forest. *International Journal of Wildland Fire* **15**:37-45.
- Knapp, E. E., J. E. Keeley, E. A. Ballenger, and T. J. Brennan. 2005. Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fires in a Sierra Nevada mixed conifer forest. *Forest Ecology and Management* **208**:383-397.
- Miller, C., and D. L. Urban. 2000. Connectivity of forest fuels and surface fire regimes. *Landscape Ecology* **15**:145-154.
- Miyaniishi, K., and E. A. Johnson. 2002. Process of patterns of duff consumption in a mixedwood boreal forest. *Canadian Journal of Forest Research* **32**:1285-1295.
- Pannkuk, C. D., and P. R. Robichaud. 2003. Effectiveness of needle cast at reducing erosion after forest fires. *Water Resources Research* **39**:1333.
- Ritchie, M. W., C. N. Skinner, and T. A. Hamilton. 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire. *Forest Ecology and Management* **247**:200-208.
- Rocca, M. E. 2004. Spatial considerations in fire management: the importance of heterogeneity for maintaining diversity in a mixed-conifer forest. Ph.D. dissertation. Duke University, Durham, North Carolina, USA.