COMBINING FIRE AND EROSION MODELING TO TARGET FOREST MANAGEMENT ACTIVITIES

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Abstract Forests deliver a number of important ecosystem services including clean water. When forests are disturbed by wildfire, the timing, quantity and quality of runoff are altered. A modeling study was carried out in a forested watershed in California to determine the risk of wildfire, and the potential post-fire sediment delivery from approximately 6-ha hillslope polygons within a 1500-km^2 basin following a wildfire event. Wildfire intensity was estimated with the FlamMap prediction tool and fire risk with the FSim tool, based mainly on topography, current vegetation conditions, and wind speed and direction. The estimation of soil burn severity was based on predicted flame length for each modeled 30-m pixel and the prefire vegetation for each hillslope polygon. Sediment delivery was estimated from each hillslope polygon using the Water Erosion Prediction Project (WEPP) Model in a GIS framework. Polygons that generated the greatest amount of sediment, impacted other values at risk in the basin, or were critical for reducing fire spread were "treated" by reducing the amount and type of fuel available for a wildfire. The fire and erosion models were run a second time for treated conditions to see if the treatment resulted in a reduced fire intensity and probability, and hence a reduced erosion rate. The estimated erosion rates the first year after the fire dropped from 46 Mg ha^{-1} before treatment to 26 Mg ha^{-1} for polygons that had received fuel treatments. If the reduction in the probability of wildfire occurrence and the effects of a quarter century of fuel treatments are considered together, then the treatments are predicted to significantly impact long-term (century scale) erosion rates by lowering "average annual" erosion rates by 19%.

INTRODUCTION

Managers in fire-prone watersheds are looking for ways to protect communities, forest resources, municipal water supplies, and other societal values from the detrimental and expensive effects of wildfire. Increased fuel loads from past decades of fire suppression (Agee 1993; Keane et al. 2002) and climate change (Flannigan et al. 2000; Westerling et al. 2006) are increasing the risks of large, high severity wildfires in Western forests and shrublands. These high-severity fires in turn increase the risk of flash floods and surface erosion (Forrest and Harding 1994; Robichaud et al. 2013). Increased post-fire erosion rates can severely degrade water quality and reduce reservoir storage capacity (Tiedemann et al. 1979; Moody and Martin 2001; Neary et al. 2005). In response to these risks, land managers responsible for protecting forestlands and watersheds, especially those that provide municipal water supplies, are considering ways to mitigate the effects of wildfire on water resources through the use of fuel reduction treatments (Sidman et al. 2015). Fuel reduction treatments, such as thinning and prescribed burning, have been shown to be effective in modifying fire behavior and fire severity (Cochrane et al. 2012; Reinhardt et al. 2008). A reduction in fire severity can then reduce threats to important ecosystem services including the availability of clean water, recreation opportunities, and timber, as well as fish and wildlife habitat. However, the costs associated with fuel reduction treatments can limit their application (GAO 1999 and 2007; Sampson et al. 2000).

A study was carried out on 1500-km^2 of the Upper Mokelumne Basin to see if the costs for fuel reduction treatments can be justified. The basin is located on the western slope of northern California's Sierra Nevada Mountains. The North Fork of the Mokelumne River cuts through granite to form deep canyons and flows through a rugged landscape with granite domes, much like its neighbor to the south – Yosemite National Park. The vegetation ranges from mixed oak woodlands below 900 m, to mixed conifer forests between 900 and 2000 m. Between 2000 and 2750 m the forests are dominated by California Red Fir (*Abies magnifica*), and above 2750 m barren rock outcrops predominate. The Mokelumne Wilderness area encompasses much of the Northern portion of the watershed. Recreational activities include fishing and camping, but the river is particularly famous for white water rafting and kayaking. The basin is an important water source for agriculture and provides drinking water to 1.3 million residents of in the San Francisco Bay area. The Mokelumne River also provides hydropower with a generating capacity of 215 MW. The extensive forest stands within the basin are under both public and private ownership. Much of the forested land is at risk to wildfire as evidenced by the 2004 Power Fire (70 km^2) within the basin (Figure 1), and the nearby Rim (2013; 1,040 km^2) and King (2014; 390 km^2) fires. Major landowners include the U.S. Forest Service, Bureau of Land Management, and Sierra Pacific Industries (Buckley et al. 2014).

In order to spatially prioritize fuel treatments and to determine the economic value of increasing treatments compared with a "do-nothing" scenario during this time of increasing fire threat, the U.S. Forest Service, The Sierra Nevada Conservancy, and The Nature Conservancy brought together a diverse set of stakeholders to form the Mokelumne Avoided Cost Analysis (MACA) committee (Buckley et al. 2014). Stakeholders included land, water and utilities managers, federal, state and local agencies, local stakeholders, and environmental organizations. The MACA committee developed a methodology to forecast the impacts of fuel treatments on wildfire risks and erosion rates in watersheds both before and after wildfire in order to link the benefits associated with fuel treatments with their costs.

MODELING APPROACH

To forecast the benefits of fuel treatments on the Mokelumne Basin we modeled erosion under four distinct conditions:

1) current vegetation conditions in the absence of fire;
2) after a fire assuming current fuel conditions;
3) after proposed fuel treatments; and
4) after a fire following the application of proposed fuel treatments.

The mapped erosion predictions following wildfire (condition 2, Figure 1) in conjunction with the burn severity predictions, asset locations within the basin and other considerations were used by the MACA Advisory committee to plan and prioritize fuel reduction treatments within the basin. The application of these treatments which included prescribed fire and mechanical and hand thinning could impact erosion rates within the watershed, so the effects of these treatments were modeled for the third condition. Fuel treatments were planned for elevations between 300 and 2,000 meters in the watershed covering most of the mixed conifer forests. Fuel loading and canopy cover were assumed to be changed as a result of these treatments. The effect of treatments on burn severity was then modeled and new predictions of burn severity were used to model post-fire erosion after treatments for the fourth condition. Our modeling results were used in two ways. The first application was to prioritize treatments based on post-fire erosion risk (Figure 1). The second application was to synthesize our modeling results from the four runs to quantify the watershed benefits and compare them to the cost of treatments to determine whether the costs of proactively treating forests prefire are justified by the savings from either not having a wildfire occur or from a reduction in wildfire severity.

We used three different models sequentially to quantify the reduction in sediment due to fuel treatments within the Mokelumne basin. The first model, FlamMap (Finney 2006), was used to predict burn severity both before and after proposed fuel reduction treatments. Probability of fire occurrence was modeled using the Fire SIMulation system (Fsim, Finney et al. 2011). The Water Erosion Prediction Project (WEPP)

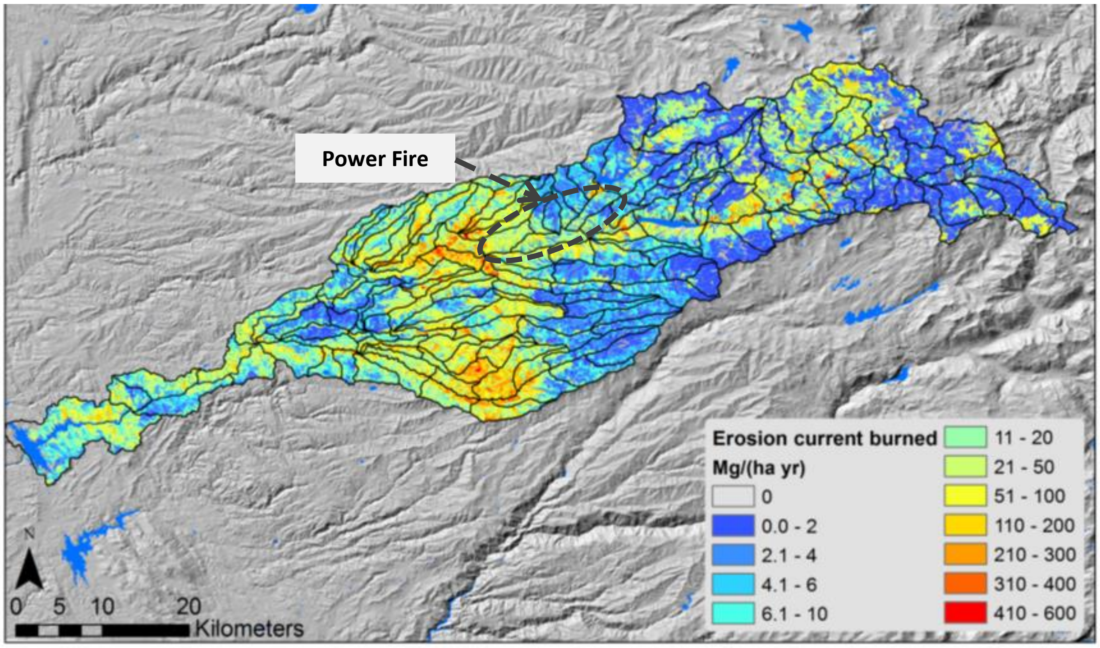

Figure 1 Map of predicted post-fire erosion for the first year after the fire for the Mokelumne Basin for current (untreated) vegetation conditions. The area burned by the 2004 Power Fire is outlined

model (Laflen et al. 1997) used burn severity predictions from FlamMap to predict hillslope erosion following wildfire both before and after treatments.

FlamMap FlamMap is a spatial fire behavior model that uses land cover, topography, and fuel characteristics data from the Landfire database (Rollins 2009), along with fuel moisture and weather data (Finney 2006). Resulting fire behavior predictions are pixel-based (30-m resolution) and include fire line intensity (kW m^{-1}), heat per unit area (kJ m^{-2}), and flame length (m). The soil and vegetation burn severity category and ground cover for erosion modeling were determined from the predicted flame length for each pixel (Table 1). Determining where to make the cutoffs in flame length for severity categories was based on the distribution of severity observed on post wildfire field studies and the distribution of fire severity following a recent fire in the basin (Power Fire, 2004; Figure 1).

FSim The Fire SIMulation system (FSim) uses historical weather data, topography, past wildfire ignitions, fuel and vegetation data to simulate wildfire ignition, fire growth, and suppression (Finney et al. 2011). The model estimates burn probability by simulating 10,000 to 50,000 years of fire seasons under the same vegetation and fuel conditions. Burn probability is the number of simulations in which a pixel burns divided by the total number of simulations (Finney et al. 2011). For the Mokelumne basin, FSim was run using vegetation data from the same Landfire database as the other modeling activities, but at a 90-m resolution. Modeling was carried out for three elevation zones in order to account for differences in ignition patterns. Calibration runs were undertaken to adjust parameters in order to match predictions with historical fire occurrences for each zone. Once calibrated, the model was run for 40,000 fire seasons. Additional details can be found in Buckley et al. (2014).

WEPP WEPP is a process-based model that predicts runoff and sediment yields from planar hillslopes and small, unchannelized watersheds (Flanagan and Nearing 1995). The surface hydrology component of the WEPP model uses climate, soils, topography, and vegetation input files to predict infiltration, runoff volume, and peak discharge for each simulated storm or snowmelt runoff event. WEPP then uses the

Table 1 WEPP soil and vegetation severity categories as determined by flame lengths predicted by FlamMap

	FlamMap Flame Length (m)			
	0	0 – 1.2	1.2-2.5	2.5≤
WEPP Burn Severity Category	Unburned	Low	Moderate	High
WEPP Soil Category and ground cover (%) if pre fire vegetation was grass	Unburned 60-80	Low 60	Low 45	Low 15
WEPP Soil Category and ground cover (%) if pre fire vegetation was forest	Unburned 99	Low 60	Low 45	High 15

same inputs and runoff predictions to calculate rill and interrill erosion, as well as sediment yield from the hillslope (Flanagan and Nearing 1995). The need to predict post-fire erosion rates across the entire 1500-km^2 Upper Mokelumne Basin necessitated the use of the Geo-spatial interface for the Water Erosion Prediction Project (GeoWEPP) (Renschler 2003). GeoWEPP facilitates the use of WEPP across large areas by converting GIS data into WEPP input files, running WEPP, and then compiling the results into a spatial maps and text summaries.

DEVELOPMENT AND COMPILATION OF INPUT DATA

Prior to preparing model inputs, land cover, soil and topography data were collected in the watershed at various elevations and forest conditions from multiple sources to ensure accuracy. The Landfire vegetation files used as input to the fire spread models were modified to incorporate detailed local knowledge of site conditions. These same files were used to support prefire WEPP runs, and to aid in developing post fire soil and vegetation files. For the spatial WEPP modeling, the Upper Mokelumne Basin was divided into 244 sub-watersheds averaging about 6 km^2 in area, using a Digital Elevation Model (DEM) and ESRI watershed tools, in order to address climate variability and for computational efficiency. Sub-watersheds were used to create smaller raster inputs (DEM, soil, land cover) for batch files. These batch files were then modeled in a batched version of GeoWEPP (Miller et al. 2011). In the cases where the sub-watersheds contained more than one drainage outlet or the model failed to run, the sub-watersheds were rerun using GeoWEPP for ArcGis 9.3. The resulting erosion prediction maps from the batch runs were then merged into a final erosion map for each of the four conditions (Figure 1).

Climate Data WEPP uses a stochastic weather generator called Cligen (Nicks et al. 1995) to generate a daily weather sequence, including the precipitation amount and duration, minimum and maximum temperatures, dew point, mean solar radiation, and wind speed and direction. The input to Cligen is from a database of more than 2,600 long term climate stations within the United States. The U.S. Forest Service has complemented this database with Rock:Clime, an interface to Cligen that estimates mean monthly rainfall amounts between stations (Elliot et al. 1999; Scheele et al. 2001). The interface also allows users to change the number of wet days within a month, and to alter the average maximum and minimum temperatures either manually, or based on an adiabatic lapse rate for maximum temperature of -6°C km^{-1} and a lapse rate for minimum temperatures of -5°C km^{-1} between the nearest weather station and the site of interest (Scheele et al., 2001). The interpolation is particularly important in mountainous areas such as the Mokelumne Basin because of the large changes in climate conditions that occur with changes in elevation over relatively short distances (Table 2), as well as the paucity of climate stations in remote mountainous areas. The interpolation procedure in Rock:Clime modifies the monthly precipitation for a selected climate station based on elevation and PRISM data (Parameter-elevation Regressions on

Table 2 Stochastically generated climate zones for the Mokelumne Basin

Physical Elevation Range (m)	Climate Zones	Modeled Elevation (m)	Avg Annual Precip (mm)
100 – 300	Tiger Low Rock:Clime/PRISM	259	799
300 – 600	Tiger Low2 Rock:Clime/PRISM	535	951
600 – 900	Tiger Creek Station	719	1176
900 – 1200	Calaveras Low Rock:Clime/PRISM	1093	1138
1200 – 1500	Calaveras Big Trees Station	1432	1383
1500 – 2000	Calaveras Big Trees High Rock:Clime/PRISM	1868	1336
2000 – 2400	Twin Lakes Station	2386	1249
$\geq$2400	Twin Lakes High Rock:Clime/PRISM	2646	1438

Independent Slopes Model, Daly et al. 2004). The PRISM database with a spatial resolution of 4 km^2 is used by Rock:Clime.

Three NOAA weather stations in the Cligen database are located within or near the Mokelumne Basin. These stations (Twin Lakes, Calaveras Big Tree, and Tiger Creek; Figure 2) were used to develop an additional five climate files with the Rock:Clime interface. The additional climates were needed to account for the impacts of elevation changes in the watershed (Table 2). Each climate input file contained 50 years of daily stochastically-generated weather data. The average elevations of the initial WEPP sub-watersheds were then used to select the appropriate climate zone (Figure 2) for each sub-watershed.

Land cover and plant/management input files for WEPP Land cover data were obtained from the Landfire Project (Rollins, 2009). For this analysis, we used the Landfire land cover data that were modified with field observations for the fire modeling runs (Buckley et al. 2014). In addition to making the process more efficient by using the same data set, this ensured consistency across the modeling efforts. We then reclassified the land cover data layer into WEPP database cover types (e.g. Forest, Young Forest, Shrubs, Bunch or “Good” Grass, Sod or “Poor” Grass) in order to model background erosion rates from the Mokelumne Basin without fire. In the WEPP database, the land cover type is linked to both vegetation and soil properties (Elliot 2004).

For modeling post-fire conditions, the FlamMap burn severity maps from before and after fuel reduction treatments were used to reclassify land cover into unburned, low, moderate, and high burn severity classes (based on Table 1). In order to model the potential erodibility effects of the fuel reduction treatments, we used the map of proposed treatments developed for this analysis (Buckley et al., 2014). We assumed that the prescribed fire treatments would have a low severity soil condition for the year following the treatment with 85 percent ground cover, and the thinning-only treatments would have unburned soil properties and 90 percent cover (Elliot and Miller 2004).

Soils Data For the WEPP modeling, we used Landfire soil layers that were derived from STATSGO (STATe Soil GeOgraphic) data (USDA 1991). This dataset included: maximum soil depth; percent rock fragments (> 2.0 mm), sand, silt, and clay. The percent-sand, -silt and -clay layers were used to classify each soil pixel into one of the four soil texture classes represented in the WEPP forest soil database (sandy loam, loam, silt loam, and clay loam). WEPP input parameters (e.g., effective hydraulic conductivity, soil albedo, and interrill and rill erodibility) specific to each soil texture class were then used in the modeling (Elliot et al. 2000). Soil properties were based on the predicted burn severity and the type of vegetation that burned (forests, shrubs or grasses).

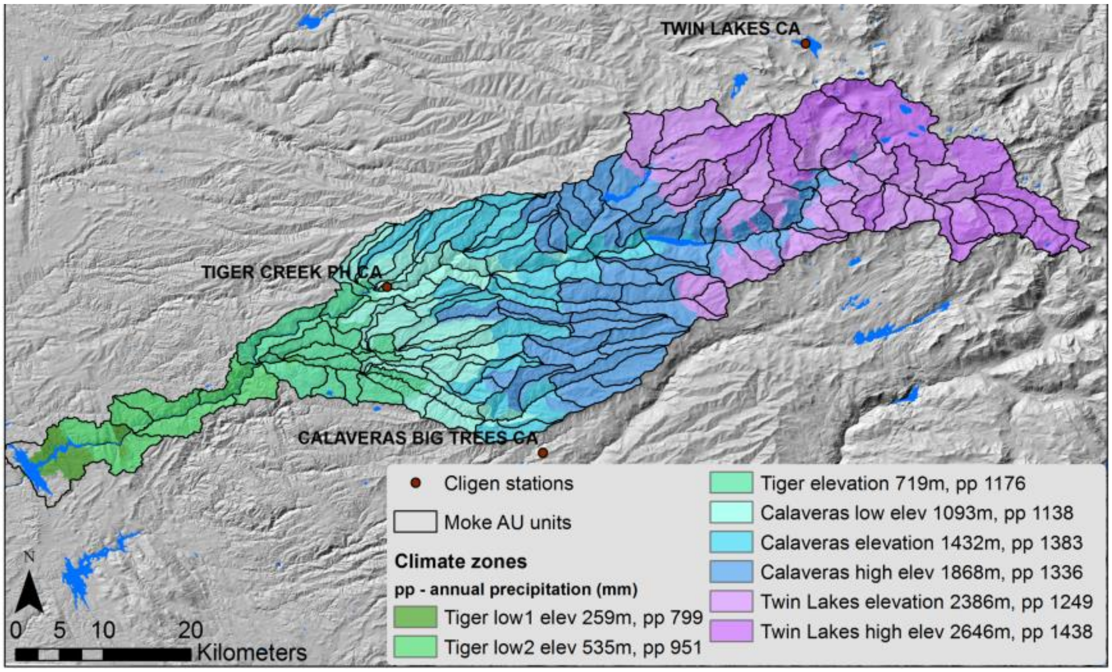

Figure 2 Map displaying the distribution of climate zones within the Mokelumne Basin and showing the boundaries of the Analysis Units (AUs)

RESULTS

Sediment delivery from hillslopes in the Mokelumne Basin was estimated and mapped for four conditions. The first condition determined background erosion rates without fire under the current vegetation conditions. Average erosion in the unburned basin was 0.67 Mg yr^{-1} ha^{-1} for the entire basin and 0.4 Mg yr^{-1} ha^{-1} in the lower elevation portion of the watershed where treatments were planned. Forested hillslopes typically did not generate significant erosion, but the steep, barren rocky slopes in the upper portions of the basin were highly erosive as is typical of high elevation areas in the Sierra Nevada Mountains (Brooks et al. 2010). The next run used the FlamMap predictions of burn severity under the current vegetation conditions to predict post-fire erosion (Figure 1). Average first year post-fire hillslope erosion in the Mokelumne Basin was 32 Mg yr^{-1} ha^{-1}, 50 times higher than the unburned conditions.

The mapped post-fire erosion predictions for current conditions along with the fire modeling results and other considerations were used by the MACA committees and stakeholders to help plan and prioritize a fuel reduction treatment strategy within the basin. The treatment selection process focused on reducing risks from fire and post-fire sediment to water utility and other infrastructure (Buckley et al. 2014). Wilderness and roadless areas were for the most part excluded from the analysis as treatments could not be carried out in these areas and they do not possess infrastructure that would be threatened by wildfire. An online GIS platform was created to allow stakeholders to review the data and then easily select treatment analysis units and provide a rational for their decisions. The watershed was divided into 148 potential treatment Analysis Units (AUs) with an average area of 10 km^2 (Figure 2). The post-fire erosion and burn probability maps were averaged by AUs and then classified into five risk quantiles. To further help stakeholders choose AUs for treatments, additional map layers containing towns, roads, building densities, land ownership, topography, transmission lines, hydropower facilities, wilderness areas, and water conveyances were provided. Stakeholder and MACA committee selections were then combined and through an iterative process, 46 AUs were selected for treatment. Recent studies indicate the minimum

Table 3. Summary of the results from the four hillslope erosion model runs for the entire Mokelumne Basin

	Current Condition	Fire Following Current Condition	Treatment Effects	Fire Following Treatment
Average Erosion in Basin	0.67 Mg ha^{-1}	32 Mg ha^{-1} in year 1	0.69 Mg ha^{-1}	26 Mg ha^{-1} in year 1
Range	0 – 84 Mg ha^{-1}	0 – 566 Mg ha^{-1}	0 – 84 Mg ha^{-1}	0 – 535 Mg ha^{-1}
Standard Deviation	3.0 Mg ha^{-1}	55 Mg ha^{-1}	2.5 Mg ha^{-1}	44 Mg ha^{-1}

Table 4. Summary of results from the four hillslope erosion model runs for only the treated portions of the Mokelumne Basin

	Current Condition	Fire Following Current Condition	Treatment Effects	Fire Following Treatment
Average Erosion in Basin	0.40 Mg ha^{-1}	46 Mg ha^{-1} in year 1	0.69 Mg ha^{-1}	26 Mg ha^{-1} in year 1
Range	0 – Mg ha^{-1}	0 – 566 Mg ha^{-1}	0 – Mg ha^{-1}	0 – 535 Mg ha^{-1}
Standard Deviation	2.5 Mg ha^{-1}	69 Mg ha^{-1}	2.5 Mg ha^{-1}	36 Mg ha^{-1}

area needed to be treated in a watershed to lower burn probability is 10-20% (Finney et al. 2007) and that strategically treating 35% would be ideal for reducing risks (Ager et al. 2013). The proposed treatment AUs covered about 29% of the Upper Mokelumne watershed (Buckley et al. 2014), which is more than enough to reduce fire probability within the entire watershed.

The application of these treatment prescriptions, which included prescribed fire, biomass removal, and thinning, would not only impact fire behavior, but also could result in soil erosion, so the effects of these treatments on soil erosion were modeled for the third condition. Fuel treatments were planned only in the lower portions of the watershed and the average predicted erosion rate from these treatments was 0.69 Mg yr^{-1} ha^{-1}, an average increase of 0.02 Mg yr^{-1} ha^{-1}over the current condition run without treatments. Canopy cover and fuel loads decreased as a result of these treatments and the treated landscape was modeled in FlamMap. The treated FlamMap burn severity predictions were used to model the first year post-fire erosion for the treated watersheds. The average first year post-fire erosion rate (after fuel treatments) for the whole watershed was 26 Mg yr^{-1} ha^{-1}, or 6 Mg yr^{-1} ha^{-1} less than the average post-fire erosion rates without treatments (Table 3). In the second year post-fire, erosion rates for both the current conditions and treated conditions would likely drop to only 10% of their first year post-fire values, and return to pre-fire levels in year three post-fire (Robichaud et al., 2008). If only the treated portions of the basin are considered; the reduction in post-fire erosion between the current conditions and treated runs is even greater: 20 Mg yr^{-1} ha^{-1} (Table 4).

Predictions of both burn severity and post-fire erosion rates are comparable to field and satellite derived measurements collected in or near the basin. Model validation of post-fire erosion is very difficult given the high variability in post-fire erosion rates and uncertainties involved when predicting future fire effects and climate scenarios. However, the ratio of high, moderate, and low burn severity from the FlamMap derived predictions for post-fire burn severity were consistent with a satellite-derived map of burn severity for the burned areas of the Power Fire that burned within the Mokelumne Basin in 2004. Field measurements of post-fire erosion rates from the nearby Cannon Fire ranged from 2.5-15 Mg yr^{-1} ha^{-1}

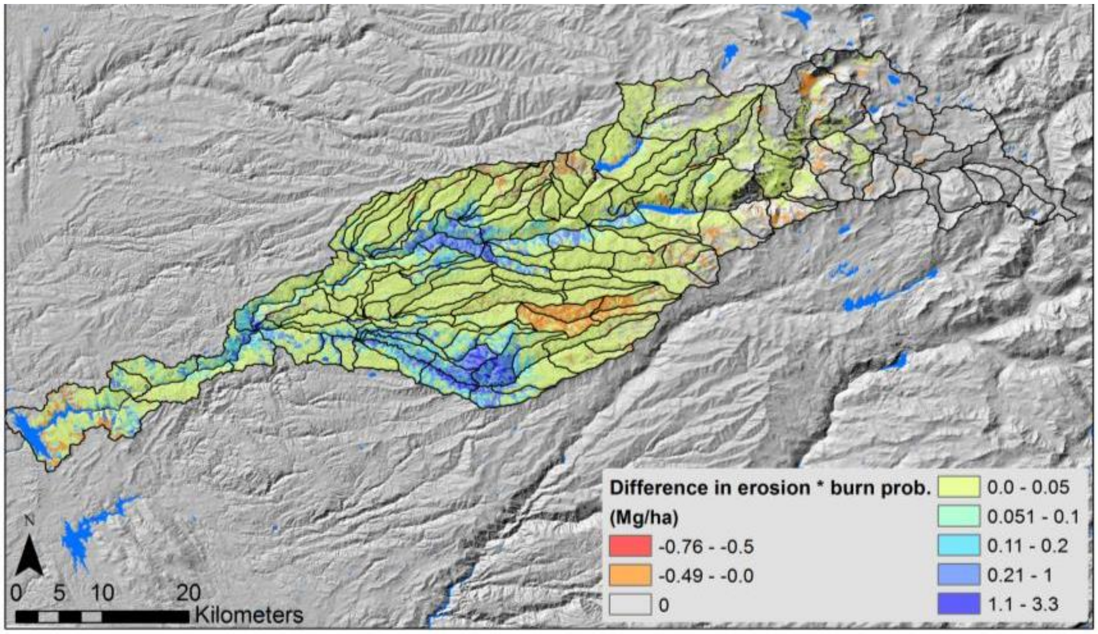

Figure 3. Map of the differences between post-fire erosion predictions for current conditions x burn probability for current conditions and post treatment x burn probability post treatment.

(Robichaud et al. 2008) and the Cannon Fire site is drier than the Mokelumne Basin, with a mean annual precipitation of only 658 mm compared to the range of 799-1438 mm expected in the Mokelumne Basin. Erosion rates measured following other wildfires further south in the Sierra Nevada Mountains were 25 Mg ha^{-1} (mulched) to 46 Mg ha^{-1} (untreated) for a high severity site in the Cedar Fire (Robichaud et al. 2013), where the annual precipitation was 398 mm yr^{-1}. While these comparisons do not validate our modeling, they do demonstrate our results are reasonable.

Frequency of Burning The fire behavior modelers (Buckley et al. 2014) also provided spatial predictions of fire probability derived from the FSim model (Finney et al. 2007) for both current conditions and after the application of fuel reduction treatments. One of the benefits of fuel reduction treatments is a decrease in fire probability due to changes in fuel load properties and canopy, a benefit that can extend into untreated areas. The probability of fire in a given year is fairly low for most of this relatively moist basin, with a fire return interval about 300 years for the forested areas. In order to incorporate fire probability into erosion modeling, it is necessary to multiply the sediment predicted following a wildfire event by the probability of that fire occurring (Elliot, 2013). We can do this for both the untreated and treated post fire erosion estimates. Figure 3 is a map of the difference between the first year post-fire erosion under current conditions multiplied by current burn probability and first year post-fire erosion following treatments multiplied by burn probability after treatments. Overall the modeled treatments are predicted to decrease burn severity, fire probability and post-fire erosion rates. The average reduction in post-fire erosion for the entire basin due to fire between the current conditions and post treatment was 0.05 Mg yr^{-1} ha^{-1}. This metric, however, does not allow us to examine the effects of the treatments on erosion rates in the absence of fire. In order to estimate long term (century scale) "average annual" erosion rates we needed to consider all four conditions (Elliot, 2013).

To estimate "average annual" erosion rates we needed to account for erosion in both fire and non-fire years, as well as the effects of treatments on erosion rates and burn probabilities (Elliot 2013; Miller et al. 2011). Under current conditions, long term hilllslope erosion rate $\textit{Average Erosion}_{cc}$ can be represented by Equation 1. If we assume the effects of fuel reduction treatments last 25 years, then Equation 2 represents long term erosion rates *Average Erosion*$_{tr}$ with regular fuel reduction treatments.

$$Average\ Erosion_{cc} = E_{cc\_fire} * bp_{cc\_fire} + (1 - bp_{cc\_fire}) * E_{nf} \quad \text{(Eq 1)}$$
$$Average\ Erosion_{tr} = E_{tr\_fire} * bp_{tr\_fire} + (1 - bp_{tr\_fire}) * (24 * E_{nf} + E_{tr})/25 \quad \text{(Eq 2)}$$

where:
E_{cc_fire} is the mapped post-fire erosion rates for current conditions.
E_{tr_fire} is the mapped post-fire erosion rates following fuel treatments.
E_{tr} is the mapped erosion rates due to the effects of the fuel treatments.
E_{nf} is mapped erosion rates for current conditions in the absence of fire.
bp_{cc_fire} is the mapped probability of fire under current conditions.
bp_{tr_fire} is the mapped probability of fire following fuel treatments.

These equations were used in conjunction with our four model runs to develop long term "average annual" erosion rates for the treated portions of the basin with and without fuel reduction treatments every twenty five years. Model results for long term average erosion rates for current conditions were 0.64 Mg yr^{-1} ha^{-1} (Equation 1 averaged for hillslopes selected for treatment, if they were not treated), compared to 0.52 Mg yr^{-1} ha^{-1} if the designated treatment area is in fact treated as modeled (Equation 2 averaged for all treated hillslopes if they were treated). Our predictions indicate that regular treatments will significantly reduce long term overall erosion rates by lowering the "average annual" erosion rate by 19%.

DISCUSSION

The goal of the MACA committee was to determine whether an economic case could be made for increased investment in fuel reduction treatments in the Upper Mokelumne Basin in the face of increasing wildfire threats. This is a challenging task as it is difficult to assign economic value to resources such as fish and wildlife habitat, tourism and recreational opportunities, and cultural sites, which ultimately were left unquantified in the final analysis. To simplify the analysis the committee focused on resources that could be readily assigned a dollar value. These included the avoided sediment costs as well as the cost of homes, infrastructure, treatment implementation costs, timber, carbon sequestration, and fire suppression and cleanup costs. Based on the fire model results and expert review, five fires from the modeling became the focus of the economic analysis, such that those five fires (or similar ones) are likely to occur within the watershed over a 30-year period. The fire behavior models predicted a significant decline in both fire size and intensity due to fuel treatments. Low and high estimates of the dollar value of the resources that would be lost if one of the five fires occurred were tabulated with and without the fuels treatments. The analysis predicted that the economic benefits of the fuels treatments were two to three times more than the costs of treatments. Total treatment cost for the 46 Analysis Units (AUs) was estimated to be $68 million (including maintenance costs over 30 years) compared to the lower estimated avoided cost of $126 million and the higher estimate of $224 million if those fires burned on an untreated landscape. The assumptions of the potential fire size and potential costs of future fires were intentionally conservative. Over the 30-year time frame, the five fires are predicted to burn a total of 21,000 ha with high severity, accounting for 27 percent of the burned area (Buckley et al. 2014). Contrasting this with two major recent wildfires that occurred on either side of the Mokelumne Basin, the Rim Fire (2013) burned 104,000 ha and the King Fire (2014) burned 39,000 ha, with 38 and 47 percent respectively, of their area burning at high severity (http://www.fs.fed.us/postfirevegcondition/index.shtml). These individual fires were much larger and burned at a higher severity than the modeled fires that were used to create cost estimates, therefore the potential costs associated with our modeled future fires are likely underestimated.

Avoided cost due to sediment may have been undervalued by this process due to an inability to sufficiently quantify the potential impacts to aquatic and recreational resources, hydropower and treatment costs from potential post-fire sediment depositions in key reservoirs. The estimated value of avoided sediment costs was approximately $1 million, attributed to lost water storage potential. This is a relatively small amount compared to the costs associated with saving structures ($32-$45.6 million) or avoiding cleanup costs ($22.5 million) (Buckley et al. 2014). The hydroelectric utility operating in the Mokelumne Basin was not concerned about sediment as the watershed is equipped with multiple water conveyances that allow the utility select different water sources (Buckley et al. 2014). The water utility relies on upstream hydroelectric dams to trap sediments before they reach the Pardee Reservoir at the lower end of the basin where most of the drinking water intakes are located. Loss of reservoir storage capacity was not a concern to either utility company, but this attitude could change due to persistent drought conditions in Western states, with reduced snowpack due to climate change (Mote, 2006) or if one of the water storage reservoirs were lost due to a reduction in useful storage capacity. The Tiger Creek Afterbay reservoir with a storage capacity of 4.8 million m^3 was constructed in 1931 for a hydroelectric plant. A rudimentary bathymetric survey carried out in 2013 estimated storage has dropped to just 1.2 million m^3, a loss of about 75% of its original capacity (Buckley et al. 2014). Elsewhere in the U.S., loss of water reservoir storage capacity in watersheds recently impacted by wildfire has cost water utilities millions of dollars in additional water treatments and dredging expenses. Denver Water has spent $26 million treating drinking water and dredging Strontia Springs Reservoir following the Buffalo Creek (1996) and Hayman (2002) wildfires and the Los Angeles County Public Works plans to spend $190 million dredging four reservoirs impacted by sediment from the 2009 Station Fire (US Department of Interior, 2013). In California, state legislators are considering increasing reservoir storage capacity, the cost of storage for new usable water averages $20/$m^3$ for the proposed reservoirs (http://www.fresnobee.com/2014/06/01/3956458/should-calif-add-new-dams.html). The loss of reservoir storage due to sediment from a single 28,000 ha fire delivering only a tenth of its sediment to the reservoir (about 100,000 m^3) would be $2 million.

CONCLUSIONS

By linking fire behavior and post-fire hydrology models we were able to create a risk assessment map that allowed land and water managers in the Mokelumne Basin to prioritize fuel reduction treatments to protect both land and water resources. These managers are seeking ways to mitigate post-fire erosion and flooding before a wildfire occurs. The potential for dramatic increases in post-fire runoff, erosion and sedimentation is well documented. The importance of targeting limited fuel treatment resources to areas where the greatest benefits are achieved is gaining recognition as society increasingly understands the importance of improved watershed management. Work is ongoing to improve the application of these models and their linkages in order to provide land managers with increasingly refined and spatially-explicit data that will help them to better protect valuable water resources in fire prone regions.

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