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Targeting forest management through fire and erosion modelling

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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 modelling study was conducted in a forested watershed in California, USA, to determine the risk of wildfire, and the potential post-fire sediment delivery from ~4-ha hillslope polygons within a 1500-km^2 basin following a wildfire event. Wildfire intensity was estimated with fire spread models. The estimation of soil burn severity was based on predicted flame length. Sediment delivery was estimated from each hillslope polygon using a Geographic Information System erosion model. Polygons that generated the greatest amount of sediment, affected 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 whether 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.

Additional keywords: FlamMap, GeoWEPP.

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Introduction

Background

Managers of 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), climate change (Flannigan *et al.* 2000; Westerling *et al.* 2006; Jolly *et al.* 2015) and change in land use (Moreira *et al.* 2011) are increasing the risks of large, high-severity wildfires in 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 (Santín *et al.* 2015) and reduce reservoir storage capacity (Tiedemann *et al.* 1979; Moody and Martin 2001; Neary *et al.* 2005; Smith *et al.* 2011; Santín *et al.* 2015). 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 (Buckley *et al.* 2014; Sidman *et al.* 2015). Fuel reduction treatments, such as thinning and prescribed burning, have been shown to be effective in modifying fire behaviour and fire severity (Reinhardt *et al.* 2008; Cochrane *et al.* 2012). 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, 2007; Sampson *et al.* 2000).

In this context of concerns about the detrimental effects of wildfire on watershed resources and the costs of fuel reduction treatments, a group of stakeholders associated with the Mokelumne River Basin in California, USA, came together in 2012 to see if an economic case could be made for increased fuel treatment in the basin. The 1500-km^2 Upper Mokelumne Basin is located on the western slope of northern California's Sierra Nevada Mountains. The North Fork of the Mokelumne River cut through granite to form deep canyons and flows through a rugged landscape with granite domes, much like its neighbour to the south – Yosemite National Park. 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 whitewater

Table 1. WEPP (Water Erosion Prediction Project) soil and vegetation severity categories as determined by flame lengths predicted by FlamMap, and the distribution of fire severity observed after the Power Fire and predicted by FlamMap for that fire

	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 prefire vegetation was grass	Unburned 60–80	Low 60	Low 45	Low 15
WEPP soil category and ground cover (%) if prefire vegetation was forest	Unburned 99	Low 60	Low 45	High 15
Power fire distribution (%)	55	24	13	9
Present study distribution (%)	12	41	29	18

rafting and kayaking. The basin is an important water source for agriculture and provides drinking water to 1.3 million residents 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 of wildfire as evidenced by the Power Fire (2004, 70 km^2) within the basin, and the nearby Rim (2013, 1040 km^2) and King (2014, 390 km^2) fires, and most recently, the Valley Fire (2015, 170 km^2) and the Butte Fire (2015, 288 km^2), which included 38 km^2 within the Mokelumne Basin. Major landowners include the US Forest Service, Bureau of Land Management and Sierra Pacific Industries (Buckley *et al.* 2014).

In order to spatially prioritise fuel treatments and to determine the economic value of increasing treatments compared with a 'do-nothing' scenario during this time of increasing fire threat in the Upper Mokelumne Basin in California, the US 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 organisations. 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. The objectives of the present paper are to describe the assumptions, methods and limitations for predicting sediment delivery from hillslopes in a forested basin as impacted by wildfire and fuel management in support of a larger economic analysis of the costs and benefits of forest fuel management activities to reduce the occurrence or severity of wildfire.

Fire intensity and burn severity

Two attributes commonly used to describe wildland fire are fire intensity (attribute of the fire) and fire or burn severity (attribute of the fire effects) (Keeley 2009; Alexander and Cruz 2012). Fire-line intensity is a common descriptor of the rate of flame-front energy release during a spreading fire. It can be helpful in understanding both active fire characteristics and effects on the landscape, as well as in the development of fire behaviour models. Fire-line intensity is a function of fire spread rate and fuel consumption (Byram 1959; Alexander and Cruz 2012). Flame length is then estimated from fire-line intensity values. Fire-line intensity is generally associated with fire or burn severity. Severity is a qualitative description of fire effects, and is commonly categorised as 'unburned', 'low', 'moderate' or 'high.' The category depends on the loss of canopy, litter and organic matter on and in the soil, leading to greater erosion risk (Hessburg *et al.* 2007; Keeley 2009; Parsons *et al.* 2010). Keeley (2009) discussed the limitations of this assumption and how it varies with plant community (Parsons *et al.* 2010), but concedes that fire-line intensity is generally linked to burn severity by post-fire managers. Severity is only one of the inputs needed for predicting soil erosion following an actual or a simulated wildfire (Elliot 2013). Keeley (2009) stated that fire or burn severity often has less influence on post-wildfire erosion than do other site attributes, in particular topography, soil properties and climate.

FlamMap

FlamMap is widely used by fuel managers in the US to target fuel treatments based on predicted damage to forest plant communities, and was the fire intensity model selected by the fire modelling team for the Mokelumne analysis (Buckley *et. al* 2014). FlamMap is a spatial fire behaviour 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 behaviour 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 modelling were determined from the predicted flame length for each pixel (Table 1). Determining where to set flame length thresholds to provide a distribution of fire severity similar to observed severity distributions was based on fire behaviour interpretations (Andrews and Rothermel 1982), distribution of severity observed on post-wildfire field observations (http://forest.moscowfsl.wsu.edu/cgi-bin/BAERTOOLS/baer-db/index.pl, accessed 10 February 2016) and in particular, the distribution of fire severity following the 2004 Power Fire in the basin (Breibart *et al.* 2004).

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

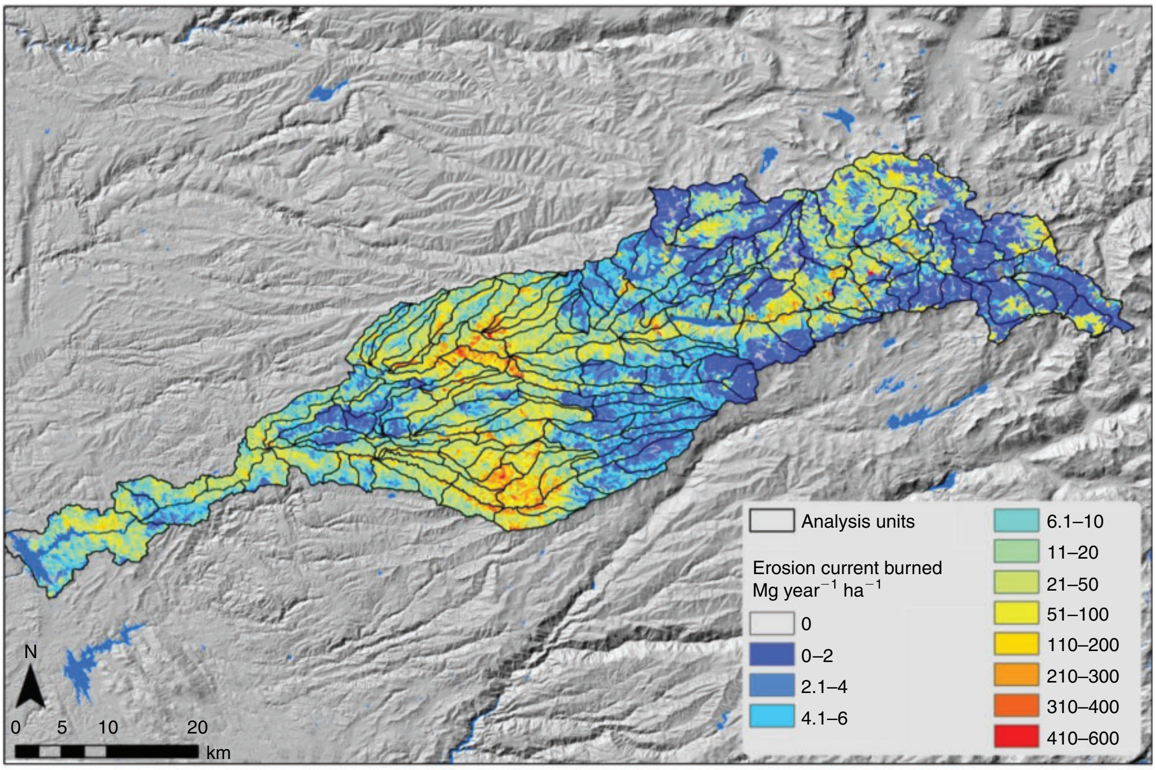

Fig. 1. Map of predicted post-fire erosion for the first year after the fire for the Mokelumne Basin for current conditions. The treatment analysis units (AUs) are outlined on the map.

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 modelling activities, but at 90-m resolution. Modelling was carried out for three elevation zones in order to account for differences in ignition patterns. Calibration runs were undertaken to adjust input variables in order to match predictions with historical fire occurrences for each zone. Once calibrated, the model was run for 40 000 fire seasons (see Buckley *et al.* 2014 for further details).

The WEPP Model

The Water Erosion Prediction Project (WEPP) Model is a process-based model that predicts runoff and sediment yields from planar hillslopes and small, unchannelised watersheds (Flanagan and Nearing 1995; Laflen *et al.* 1997). 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 same inputs and runoff predictions to calculate rill and interrill erosion, as well as sediment yield from the hillslope (Flanagan and Nearing 1995). For the WEPP forest vegetation database, Elliot (2004) categorised forest vegetation as Mature Forest, Young Forest, Low-Severity Fire and High-Severity Fire in an online interface to the WEPP model. Elliot's (2004) database consisted of soils with properties that were dependent on the forest vegetation or burn severity category and the soil texture (sandy loam, silt loam, clay loam or loam). In addition, the ground cover resulting from the vegetation condition was a critical input to the WEPP model. The relationships among plant community, fire intensity, burn severity and soil erosion are central to the theme of the present manuscript.

Methods

Modelling approach

To forecast the benefits of fuel treatments on the Mokelumne Basin, erosion was modelled under four distinct conditions:

1. current vegetation fuel conditions in the absence of fire;
2. after a fire assuming current vegetation 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, Fig. 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 prioritise 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 modelled for the third

Table 2. A pixel-based assessment of FlamMap predictions of burn severity from 10 preliminary calibration wildfires using the flame length thresholds shown in Table 1 and thresholds calibrated for the specific site

Fires	Mokelumne crosswalk overall accuracy (%)	Calibrated crosswalk overall accuracy (%)
Rim Fire, CA	42	37
Powerhouse, CA	27	56
Chips, CA	41	32
Waldo, CO	37	39
Little Sand, CO	49	30
Whitewater Baldy, NM	34	35
Little Bear, MN	34	36
Poco, AZ	49	23
Mistake Peak, AZ	25	25
Sheep, ID	28	29

condition. Fuel treatments were proposed for elevations between 300 and 2000 m 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 modelled and new predictions of burn severity were used to model post-fire erosion after treatments for the fourth condition. The modelling results were used in two ways. The first application was to prioritise treatments based on post-fire erosion risk. The second application was to synthesise the modelling results from the four runs to quantify the watershed benefits and compare them with the cost of treatments to determine whether the costs of proactively treating forests before fire are justified by the savings from either not having a wildfire occur or from a reduction in wildfire severity.

Three different models were applied sequentially to quantify the reduction in sediment due to fuel treatments within the Mokelumne basin (Buckley *et al.* 2014). The first model, FlamMap (Finney 2006), was used to predict burn severity both before and after proposed fuel reduction treatments. The probability that each cell on the landscape may be burned in 40 000 potential fire seasons was modelled using the FSim system (Finney *et al.* 2011). FSim also predicted the perimeters of fires that occurred within the 40 000 fire seasons. The WEPP model (Laflen *et al.* 1997) used fire intensity predictions from FlamMap along with other watershed properties to predict hillslope erosion following wildfire both before and after treatments. FSim was run for 90-m pixels, whereas both FlamMap and WEPP were run using 30-m pixels.

FlamMap runs for the Mokelumne Basin were created using LANDFIRE data heavily customised with local knowledge. The resulting predictions of flame length and burn severity were deemed reasonable as the most severe burns were on heavily vegetated north slopes (more fuel) along the North Fork of the Mokelumne River and Salt Springs Reservoir. The predictions of high-severity fires on north-facing slopes were anecdotally confirmed by the local fire chief during an onsite visit before the commencement of modelling in November 2012.

Preliminary FlamMap results from 10 recent wildfires are presented in Table 2. In these analyses, standard LANDFIRE FlamMap inputs were used to predict burn severity and the results were compared with observed soil burn severity maps from US Forest Service post-fire Burned Area Emergency Response (BAER) teams. Overall accuracy is the percentage of pixels correctly classified divided by total number of pixels. For the first set of predictions, the standard thresholds from Table 1 were applied. The second set of predictions utilised custom crosswalk tables created for each fire based on the distribution of burn severity classes from a neighbouring historical fire. These typical results (Lewis *et al.* 2006) show why research is ongoing to improve the methodology for predicting burn severity (Holden *et al.* 2009; Parks *et al.* 2014).

The initial FlamMap burn severity predictions from 10 recent fires demonstrated the Mokelumne crosswalk table (Table 1) performed as well as calibrating FlamMap flame lengths to recent historical fire events. The overall accuracy of using FlamMap with the Mokelumne flame-length crosswalk table for these 10 fires was 38% compared with the overall accuracy achieved by using distributions from nearby historical fires, which had an accuracy of 36% of the pixels being correctly predicted.

Predicting post-fire erosion rates across the entire 1500-km^2 Upper Mokelumne Basin necessitated the use of the geospatial interface for the Water Erosion Prediction Project (GeoWEPP) (Renschler 2003). GeoWEPP facilitates the use of WEPP across large areas by converting Geographic Information System (GIS) data into WEPP input files, running WEPP, and then compiling the results into spatial maps and text summaries.

Development and compilation of 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 modelling, the Upper Mokelumne Basin was divided into 244 subwatersheds averaging ~6 km^2, using a digital elevation model (DEM) and ESRI watershed tools. Subwatersheds were used to create smaller raster inputs (DEM, soil, land cover) for batch files. These batch files were then modelled in a batched version of GeoWEPP (Miller *et al.* 2011). In the cases where the subwatersheds contained more than one drainage outlet or the model failed to run, the subwatersheds 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 (Fig. 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, peak intensity 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 2600 long-term climate stations within the United States. The US 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;

Table 3. Stochastically generated climate files for the Mokelumne Basin

Physical elevation range (m)	Climate file	Modelled elevation (m)	Average annual precipitation (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
≥2400	Twin Lakes High Rock : Clime-PRISM	2646	1438

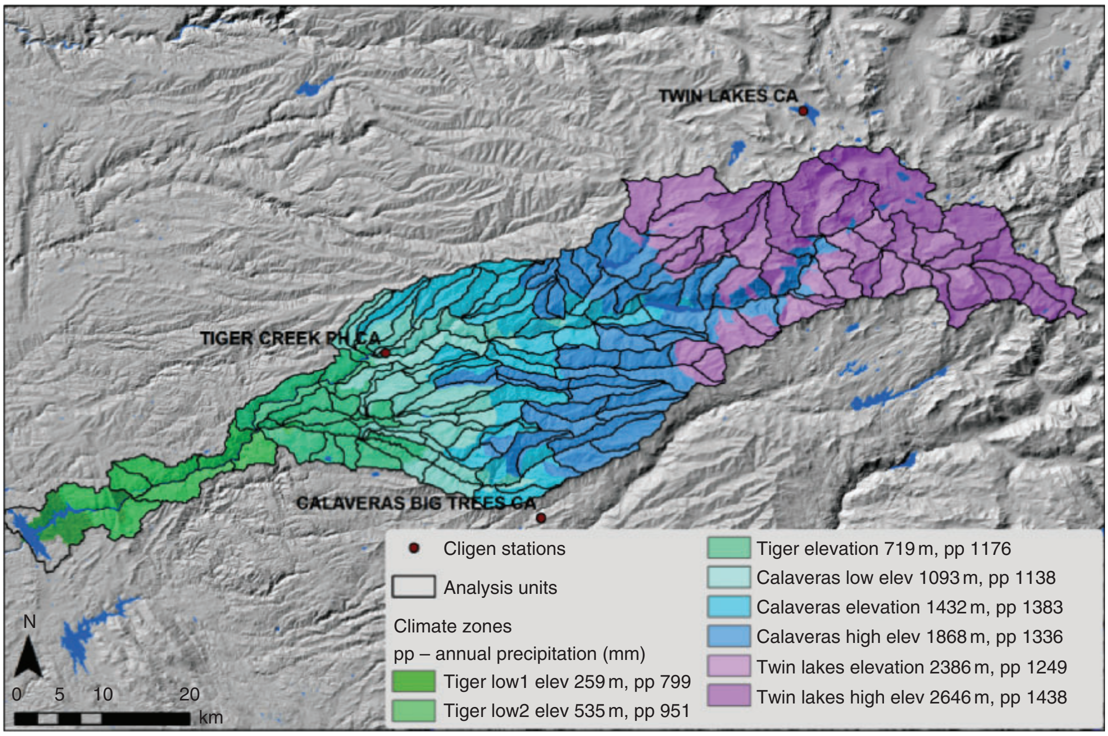

Fig. 2. Map displaying the distribution of climate forecasts within the Mokelumne Basin and the location of the three National Oceanic and Atmosphere Agency weather stations (Twin Lakes, CA; Tiger Creek Power House, CA; and Calaveras Big Trees, CA). The treatment analysis units (AUs) are outlined on the map.

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 between the nearest weather station and the site of interest. 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 short distances (Table 3), 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 Independent Slopes Model; Daly *et al.* 2004). The PRISM database with a spatial resolution of 4 km^2 is used by Rock : Clime.

Three US National Oceanic and Atmosphere Agency (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; Fig. 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 3). Each climate input file contained 50 years of daily stochastically generated weather data. The average elevations of the initial WEPP subwatersheds were then used to select the appropriate climate file (Fig. 2) for each subwatershed.

Land cover, ground cover and vegetation input files for WEPP

Land-cover data were obtained from the LANDFIRE Project (Rollins 2009). For erosion modelling the same LANDFIRE land-cover data that were modified with field observations for the fire modelling runs were used (Buckley *et al.* 2014).

In addition to making the process more efficient by using the same dataset, this ensured consistency across the modelling efforts. The next step was to reclassify the land-cover data layer into WEPP database cover types (e.g. Forest, Young Forest, Shrubs, 'Tall' (bunch) Grass, 'Short' (sod-forming) 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 modelling post-fire conditions, the FlamMap fire intensity maps from before and after fuel reduction treatments were used to reclassify land cover into unburned, low, moderate, and high burn severity classes (Table 1). In order to model the potential erodibility effects of the fuel reduction treatments, the map of proposed treatments developed for this analysis was used. It was assumed that the prescribed fire treatments would have a low-severity soil condition for the year following the treatment with 85% ground cover, and the thinning-only treatments would have unburned forest soil properties and 90% cover (Elliot and Miller 2004; Dobre *et al.* 2014).

Soils data

For the WEPP modelling, the LANDFIRE soil layers that were derived from STATSGO (STATe Soil GeOgraphic) data (USDA 1991) were used to build soil input files for WEPP. This dataset included: maximum soil depth, percentage rock fragments (>2.0 mm), sand, silt and clay. The percentages of sand, silt and clay in the soil 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 rill erodibility) specific to each soil texture class were then used in the modelling (Elliot *et al.* 2000). Soil properties also vary according to predicted burn severity and the type of vegetation that burned (forests, shrubs or grasses) (Pierson *et al.* 2001; Elliot 2004; Robichaud *et al.* 2007).

Topographic data, watershed delineation and processing

A DEM was downloaded from the National Elevation Dataset at 30-m resolution (Gesch *et al.* 2002; Gesch 2007). GeoWEPP utilises TOPAZ, Topographic Parameterization (Garbrecht and Martz 1999), to delineate watersheds and create the polygon slope length, steepness and width files needed to run WEPP for each hillslope polygon and channel segment. Required input parameters for TOPAZ include the critical source area (CSA) to define a stream first-order ephemeral channel and minimum first-order channel length (MSCL) (Renschler 2003). The default GeoWEPP settings were accepted for these variables, 5 ha for CSA and 100 m for MSCL, which resulted in a mean hillslope size of ~4 ha.

Results

Sediment delivery from hillslopes in the Mokelumne Basin was estimated and mapped for the four conditions: (1) current vegetation fuel conditions in the absence of fire; (2) after a fire assuming current fuel conditions; (3) after the fuel treatments and no fire; and (4) after a wildfire following fuel treatment. The first condition determined background erosion rates without fire under the current vegetation conditions. The mean predicted sediment delivery from ~36 000 hillslope polygons within the unburned basin was 0.67 Mg year^{-1} ha^{-1} and 0.4 Mg year^{-1} ha^{-1} from ~9900 hillslopes 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 erodible as is typical of high-elevation areas in the Sierra Nevada Mountains (Brooks *et al.* 2016). The second condition used the burn severity based on the FlamMap predictions for the current vegetation conditions to predict post-fire erosion (Fig. 1). Average first year post-fire hillslope erosion in the Mokelumne Basin was 32 Mg year^{-1} ha^{-1}, 50 times higher than the unburned conditions.

The mapped post-fire erosion predictions for current conditions along with the fire modelling results and other considerations were used by the MACA committees and stakeholders to help plan and prioritise a fuel reduction treatment strategy within the basin. The treatment selection process focussed on reducing risks from fire and post-fire sediment to water utility and other infrastructure resources (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 rationale for their decisions. The watershed was divided into 148 potential treatment analysis units (AUs) with an average area of 10 km^2 (Figs 1–4). 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 (Fig. 3). Recent studies indicate the minimum area needing to be treated in a watershed to lower burn probability is 10–20% (Ager *et al.* 2007; Finney *et al.* 2007) and that strategically treating 35% would be ideal for reducing risks (Ager *et al.* 2013). The proposed treatment AUs covered ~29% of the Upper Mokelumne watershed (Buckley *et al.* 2014), which should be 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 behaviour, but also could result in soil erosion, so the effects of these treatments on soil erosion were modelled for the third condition. Fuel treatments were planned only in the lower portions of the watershed and the mean predicted sediment rate basin-wide from treating ~9900 hillslope polygons was 0.69 Mg year^{-1} ha^{-1}, an increase of 0.02 Mg year^{-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 modelled 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 year^{-1} ha^{-1}, or 6 Mg year^{-1} ha^{-1} less than the average post-fire erosion

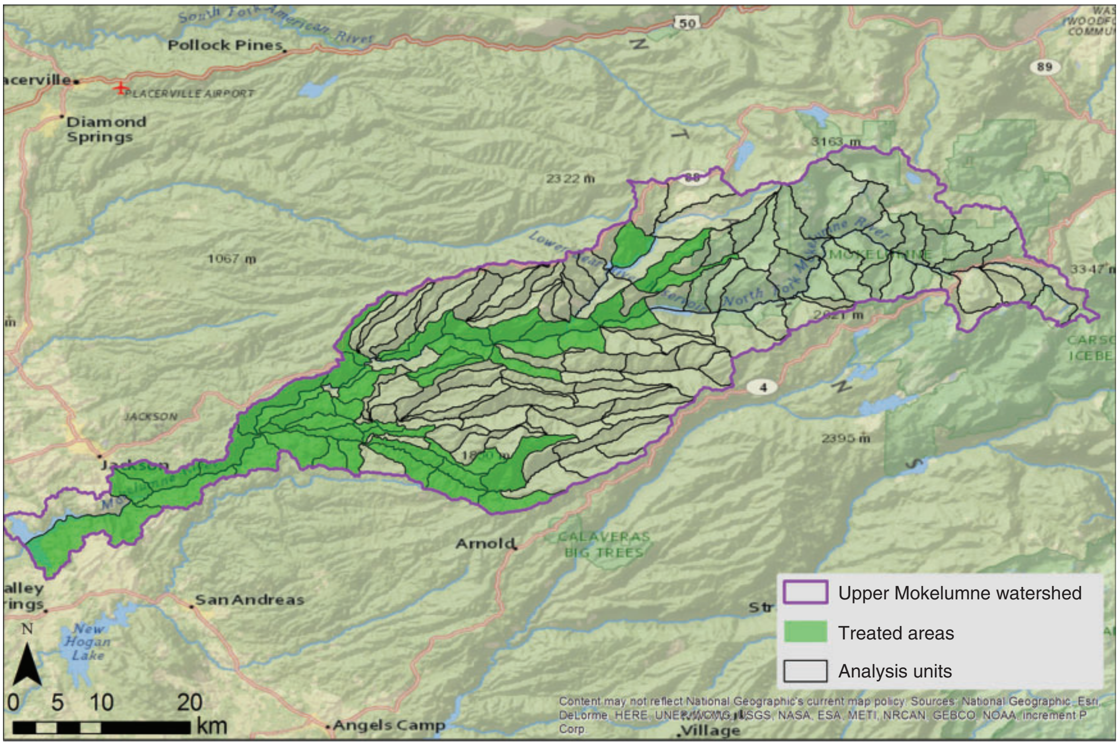

Fig. 3. Areas selected for treatment. The treatment analysis units (AUs) are outlined on the map.

rates without treatments. In the second year post-fire, erosion rates for both the current conditions and treated conditions are predicted to drop to only 10% of their first year post-fire values, and return to prefire levels within 5 years (Robichaud *et al.* 2007). A summary of predicted erosion rates for the entire basin is found in Table 4. 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 year^{-1} ha^{-1} (Table 5).

Predictions of both burn severity and post-fire erosion rates are comparable with 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 (Robichaud *et al.* 2007; Keeley 2009). However, the ratio of high, moderate and low burn severity from the FlamMap-derived predictions for post-fire burn severity was consistent with a satellite-derived map of burn severity for the 2004 Power Fire that burned within the Mokelumne Basin (Table 1). Field measurements of post-fire erosion rates from the nearby Cannon Fire ranged from 2.5 to 15 Mg year^{-1} ha^{-1} (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 with 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 year^{-1}.

Table 4. Summary of the results from the four hillslope erosion model runs for the entire Mokelumne Basin (~36 000 hillslope polygons for 1500 km^2)

	Current condition (Mg ha^{-1})	Fire following current condition (Mg ha^{-1})	Treatment effects (Mg ha^{-1})	Fire following treatment (Mg ha^{-1})
Mean erosion	0.67	32 in year 1	0.69	26 in year 1
range	0–84	0–566	0–84	0–535
Standard deviation	3.0	55	2.5	44

Table 5. Summary of results from the four hillslope erosion model runs for only the treated portions of the Mokelumne Basin (~9900 hillslope polygons for 409 km^2)

	Current condition (Mg ha^{-1})	Fire following current condition (Mg ha^{-1})	Treatment effects (Mg ha^{-1})	Fire following treatment (Mg ha^{-1})
Mean erosion	0.40	46 in year 1	0.69	26 in year 1
range	0–84	0–566	0–8	0–535
Standard deviation	2.5	69 Mg ha^{-1}	2.5	36

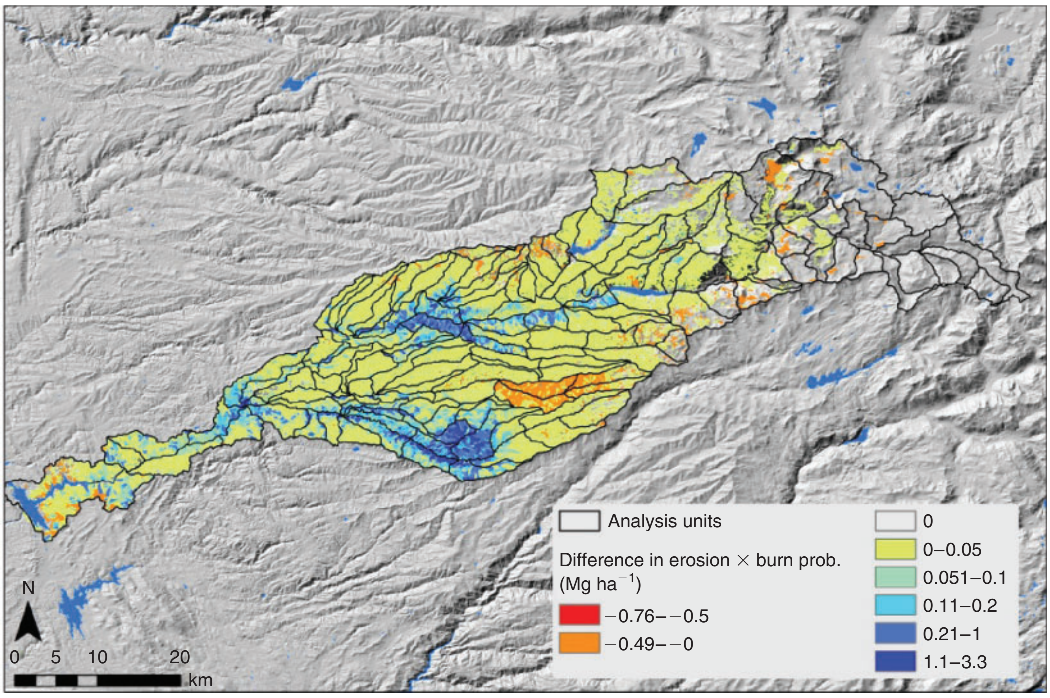

Fig. 4. Map of the differences between post-fire erosion predictions for current conditions × burn probability for current conditions and post treatment × burn probability post treatment.

Although these comparisons do not validate the modelling, they do demonstrate the results are reasonable.

Frequency of burning

The fire behaviour modellers (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 moist basin, with predicted fire return intervals typically ~200–400 years (Buckley *et al.* 2014). In order to incorporate fire probability into erosion modelling, it is necessary to multiply the predicted sediment delivery from each hillslope polygon following a wildfire event by the average probability of fire occurring for all the pixels within the boundaries of that polygon (Elliot 2013). This can be done for both the untreated and treated post-fire erosion estimates. Fig. 4 is a map of the difference between (i) the first year post-fire erosion under current conditions multiplied by current burn probability, and (ii) first year post-fire erosion following treatments multiplied by burn probability after treatments. Overall the modelled treatments are predicted to decrease burn severity, wildfire 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 year^{-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, all four conditions needed to be considered (Elliot 2013).

To estimate 'average annual' erosion rates, it is necessary 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 hillslope erosion rate (*Average Erosion$_{cc}$*) can be represented by Eqn 1. If the assumed effects of fuel reduction treatments last 25 years, then Eqn 2 represents long-term erosion rates (*Average Erosion$_{tr}$*) with regular fuel reduction treatments.

$$Average\ Erosion_{cc} = E_{cc\_fire} \times bp_{cc\_fire} + \left(1 - bp_{cc\_fire}\right) \times E_{nf} \quad (1)$$

$$Average\ Erosion_{tr} = E_{tr\_fire} \times bp_{tr\_fire} + \left(1 - bp_{tr\_fire}\right) \times \left(24 \times E_{nf} + E_{tr}\right)/25 \quad (2)$$

where:

E_{cc_fire} is the mapped post-fire erosion rates for current conditions (Mg ha^{-1}),
E_{tr_fire} is the mapped post-fire erosion rates following fuel treatments (Mg ha^{-1}),
E_{tr} is the mapped erosion rates due to the effects of the fuel treatments (Mg ha^{-1}),
E_{nf} is mapped erosion rates for current conditions in the absence of fire (Mg ha^{-1}),
bp_{cc_fire} is the mapped probability of fire under current conditions (decimal),
bp_{tr_fire} is the mapped probability of fire following fuel treatments (decimal).

These equations were used in conjunction with the 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 25 years. Model results for long-term average erosion rates for current conditions were 0.64 Mg year^{-1} ha^{-1}, compared with 0.52 Mg year^{-1} ha^{-1} if the designated treatment area is treated as modelled. The predictions indicate that regular treatments (every 25 years) 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 focussed on resources that could be readily assigned a dollar value. These included the avoided sediment costs as well as the costs of homes, infrastructure, treatment implementation, timber, carbon sequestration, and fire suppression and clean-up.

The sediment modelling results from the current condition runs (conditions 1 and 2) factored heavily into the treatment selection process of the MACA committee. The modelling results allowed the MACA committee to factor in potential risk from a wildfire to downstream assets rather than only on assets at direct risk from the potential flames themselves. This expanded the area of the treatment scenario to more remote areas of the watershed than might not have been included if only the fire model results were used to determine the treatment scenario. The sediment modelling demonstrated the potential impacts to assets beyond the burn area itself, increasing the number of stakeholder groups that became involved in the MACA committee.

The importance of the analysis described in this paper was underscored in two ways in 2014, when sedimentation following the 40 000-ha King Fire, 60 km north of the Mokelumne Basin, threatened a municipal watershed. The databases developed and experience gained in the MACA analysis allowed us to rapidly carry out an erosion risk assessment following the King Fire. In a post-fire analysis using the same WEPP tools as the current study, hillslopes with the greatest risk of sediment delivery were targeted for post-wildfire mulching. More than US$1 million was spent on mitigation, with the costs shared by the Sacramento Municipal Utility District and the US Forest Service to protect a hydroelectric and water supply reservoir downstream of the fire (Jeff TenPas, USFS Region 5 BAER coordinator, pers. comm., 10 April 2015). Had those hillslopes been treated to reduce the fuel load, the likelihood and severity of the wildfire in that sensitive area may have been reduced (Reinhardt *et al.* 2008; Cochrane *et al.* 2012).

There was a low probability of fire in any given pixel in this basin as predicted by the FSim model (0.0025 to 0.005). As there are 170 000 pixels, the probability of at least one cell experiencing a fire in any given year is greater than 0.999, and assuming a probability of 0.003, on average, approximately five hundred 90-m cells would be burned each year (B. Bird, Rocky Mountain Research Station statistician, pers. comm., November 2015), or ~400 ha. In 30 years, this would be 12 000 ha (120 km^2) burned. The FSim results including individual cell probabilities and potential fire boundaries were analysed by the specialists in Buckley *et al.* (2014) focussing on the lower-elevation, non-wilderness part of the basin where fuel treatments could be applied. They determined that in any given year, 10% of this area has a 1 in 126 chance of burning. This led to a prediction that within the next 30 years, fire will burn ~190 km^2 in the basin, similar in magnitude to the simple prediction above. The Butte Fire (2015, 273 km^2) burned 37.9 km^2 of the lower Mokelumne Basin. Thus, in the first year following the study of Buckley *et al.* (2014), 20% of the predicted burn area for the next 30 years has burned. Interpreting the probability of fire is further complicated because the FSim runs were carried out using historic climate scenarios. Fire occurrence and severity are predicted to increase under future climates (Westerling *et al.* 2006). Also, the version of FSim used for the current analysis may not have been giving correct consideration to canopy effects (J. Scott, fire modelling consultant, pers. comm., November 2015). Another consideration in interpreting these results is that the recent extended drought in this region has resulted in an increase in both fire size and severity, so having a large fire occur at this time would be expected. Whether this increase in fire occurrence is due to normal climatic cycles, recent fire suppression activities leading to an accumulation of fuel (Agee 1993; Steel *et al.* 2015) or long-term climate change as suggested by many (Westerling *et al.* 2006; Geological Society of America 2015) is beyond the scope of the present manuscript.

Based on the FSim results and expert review, five simulated fires from the modelling 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 behaviour 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 proposed 46 AUs was estimated to be US$68 million (including maintenance costs over 30 years) compared with the lower estimated avoided cost of US$126 million and the higher estimate of US$224 million. 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 at high severity, accounting for 27% of the burned area (Buckley *et al.* 2014). Contrasting this with four major recent wildfires that occurred on either side of the Mokelumne Basin: the Rim Fire (2013) burned 104 000 ha, 38% high severity; the King Fire (2014) burned 39 000 ha, 47% high severity (http://www.fs.fed.us/postfirevegcondition/index.shtml, accessed 11 February 2016); the Butte Fire (2015) burned 27 300 ha, 20% high severity; and the Valley Fire burned 27 300 ha with 27% high severity. These individual fires were much larger and two burned at a higher severity than the modelled fires that were used to create cost estimates; therefore, the potential costs associated with the modelled future fires are likely underestimated.

Avoided cost due to sediment may have been undervalued by this process owing 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 ~US$1 million, attributed to lost water storage potential. This is a relatively small amount compared with the costs associated with saving structures (US$32–45.6 million) or avoiding clean-up costs (US$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 to 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 owing to persistent drought conditions in Western states, with reduced snowpack due to climate change (Mote 2006; Rauscher *et al.* 2008) or if one of the water storage reservoirs were lost owing 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 ~75% of its original capacity (Buckley *et al.* 2014). Elsewhere in the US, 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. In Colorado, Denver Water has spent US$26 million treating drinking water and dredging the Strontia Springs Reservoir following the Buffalo Creek (1996) and Hayman (2002) wildfires (US Department of the Interior 2013). In California, the Los Angeles County Public Works plans to spend US$190 million dredging four reservoirs impacted by sediment from the 2009 Station Fire (US Department of the Interior 2013). California state legislators are considering increasing reservoir storage capacity by building new reservoirs. The cost of storage for usable water averaged US$20 m^{-3} for the proposed reservoirs (http://www.fresnobee.com/2014/06/01/3956458/should-calif-add-new-dams.html, accessed 19 August 2015). 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 (~100 000 m^3) would be US$2 million. Sediment delivery, however, may not be immediate, but will likely take time as eroded sediment from wildfires is often deposited in upland channels, and then is gradually routed downstream during large runoff events (Smith *et al.* 2011; Elliot 2013).

Conclusions

The objectives of this paper are to describe the assumptions, methods and limitations for predicting sediment delivery from hillslopes in a forested basin as impacted by wildfire and fuel management in support of a larger economic analysis of the costs and benefits of forest fuel management activities to reduce the occurrence or severity of wildfire. By linking fire behaviour and post-fire hydrology models, a risk assessment map was created that allowed land and water managers in the Mokelumne Basin to prioritise fuel reduction treatments to protect both land and water resources. The erosion analysis was particularly beneficial in engaging downstream water users in considering the costs and benefits of watershed management practices to reduce the impacts of wildfire on downstream water resources. Offsite stakeholders are not commonly engaged in forest management planning processes. This methodology helped to bring together watershed managers and water users who had not realised they too were stakeholders in forest fuel management. 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 accuracy and application of both the fire spread and watershed models and their linkages in order to provide land managers with increasingly refined and spatially explicit data that will allow them to better protect valuable water resources in fire-prone regions.

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