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Economic benefits of reducing fire-related sediment in southwestern fire-prone ecosystems

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[1] A multiple regression analysis of fire interval and resulting sediment yield (controlling for relief ratio, rainfall, etc.) indicates that reducing the fire interval from the current average 22 years to a prescribed fire interval of 5 years would reduce sediment yield by 2 million cubic meters in the 86.2 square kilometer southern California watershed adjacent to and including the Angeles National Forest. This would have direct cost savings to Los Angeles County Public Works in terms of reduced debris basin clean out of $24 million. The net present values of both 5- and 10-year prescribed fire intervals are positive. However, given other multiple use objectives of the USDA Forest Service, a 10-year prescribed fire interval may be more optimal than a 5-year fire interval. *INDEX TERMS:* 6304 Policy Sciences: Benefit-cost analysis; 6329 Policy Sciences: Project evaluation; 1815 Hydrology: Erosion and sedimentation; *KEYWORDS:* California, erosion, forest fire, national forests, recreation, sediment

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1. Introduction and Research Objectives

[2] Throughout the world, from Australia to the United States, wildfires have resulted in accelerated erosion in municipal watersheds. Nowhere is this problem more evident than in Southern California. The mountains of Southern California are home to several hundred thousand residents and are visited by several million recreationists each year. However, these forests are a fire-prone ecosystem and a significant watershed that is susceptible to postfire erosion. The purpose of this paper is to estimate the sediment cost savings and recreation losses avoided from prescribed burning treatments in these fire-prone watersheds.

[3] The watershed cost savings take the form of reduced sediment removal in debris basins and reduced need for emergency infrastructure protection. Other savings include reduced watershed rehabilitation via hydroseeding, as well as reducing the lost recreation visitor days due to emergency fire closures of watershed recreation facilities.

[4] This analysis provides quantitative estimates of the sediment reduction and associated cost savings to society from using prescribed burning to generate a more frequent, low intensity fire regime in the wildland-urban interface of the San Gabriel Mountains of Southern California. We compare these benefits from reduced sediment to the costs of prescribed burning to estimate what frequency of prescribed burning is economically justified. We believe the methodology developed in this paper has broad applicability to other forested municipal watersheds around the world.

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2. Literature Review

[5] Fire and erosion has been a longstanding concern in forest management for decades, and on the San Gabriel Mountains since at least 1948. It was in that year that *Buck et al.* [1948] first investigated the potential damages caused by increased run-off and erosion following wildfire. They measured potential damages on infrastructure such as roads and electrical lines, as well as residential and business properties in and around the San Gabriel Mountains. As they noted, this information on potential damages is useful in formulating appropriate fire response strategies. A few years later *Rowe et al.* [1954] performed a hydrologic analysis of the effects of fire on peak discharges and erosion rates in the San Gabriel Mountains. They found the first year postfire erosion averaged 35 times the unburned levels.

[6] These concerns have escalated dramatically in the last 50 years as the level of development in the wildland-urban interface has increased substantially. Increasing number of homes and value of homes in the wildland-urban interface not only face fire risk, but those surviving the fire, face postfire risks in the form of debris flows and sediment. *Wells et al.* [1987] demonstrated that wildfire in southern California increased sedimentation by more than an order of magnitude over unburned areas. They also found that wildfires in an area lowered the threshold amount of rainfall

intensity necessary to trigger debris flows. These results are similar to those of *Johansen et al.* [2001] who found that burned plots around the Cerro Grande fire in Los Alamos, New Mexico produced 25 times more sediment than unburned plots.

[7] In response to the increasing level and value of development in wildland-urban interface, public works departments have built and maintain debris basins to trap sediment and debris at the mouth of canyons. However, this is an increasingly expensive solution. In some watersheds, increased postfire erosion and debris have also added to water supply system costs. It has been increasingly common after fires for debris to end up in water supply reservoirs, as recently happened after the Buffalo Creek fire outside of Denver, Colorado. This necessitated an emergency clean out of debris from the reservoir. In addition, the added sediment results in lost reservoir water storage capacity and increased treatment costs [*Martin and Moody*, 2001; *Holmes*, 1988; *Moore and McCarl*, 1987].

[8] All of these costs have spawned a search for ways to reduce these episodic sediment and debris events following wildfire. *Wohlgemuth et al.* [1999] was among the first to suggest that one of the many benefits of prescribed fire would be as a sediment management tool. *Wohlgemuth et al.* [1999] quantified the extent of sediment reduction in areas that had been previously prescribed burned prior to the wildfire. They found one-tenth to one-twentieth as much sediment coming from previously prescribed burned areas as compared to areas without prescribed burning prior to the wildfire.

[9] The remainder of this paper (1) tests the hypothesis that repeated fires would result in a statistically significant reduction in sediment yield in a wide range of watersheds along the San Gabriel Mountains, (2) quantifies in monetary terms the cost savings that would have resulted from prescribed burning, and (3) determines what prescribed fire frequency interval would be economically justified.

3. Study Area and Values at Risk

[10] The study area includes watersheds in the Los Angeles County foothills encompassing the Angeles National Forest and adjacent private land, generally referred to as the San Gabriel Mountains. The area extends from the community of San Fernando to San Dimas.

[11] This study area was chosen because it is typical of wildland-urban interface areas where thousands of houses exist in fire-prone ecosystems and these private lands abut public land (in this case the Angeles National Forest). These mountain ranges and canyons are fairly steep, with elevation gradients of 150 to 850 feet per mile. Most of our study area is below 5000 feet above sea level. Vegetative composition of brush in the area is known as chaparral, a very flammable vegetative community. The area is subject to Santa Ana winds in the fall that dries the vegetation, and often results in high intensity wildfires in one or more areas of the watershed each year.

[12] To protect private property, water supply and public infrastructure in this fire-prone ecosystem, Los Angeles County Public Works has constructed 41 debris basins to intercept materials that come down these canyons. These debris basins are usually cleaned out annually to maintain sufficient storage capacity for the up coming winter rainy season flows. If a wildfire occurs in these watersheds, the wildfire often removes much of the vegetation that holds the soils in place. Thus, when wildfires occur during the fall season, LA County is put into an emergency situation of cleaning the basins out after the first rains of winter deposit the large amount of material in the basins. To maintain space for the remaining winter rainy season, the large inflow of material must be removed quickly. This is very costly to LA County due to the overtime premiums to pay for the round the clock emergency clean-outs.

[13] This pattern (fall wildfires followed by initial winter rains discharging a large volume of material in the debris basins just when their capacity is needed for subsequent rains) can possibly be altered by the use of prescribed burning on regular intervals (e.g. 5 years). Frequent prescribed burning would result in less runoff into the basins when the rains come in the following winter. It is likely that the amount of additional debris from a prescribed fire would be small enough to be handled by the routine debris basin clean out, avoiding the need for emergency clean outs. More importantly, frequent prescribed burning could reduce the intensity of any fires that occur in the watershed by reducing the available fuels. Reduced fire intensity will leave some of the larger bushes and trees standing, and along with their intact root system, will reduce erosion from rainfall. Therefore the amount of material coming down after a wildfire would be greatly reduced, again avoiding emergency clean out costs.

[14] To test these ideas, we conduct a linked hydrological and economic analysis. The first step in this analysis is to determine statistically if sediment and debris flows can be reduced from repeated fire.

4. Statistical Analysis of the Relationship Between Fire Frequency and Sediment Yield

4.1. Hydrological Data

[15] Sediment discharge to debris basins records were collected for 41 watersheds along the southern flank of the San Gabriel Mountains of Los Angeles County. These records include topographic characteristics, fire histories, rainfall amounts, and sediment yields into debris basins in these watersheds over a 30–60 year period, depending on the age of the debris basin.

[16] The sediment yield (in cubic meters) indicates the amount of new sediment accumulation in the debris basins for a given year, based on either a survey of the deposit or the removal of the material. Watershed area was measured in square kilometers from USGS 7.5' quadrangles. Relief ratio is an index of watershed steepness, determined by the vertical elevation range divided by the horizontal length of the master stream.

[17] Years since fire or fire interval is the time since the last burn in a watershed; year zero is the year a fire occurred. Percent burned in the last fire is the proportion (0.0 to 1.0 in 0.05 increments) of the watershed area that was consumed in the most previous burn, based on fire history maps from LA County. However, it is worth noting that the fire events in the database are not prescribed burns. We are using repeated wildfire events in the same area as natural experiments to mimic what would occur with frequent prescribed burning. We recognize that repeated

wildfires may burn somewhat hotter than prescribed fires so that sediment reductions associated with repeated wildfires may be somewhat different than with frequent prescribed fire. Nonetheless, we think the ability to utilize data from this natural experiment is still quite insightful and a reasonable proxy for evaluating an equivalent prescribed fire regime. The advantage of using these natural wildfire experiments is that we obtain a broader geographical representation within our study area than could realistically be obtained by extrapolating the few, small prescribed burning experimental plots to the large policy relevant area.

[18] Rainfall (in millimeters) is a particularly important influence on sediment delivery to the debris basins. A comprehensive measure called SumT5RainmmT1 (total mm of rainfall in the five largest events during the water year following the fire) was developed from rainfall records. In addition, RainLag (the number of days between the fire and first significant rainfall (defined as 0.5 inches or more)) was thought to be an important variable.

4.2. Sediment Yield Modeling

[19] A given sediment yield response from any watershed is going to be the result of a complex set of interactions among these physical site characteristics, fire characteristics, and rainfall characteristics. One way to model these interactions is to use a paired watershed approach. Specifically, in watersheds that burned multiple times, a prefire/postfire comparison may be made to ascertain the effect of fire interval, controlling for rainfall and other influences. This approach allows us to test for the effect of prior fires on subsequent sediment yields. As there are good comparisons for unburned versus postburn sediment yields for virtually all 41 watersheds, the sediment yield reduction function is estimated with multiple regression and then the equation used to calculate sediment responses for various fire interval scenarios.

4.3. Statistical Analysis Methods

[20] Multiple regression analysis was used to estimate sediment discharge as a function of fire interval controlling for other variables. Specifically the equation estimated is

$$\text{Sediment per km}^2 = \text{func (FireInterval, RainLag, SumTOT5RainmmT1, Relief Ratio, Percent Area Burned)},$$

where FireInterval is the number of years between fires (mean 22 years), RainLag is the number of days between the fire and first significant rainfall (defined as 0.5 inches or more), SumTOT5RainmmT1 is the total mm of rainfall in the five largest events during the water year following the fire (mean 8 mm), Relief Ratio is the elevation ratio of the watershed (mean.3), and Percent Area Burned is the percent of the watershed burned (mean 71%).

[21] In terms of the functional form of the relationship between physical and hydrology variables, *Anderson* [1957] provided two reasons that the relationship may best be characterized as a log-log relationship: (1) The level of sediment yield is usually not a linear additive function of the watershed variables but rather depends on the levels of the other watershed variables. The log-log form is a straightforward way of linearizing such a multiplicative relationship between the watershed variables. (2) The variability in sediment yield is generally proportional to the relative magnitude of the independent variables [*Anderson*, 1957, p. 921]. Therefore the log of all variables was used in the multiple regression analysis.

[22] After some exploratory analysis of the data, it was discovered that four drainage basins (Cooks for 1957, 1960 and 1976; Lincoln for 1994, Smadreavilla for 1979 and Snova for 1976) reported zero sediment in a year after a fire. These specific observations were verified with LA County's original data, and this indicated that no sediment was removed from these debris basins in those years. LA County was not able to offer a direct explanation other than the possibility that sediment yield that year was not large enough to warrant clean out. Specifically, there was still space in the debris basin to handle inflows from the winter rains. Further inspection of the data indicated that the six zeros were associated with drought conditions, e.g., 1976 was one of the driest on record in California. Despite a fire burning through the area, there was simply so little rain that not enough sediment was moved downstream into the debris basins in a quantity large enough that warranted a clean out. Looking at the first substantial year of rain after the fire showed that substantial quantities of sediment were recorded deposited in the debris basins.

[23] While there were just six of these zero observations, to test the sensitivity of our results to inclusion versus exclusion of these six observations, two multiple regression models were run. The first model infers what the sediment movement into the debris basin would have been that year based on sediment discharge over the subsequent two years and rainfall during that same 2-year period. Specifically, we calculated this inferred sediment in two steps. First was to calculate the reported cubic meters of sediment in the 2 years after the year of zero reported sediment after the fire. This sum was divided by the sum of rainfall during that same time period. This yielded cubic meters of sediment per mm of rainfall during that time period. That number was then multiplied by the rainfall for the year of zero

Table 1a. Sediment Model Regression Results Including Inferred Sediment for Zero Reported Sediment[a]

Variable	Coefficient	t Statistic	Probability	Mean
Constant	6.6611	6.110	0.0000	n/a
Ln(FIRE INTERVAL)	0.5772	3.125	0.0027	22.74
Ln(RAIN LAG in days)	−0.3372	−2.281	0.0260	38.68
Ln(RELIEF RATIO)	0.8237	1.498	0.1394	0.302
Ln(SUMT5RAINMMT1)	1.3852	5.101	0.0000	7.88
Ln(PERCENT BURN)	0.6141	3.510	0.0009	0.714
R^2	0.5551			
Adjusted R^2	0.5180			
F statistic	14.9720			
Prob(F statistic)	0.0000			
Mean dependent variable	8.5566			
Standard error of regression	1.0447			

[a]Dependent variable is LADJSEDKM: log of sediment/km, with inferred sediment for 0 s. Sample: 1 66.

Table 1b. Sediment Model Regression Results Excluding Zero Reported Sediment Observations[a]

Variable	Coefficient	t Statistic	Probability	Mean
Constant	6.4423	6.069	0.0000	n/a
Ln(FIRE INTERVAL)	0.5500	2.863	0.0060	22.45
Ln(RAIN LAG)	−0.3783	−2.588	0.0124	38.03
Ln(RELIEF RATIO)	0.3618	0.681	0.4984	0.307
Ln(SUMT5RAINMMT1)	1.3831	5.379	0.0000	8.10
Ln(PERCENT BURN)	0.6989	4.277	0.0001	0.715
R^2	0.5888			
Adjusted R^2	0.5507			
F statistic	15.4650			
Prob(F statistic)	0.0000			
Mean dependent var	8.6914			
Standard error of regression	0.9583			

[a]Dependent variable is LSEDKM: log of sediment per km^2. Sample: 60

reported sediment to yield an estimate of sediment that came down into the debris basin that year. Using this procedure, we calculated inferred sediment for the six zero observations. These observations along with the reported sediment were then used to estimate the regression reported in Table 1a.

4.4. Statistical Regression Results

[24] Table 1a presents the results of the multiple regression model with 66 observations, six of which use inferred sediment yield, as well as the mean of the variables.

[25] Table 1a indicates a reasonably good explanatory power of slightly over 50% of the variation in sediment from the 66 observations is explained by the five independent variables. The longer the fire interval is, the greater the sediment that comes down into the debris basin in the year of the fire. Since the dependent and independent variables are logged, the coefficients can be interpreted as an elasticity. Thus a 1% decrease in the number of years between fires leads to a 0.577% decrease in annual sediment. The signs of the other variables are plausible, i.e., the greater the percentage of the watershed burned (PERCENT BURN) and the more rain that fell that winter (SUMT5RAINMMT1), the greater the annual flow of sediment was into the debris basins.

4.5. Model Excluding Zeros

[26] The second model estimates exclude those six observations on the basis that these are possibly erroneous in that some sediment did move down, but there was sufficient debris basin capacity that it was not removed, and hence not recorded in the data. When the regression is applied to explaining these 60 observations, the model also has a reasonable explanatory power, with 55% of the variation explained (i.e., the adjusted R square is 0.55). As shown in Table 1b, the model also has theoretically consistent signs and statistical significance on Fire Interval, Rain Lag, SumT5RainmmT1, Percent Burn, etc. Most important is that the coefficient on Fire Interval remains statistically significant and nearly identical in magnitude to the model with inferred sediment in Table 1a.

5. Using the Regression Equation as a Sediment Simulation Model for Prescribed Burning

[27] The regression equation is used to forecast the reduction in sediment per km^2 if the fire interval is reduced from the current average fire interval of 22.45 years to shorter fire frequencies such as 5 years or 10 years. This is done by incrementing the level of the Ln FIRE INTERVAL variable using 5 years, 10 years, and 15 years.

Table 2. Simulation Model of the Change in Sediment Yield per km^2 With Changes in the Fire Interval (Years)

Variable	Coefficient	Mean/level	Ln(Mean)	Product
	Sediment Yield With Current 22.45 Year Average Fire Interval			
Constant	6.6611	1	1.0000	6.6611
LFIREINTERVAL	0.5772	22.45	3.1113	1.7957
LRAINLAG (Days)	−0.3372	38	3.6376	−1.2266
LRELRATIO	0.8237	0.3075	−1.1793	−0.9714
LSUMT5RAINMM	1.385	27.002	3.2958	4.5647
LPCTBURN	0.614	0.715	−0.3355	−0.2060
Sum of Products				10.6175
Estimated sediment per km^2 = (antilog of sum)				40,843
	Five-Year Fire Interval			
Constant	6.6611	1	1.0000	6.6611
LFIREINTERVAL	0.5772	5	1.6094	0.9289
LRAINLAG (Days)	−0.3372	38	3.6376	−1.2266
LRELRATIO	0.8237	0.3075	−1.1793	−0.9714
LSUMT5RAINMM	1.385	27.002	3.2958	4.5647
LPCTBURN	0.614	0.715	−0.3355	−0.2060
Sum of Products				9.7507
Estimated sediment per km^2 fire interval (5) = (anti log of sum)				17,166
Reduction in sediment per km^2 if 5-year fire interval				23,677
	Expansion to Total Watershed Area of 86.2 km^2			
Overall Watershed Total Sediment Reduction M^3				2,040,957

Table 3. Annual Sediment Reductions per Square Kilometer With Alternative Fire Intervals

Fire Interval, Years	Annual M^3/km^2 After Fire	Reduced Annual Sediment M^3/km^2 Shorter Fire Interval
22	40843	
15	32367	8476
10	25614	15229
5	17166	23677

[28] Table 2 presents the results of such calculations holding the other variables at their mean. We use the regression equation from Table 1a, as it uses the entire record of observations, and has greater precision on the estimated fire interval coefficient. There is little difference in results, however as the two fire interval coefficients (elasticities) are quite similar at 0.55 versus 0.57. To conserve space, the simulation model analysis using the regression equation in Table 1b is not reported but is available from the first author.

[29] As is evident from the results of Table 2, a more frequent fire interval reduces the annual sediment yield per km ^{2} by more than half. The bottom line results of this table indicate that over the entire study area of 86 km^2, a 5 year fire interval would reduce annual sediment inflows to LA County debris basins by 2 million cubic meters each year.

[30] Table 3 explores different fire frequencies and associated reductions in annual sediment yield. As Table 3 indicates, there are significant annual reductions in cubic meters of sediment as the fire interval gets shorter. Since it is the amount of sediment coming down at one time that is the problem, cost savings would be realized by reducing the peak amounts of sediment coming down. As calculated in Table 2, using a 5 year fire interval instead of a 22-year fire interval, the annual reduction in sediment is 23,677 cubic meters per km^2. As shown in Table 3, a 10-year fire interval would result in a reduction in sediment of 15,229 cubic meters per km^2.

6. Cost Savings From Sediment Reduction

6.1. LA County Debris Basin Clean-Out Costs

[31] The major cost savings from reduced sediment yield is decreased debris basin clean-out costs to LA County Public Works. Clean out costs were obtained from L.A. County Public Works for the 41 debris basins in our study area for the time period of 1969 to 1995. This data on debris basin clean out includes both emergency clean out and more routine clean out costs. These costs were updated for inflation to 2000 dollars. The average cost across all years and all basins is nearly $12 per cubic meter, with the range being $2.48 to $30.49. Some of the variation in costs per cubic meter may be related to the distance the removed sediment must be transported. This ranges from as little as a half mile to as much as 7 miles away. Some of this variation in cost is related to how wet the sediment is at the time it is hauled away (L. Soriano, L.A. County Public Works, personal communication, 1 August 2002). If heavy rains occur right after fires, this can wash large amounts of material into the debris basin, filling the basins. If this debris flow occurs early in the rainy season, these become emergency clean outs, as this material must be quickly removed to provide space for subsequent debris flows that winter. Removing that material when it is wet, requires half loads of trucks due to the weight, essentially doubling the cost per unit removed. Unfortunately data on water content of the sediment is not available to explicitly incorporate this factor separately into a formal cost analysis.

[32] Using the average cost of $11.87 per cubic meter, the direct cost saving to LA County Public Works of the 2 million cubic meter annual reduction in sediment associated with a 5-year fire interval (Table 2), would be $23.74 million.

6.2. Forest Recreation at Risk

[33] The private residential land in the watershed is bordered by the Angeles National Forest. As a whole this National Forest receives an estimated 3.5 million to 4 million visitors each year, making it one of the most visited National Forests in California [*USDA Forest Service*, 2001]. Recreation visitation to the Angeles National Forest accounts for 15% of all National Forest visits in California [*USDA Forest Service*, 2001].

[34] Within our study area, there are five developed campgrounds and 21 developed picnic sites. There are also 15 backcountry trail camps that provide tables and fire grates. The area also contains more than 20 hiking trails. Given these facilities, it is not surprising that the most common activities are hiking and picnicking. The quality of the recreation experience can be adversely affected by nearby wildfire, and the entire area and facilities can be closed to public access for an extended time period if the area is subject to a wildfire. Therefore reducing wildfire generates economic benefits to visitors.

[35] To estimate recreation use at risk from fire in the study area we drew upon data from the USDA Forest Service National Visitor Use Monitoring (NVUM) survey. Specifically, we identified sample days at General Forest Area access points (GFAs), Day Use Developed Sites (DUDS) and Overnight Use Developed Sites (OUDS) sampled by the USDA Forest Service that were within our study area. This included 41 sample days at GFAs, 30 days at OUDS and 56 days sampled at DUDS. Given the average length of stay factors from the survey, an estimated 1,038,381 visits to our study area represent 1,049,315 visitor days.

[36] The value to the visitor and society from recreation is measured using the visitor's net willingness-to-pay or consumer surplus (e.g., willingness to pay in excess of costs to travel to the site). The travel cost method (TCM) for estimating a recreation demand curve is one of the recommended approaches for calculating net willingness-to-pay [*U.S. Water Resources Council*, 1983]. Unfortunately, the individual survey data contained only a fraction of the respondents completing the travel cost portion of the survey. Thus we were unable to estimate a site specific TCM demand curve for recreation in our study area of the Angeles National Forest. In such situations, it is common to draw upon values reported in the literature to infer a value. This technique is known as benefit transfer [*Brookshire and Neill*, 1992] and is used by federal agencies such as U.S. Environmental Protection Agency and the USDA Forest Service for performing benefit-cost analyses.

Table 4. Existing Study Area Visitation and Value

Site Type	Total Annual Site Visits	Total Annual Visitor Days	Value per Day	Total Recreation Value
Overnight dev. site	78,100	89,034	$30.13	$2,682,944
Day use dev. site	362,113	362,113	$28.95	$10,483,159
General forest rec.	598,169	598,169	$22.87	$13,680,120
Total	1,038,381	1,049,315		$26,846,223

[37] The U.S. Forest Service has published a report for use in conducting benefit transfers. This report provides the net willingness to pay per visitor day calculated from TCM and contingent valuation studies [*Rosenberger and Loomis*, 2001]. Table 3 of *Rosenberger and Loomis* [2001, p. 13] provides values per day for the geographic area containing our study area. The value per day from existing studies is $28.95 for picnicking, $22.87 for hiking, and $77.27 for camping. In the baseline situation, we have visitor days disaggregated by developed sites (e.g., Day Use Developed Sites and Overnight Developed Sites) and General Forest Recreation. A weighted average of the value of hiking, picnicking and camping was used, where the weights are the percentage of users in each of the three recreation activities. Table 4 presents a summary of the total annual visitor days and total annual recreation value in our study area.

[38] The recreation value at risk from fire is $26.8 million annually. This is quite substantial, and suggests avoiding recreation closures due to fire or postfire flooding is potentially an important benefit of avoiding catastrophic wildfires in our study area. In the next section, we incorporate the benefits of avoiding wildfire closures into the benefit-cost analysis.

6.3. Benefit Cost Comparison of 5- and 10-Year Fire Interval

[39] While Table 3 indicates that a 5-year fire interval results in a larger reduction in annual sediment yield than a 10-year fire interval, this did not consider other multiple use resources, or costs. A 5-year fire interval may be too short in southern California chaparral forests to allow sufficient regeneration of climax vegetation species needed to maintain ecological integrity and biodiversity. This could adversely affect some wildlife that depends on the more mature vegetation. In addition, prescribed burning is expensive. Because of the build up of fuel over an average 20-year time period, the initial prescribed burning requires significant precautionary resources be available. The initial prescribed burning costs on our study area watersheds in the Angeles National Forest average $200 per acre (D. Fazer, unpublished data, 2003). This is similar to the $250 an acre cost for the adjacent San Bernadino National Forest for initial prescribed burns (N. Walker, Division Chief, San Jacinto Ranger District, prescribed fire costs, personal communication to Lucas Bair, Colorado State University, 26 January 2001). Subsequent reentries every 5 years are less costly, with a cost of about 40% of the initial prescribed burning costs (D. Fazer, unpublished data, 2003). These reduced costs are due to less precautionary standby fire suppression resources needed with a reburn rather than with the original burn, since the fuel load on a 5-year reburn would be much lower than with the initial burn. A 10-year reburn cycle would also have less costs than the initial prescribed burn. However, the 10-year reburn costs would be more on the order of 80% of the initial costs, as fuel loads would be starting to approach those of the preburn condition (R. Summers, unpublished data, 2003). We use these cost factors in our calculation of the present value of the 5- and 10-year burning cycles.

[40] Table 5 displays the results of a net present value analysis of the watershed and recreation cost savings with a 5- and 10-year fire interval over a 20-year time period. We selected 20 years since this is the average time in our dataset between wildfires. This analysis compares the sediment reduction benefits from a wildfire in year 20 with, and without prior prescribed burning on a 5-year and 10-year cycle (it is possible that prior prescribed burning would reduce the likelihood of a wildfire or reduce the extent of the area burned by a wildfire; we are not able to quantify these benefits). Using the sediment reductions from Table 3, we calculated the amount of sediment that would come off in year 20 from a wildfire with no prior prescribed burning versus what would come off in year 20 with a 10-year and 5-year prescribed burning program. Using the reduced cost of sediment removal, the benefits in year 20 from a 5-year fire interval are $281,046 and $180,768 with a 10-year fire interval. Using the USDA Forest Service discount rate of 4%, this yields a present value of cost savings 20 years from now of the 5-year fire interval of $128,266 and $82,500 for a 10-year fire interval. Note these cost savings do not include additional cost savings from prescribed burning such as avoiding watershed rehabilitation after wildfire (e.g., hydroseeding) or emergency infrastructure protection.

[41] To this we add the present value of avoiding a recreation closure per km^2. This benefit was calculated using the recreation use data and values per day described in the previous section and experience with previous wildfire-related recreation closures in this area. Specifically, we use the data in Table 4 as well as the duration and extent of prior recreation closures due to wildfires to estimate recreation losses that would be avoided if frequent prescribed burning was used. In particular, repeated prescribed burning would reduce the severity of any wildfire and watershed damage that would occur, such that no recreation closure would be necessary. To develop the specifics, we used recreation closure duration from the Kinneloa wildfire that occurred in our study area watershed during October 1993. The Kinneloa wildfire resulted in closure of six trails in our study area for almost six months, involving 44 weekend day or holiday closures and 110 weekday closures. Using the data from the USDA Forest Service National Visitor Use Monitoring and the General Forest Area visitor use strata, we calculated the lost forest recreation use and value (using the benefit transfer valuation procedure described above). To adapt this figure to our fire interval analysis, we first calculated the loss in visitor days and value per square kilometer of the Kinneloa area ($19,286). Then this was discounted out to 20 years ($8,802), the typical wildfire interval in our data set using the USDA Forest Service discount rate of 4%.

[42] To calculate net present value (NPV), we subtracted the initial and follow-up costs of prescribed burning for the Angeles National Forest, calculated as described earlier. These costs were then discounted at 4% for the year in

Table 5. Net Present Value (NPV) of 5- and 10-Year Prescribed Burning Fire Intervals

Fire Interval, years	Present Value of Benefits/km^2: Watershed Savings	Present Value of Benefits/km^2: Recreation	PV of Prescribed Burning Costs/km^2	Net Present Value/km^2
5	$128,266	$8,802	$89,962	$47,106
10	$82,500	$8,802	$76,098	$15,204

which the reburn took place (Table 5). Just considering the watershed cost savings and recreation closure avoided, a 5-year fire interval has the highest net present value at $47,106 per km^2. A 10-year fire interval also has a positive NPV of $15,204 per km^2. However, if there are other multiple use costs associated with the shorter fire interval, then the 5-year fire interval might have a lower net present value, although whether it would be less than the 10-year fire interval is not known at this time.

6.4. Sensitivity Analysis

[43] Thus far the analysis was predicated upon certain simplifying assumptions. In particular, those watershed cost savings were represented by the average sediment removal cost, and that there were no recreation losses from prescribed burning. As a reviewer pointed out, given the wide range of sediment removal costs, areas with higher sediment removal costs might justify a shorter fire interval than areas with lower sediment removal costs. Finally, recreation use might be adversely affected by prescribed burning. This section reports on such sensitivity analyses.

[44] While sediment removal/disposal costs averaged $12 a cubic meter, sediment removal costs ranged from $2.48 to $30. To evaluate the sensitivity of the burn interval to the range of costs we used the upper 5% cost per cubic meter ($23) and the lower 5% costs ($4). Table 6 displays these results for the high and low cost. For canyons where sediment removal and disposal cost was $23 per cubic meter, the shorter 5-year fire interval has an even higher NPV, at $167,375 per km^2. For canyons with lower than average sediment removal costs ($4), the NPV of a 5 and 10-year fire interval are both negative and quite similar in size (−$37,937 for the 5 year and −$39,495 for the 10 year). Thus, in these canyons, prescribed burning could not be justified solely on the watershed cost savings, and other multiple use and property protection benefits would need to total at least $38,000 to economically justify repeated prescribed burning.

[45] With respect to the effect of prescribed burning on recreation use, to the authors' knowledge this has not been tested specifically for southern California. However, it has been tested for Colorado [*Loomis et al.*, 2001]. On the basis of that analysis, there was a 5% reduction in recreation use value (change in days time change in value per day) for hikers during the year of the prescribed burn as compared to no prescribed burn. Therefore we reduced the average recreation use values per km^2 in our study area in each year with a prescribed burn. Thus for a 5-year fire interval that would be four times over the 20-year period of analysis. For the 10-year fire interval that would be twice over the 20-year period of analysis. These results are reported in Table 6. In this scenario, the NPV is slightly negative for the 5-year fire interval (−$432 per km^2) while it is quite negative for the 10-year fire interval (−$10,888 per km^2).

7. Conclusion

[46] This research demonstrates an approach that can be used with fire frequency and erosion data to estimate a relationship between fire interval and sediment yield. In our study area in the wildland-urban interface of the San Gabriel Mountains of Southern California, we found a statistically significant relationship between fire frequency and annual sediment yield following wildfires. A 1% decrease in years between fires results in a 0.58% decrease in annual sediment yield into the debris basins. In our study area, this suggests that a 5-year fire interval would reduce annual sediment yield per km^2 from 40,843 M^3 with the current fire interval to 17,166 M^3 with a 5-year fire interval. This annual reduction in sediment would save Los Angeles County Public Works $24 million annually in terms of reduced routine and emergency debris basin clean-out costs. This $24 million in annual cost savings from avoiding wildfire induced sediment flows does not include additional cost savings from avoiding the need for postwildfire watershed rehabilitation and infrastructure protection. The inclusion of these additional cost savings from prescribed burning program would further increase the net benefits of such a program.

[47] The net present value of a 5- and 10-year prescribed burning intervals are both positive for average sediment removal costs, when recreation use is not adversely affected by the prescribed burning. When recreation benefits are adversely affected by prescribed burning, the 5-year prescribed burning interval is closest to break-even at just −$403 per km^2. However, the 5-year fire interval may be too short a time period to maintain ecological integrity and biodiversity of many native plants and associated animal species. The USDA Forest Service is required to take these other multiple use considerations into account in making fire and watershed management decisions.

[48] The broader implications of this research suggest that watershed benefits can be a substantial addition to traditional wildfire hazard reduction benefits arising from prescribed burning. Resource managers working in the wildland-urban interface should include the cost savings

Table 6. Sensitivity of NPV of 5- and 10-Year Fire Intervals to Differing Assumptions

Fire Interval, years	Present Value of Benefits/km^2: Watershed Savings	Present Value of Benefits/km^2: Recreation	PV of Prescribed Burning Costs/km^2	Net Present Value/km^2
	Upper 5% Cost of Sediment Removal			
5	$248,535	$8,802	$89,962	$167,375
10	$159,857	$8,802	$76,098	$92,561
	Lower 5% Cost of Sediment Removal			
5	$43,223	$8,802	$89,962	−$37,937
10	$27,801	$8,802	$76,098	−$39,495
	Loss of Recreation Benefits from Prescribed Burning			
5	$128,266	−$38,735	$89,962	−$432
10	$82,500	−$17,290	$76,098	−$10,888

from less sediment clean out, reduced watershed rehabilitation costs, and avoided recreation area closures when performing economic evaluations of prescribed burning.

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