Use of *FARSITE* for Simulating Fire Suppression and Analyzing Fuel Treatment Economics

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Abstract

A module was developed to simulate the effects of suppression on fire growth in *FARSITE*. This capability provides one component of a simulation system that could ultimately be used for analyzing fire management operations and planning alternatives. Both ground and air attack have been incorporated. An example application is described for the Camp Creek Watershed in the foothills of the Sierra Nevada, California. This area is typical of the wildland-urban intermix, a situation with the greatest potential financial consequences of wildland fire. The effectiveness of suppression attack on a wildfire was simulated for two management scenarios: one with the current fuel conditions and one with a modest 15-year program of fuel treatments on public lands. Costs to both scenarios associated with fuel management and fire suppression were estimated. Crew availability and arrival times were estimated from experience in this area. The simulation showed that fuel treatments with the specified effects on fuel structure did slow fire growth and thereby allowed attack resources to contain the fire more quickly. The economic analysis supports the idea that a fuel management program can reduce costs of suppressing wildfires and damages in adjacent lands.

Introduction

The *FARSITE* fire growth model (Finney 1994, 1998) is increasingly used as a planning tool for exploring effects of fuel management options on fire growth (Stephens 1995). It has also been used to demonstrate consequences to fire behavior of specific fuel treatments (Van Wagtendonk 1996). The value of using *FARSITE* is its ability to mechanistically model fire growth with complex fuels, weather, and topography. *FARSITE* uses the same fire behavior models most fire managers are familiar with in the BEHAVE program (Andrews 1986) and displays color maps of fire behavior across a landscape. The deterministic nature of *FARSITE* simulations allows the results to be directly related to the causative factors.

A natural progression of these simulations is to attempt to address their broader implications to fire suppression effectiveness and fuel management economics. Large fires (e.g. ones that escape initial attack) are of primary concern because of their expense and damage but are difficult to model in a generic way or to predict in terms of economic implications (Dimitrakopolous and Martin 1988). Efforts to do this have required computerized tools such as FOCUS (Bratten and others 1981), FEES (Mills and Bratten 1982), CFES (Fried and others 1988), NFMAS (USDA Forest Service 1987). None of these models, or other approaches to fire and fuel management economics (Maxwell and others 1983, Murphy 1972, Omi 1977) are spatially explicit or consider directly the effects of a heterogeneous fire environment on suppression or fire size. The heterogeneity of many landscapes and variability of weather patterns is too complex for analytical methods of fire growth (Van Wagner 1969, Catchpole and others 1982, 1992, Anderson 1983) as well as for fire suppression (Anderson 1989, Fried and Fried 1996). A simulation can, however, accommodate highly heterogeneous conditions and represent both fire growth and suppression effects in a detailed manner.

As a step toward the goal of more comprehensive fire planning, a new module has been developed for *FARSITE* to simulate suppression actions. The simulated ground attacks are capable of responding to heterogeneous fuels and topography as well as the changing fire front. Air attack applies a length of retardant pattern by coverage level; it remains effective in stopping fire growth for a specified time period. Not all factors known to affect line construction or retardant can be simulated, however. There are still many unknowns and inconsistencies in studies of line construction (Hirsch and Martel 1996). The approach used for initial attack simulation is therefore simple and deterministic. Its parameters are limited to those that can be determined by the user and which have the most supporting data on their effect on line production. The simpler methods also limit the number of complex interactions that can obfuscate interpretations of simulation results.

This paper demonstrates the use of the attack module developed for *FARSITE* in simulating ground and air attack on a hypothetical wildfire in the Camp Creek Watershed, Sierra Nevada, California.

Methods

FARSITE simulates fire growth using the wave-propagation method referred to as Huygens' principle. Each fire front is represented as a fire polygon. The vertices of a fire polygon are the source of fire behavior calculations for surface fire (Rothermel 1972) and crown fire (Van Wagner 1977). Huygens' principle assumes that a wave front of a given shape can be propagated from points on its edge that act as independent sources of wavelets of that same shape (Anderson and others 1982). In this case, fires are ellipses that become more eccentric with steeper slopes and faster winds (Alexander 1985). Fire size depends on spread rate. Thus, at each vertex, data on fuels, weather, and topography are obtained to calculate the size, shape, and orientation of the elliptical wavelets that determine the local spread rate and direction of the fire front (Richards 1990). The spread rate at each point is multiplied by the timestep to achieve a fixed amount of fire growth in the proper direction. The fuels and topography are input as spatial GIS raster themes and the weather is most often provided as a weather and wind stream (Finney 1998).

Attack Simulation

Attack simulation requires the user to provide realistic data on fireline production and retardant drop configurations for aircraft. The user must be able to justify the input capabilities. *FARSITE* is designed to use this information and record the use of suppression resources. The ground-based attack features of *FARSITE* include three tactics: direct, indirect, and parallel attack. Direct attack suppresses fire growth immediately at the fire edge while progressing along the fire front. Indirect attack builds impermeable fireline along a predetermined route irrespective of the fire location. Parallel attack builds impermeable fireline at a fixed horizontal distance from the fire front. Both indirect and parallel attacks can conduct burnout operations by lighting fire progressively from the advancing edge of the holding line. All attacks are conducted according to the spatial and temporal resolutions that govern fire growth. This means that line production will be sensitive at those tolerances to spatial variations in fuels and topography and to the temporal variations in fire growth (Finney 1997). The horizontal rate of line production is assumed to be constant in a plane parallel to the ground surface. The horizontal projection of this rate is however a function of the cosine of the slope. This results in less line production per unit horizontal distance up or down steep slopes than on flat terrain.

The performance of any of these ground attacks is dependent on the capabilities of an assigned crew. Crew types and their capabilities are defined by the user in terms of horizontal line production rate by surface fuel type and a flame length limit for direct attack. The user can assign any number of attacks to any number of fire fronts in the simulation. The user's discretion is required for addressing the logistics of crew arrival time and availability because these aspects are not part of the simulation.

The air attack simulation requires the user to specify for each aircraft the length of the retardant drop by coverage level. These relationships can be calculated for many types of aircraft (George 1981, 1992). The retardant pattern is buffered to the width of the distance resolution with the assumption that it is impermeable to surface fire or crown fire spread (but not spotting) for a specified time span. The user must specify the duration that the retardant will effectively stop fire spread; the retardant drop is eliminated after that time expires.

Example Application

The attack features were applied in a simulation of a hypothetical wildfire in the Camp Creek Watershed, Eldorado National Forest, California. Camp Creek is located on the Placerville Ranger District and is a major tributary to the North Fork of the Cosumnes River (fig. 1). The watershed is characterized by steep topography, late successional forests, and surface fuel complexes capable of sustaining high fire intensities when burned under severe fire weather conditions (Sapsis and others 1996). The inner gorge runs in a westerly direction that opens to the Sierra Nevada foothills at the confluence of Camp and Sly Park Creeks.

Camp Creek comprises the largest contiguous parcel of USDA Forest Service land among the surrounding private holdings (fig. 1). Ownership is a mixture of National Forest, industrial private timberlands, and small private parcels, some of which have been developed for housing. Camp Creek is representative of the wildland-urban intermix typical of the Sierra Nevada foothills. Thus, fire managers in this area have been greatly concerned about fuel hazards in and around the developed areas, particularly to the north of Camp Creek. Surface and crown fuels on all lands contribute to a relatively continuous fuel complex with the potential for broad destruction and loss of life if a fire should occur under extreme conditions. The foothills

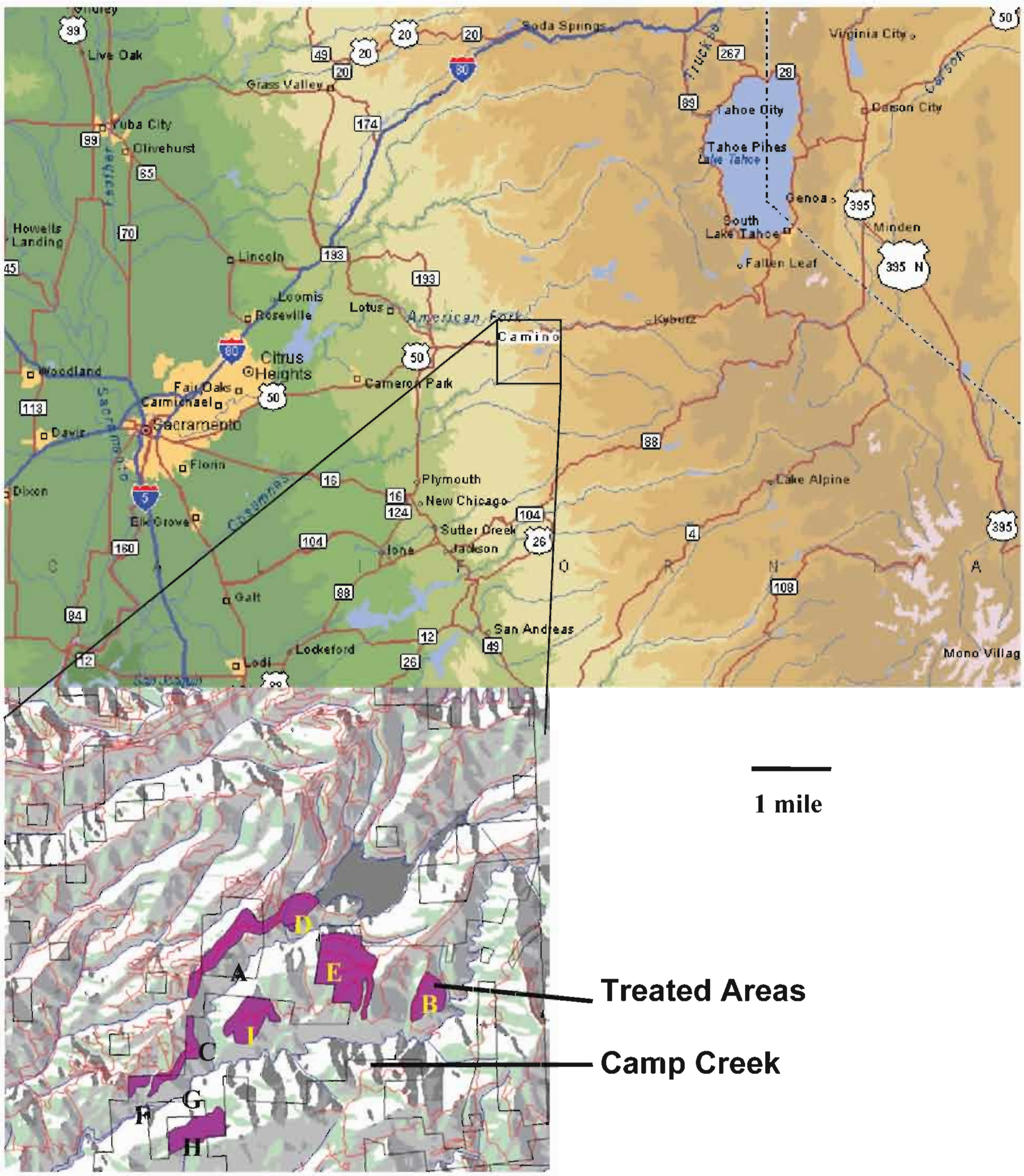


Figure 1*. Location map of Camp Creek near the Cosumnes River in the Sierra Nevada Foothills (A). Close-up view of Camp Creek watershed showing the simulated fuel treatment areas (B). Descriptions of each treatment unit (A-I) are listed in table 1.*

of the central and northern Sierra Nevada are in general prone to these kinds of fires (i.e., Stanislaus Complex 1987, Forty-Niner Fire 1988, Fountain Fire 1992, and Cleveland Fire 1994) and result in losses up to several 100 million dollars.

The ridge to the immediate north of Camp Creek is populated with thousands of single family homes and three major subdivisions that include Gold Ridge Forest, Sly Park Hill, and Sierra Springs. These areas are known to be at risk from wildfire occurring in the Camp Creek watershed and adjacent lands. Recent real estate listings suggest values in these areas are characterized by moderately valued homes ($110,000 to $200,000). Many of the older homes, 20 to 30 years old are two bedroom, one bath and were originally summer homes or second homes for families in Sacramento Valley and Bay Area. Parcel size in the area ranges from 1/4 acre to 1.5 acres for approximately 50 percent of the homes, 45 percent are situated on 3 to 10 acre parcels and the last 5 percent are on parcels larger than 25 acres. Civic Codes and Regulations (CC & R's) for many homes in the organized sub-divisions such as Sierra Springs and Gold Ridge Forest include cedar shake roofs and green islands of vegetation between homes for privacy screening.

The question addressed in this example was: "What are the economic implications and effectiveness of a modest fuel treatment program conducted largely on Federal lands around Camp Creek under severe wildfire conditions?" Two fire simulations were performed: one with no fuel management and the second with surface and crown fuels modified to reflect 15 years of fuel management efforts. Treatments consisted of commercial thinning and slash and surface fuel reduction by burning similar to some of those examined by Van Wagtendonk (1996) (fig. 2). Mechanical thinning was necessary to reduce the crown bulk density (from 0.26 to 0.15 kg m^{-3}) and thereby elevate the threshold for transition to active crown fire (Van Wagner 1977), and to raise the effective crown base height (from 1 m to 4 m) to vertically separate the aerial and surface fuels and reduce the potential for transition from a surface to crown fire. Important to these modifications was the removal of the smaller trees with low crown foliage, ladder fuels, and some co-dominant trees that formed a continuous crown layer. Despite the emphasis on smaller trees, actual timber sale data confirm that enough merchantable timber was harvested to largely offset the cost of mechanical thinning. We assumed that this initial treatment cost $120/acre on Forest Service lands, and $200/acre on private lands. Prescribed fire was necessary to dispose of logging slash and consume pre-existing surface fuels. Maintenance treatments at 7-year intervals were required to limit accumulations of surface fuels and development of understory ladder fuels and assumed the use of broadcast understory prescribed fire at a cost of $60/acre (table 1).

Treatment units were located strategically to anticipate wildfires spreading out of Camp Creek to the north. The inaccessibility and fuel hazard in the drainage itself is considered a threat to the surrounding developed lands. The treatment units were primarily located on Federal lands, although a minor portion of some treatments was extended to adjacent private lands assuming cooperation with landowners. The spatial arrangement of the treatments was designed to be practical from both an operational and financial perspective. Treatments were discrete units, located on gentle topography, ridge tops, and in relation to existing roads. These treatments were not intended to be permanent "fuel-breaks" (Omi 1996), but instead dynamic parts of a landscape mosaic that is managed and perhaps extended as a spatial rotation of treatments.

The fire simulation scenario was devised to reflect a combination of factors that represent a realistic and serious threat to developed properties to the north of Camp Creek. This scenario consisted of historically common ignition sources, start locations, extreme fire weather

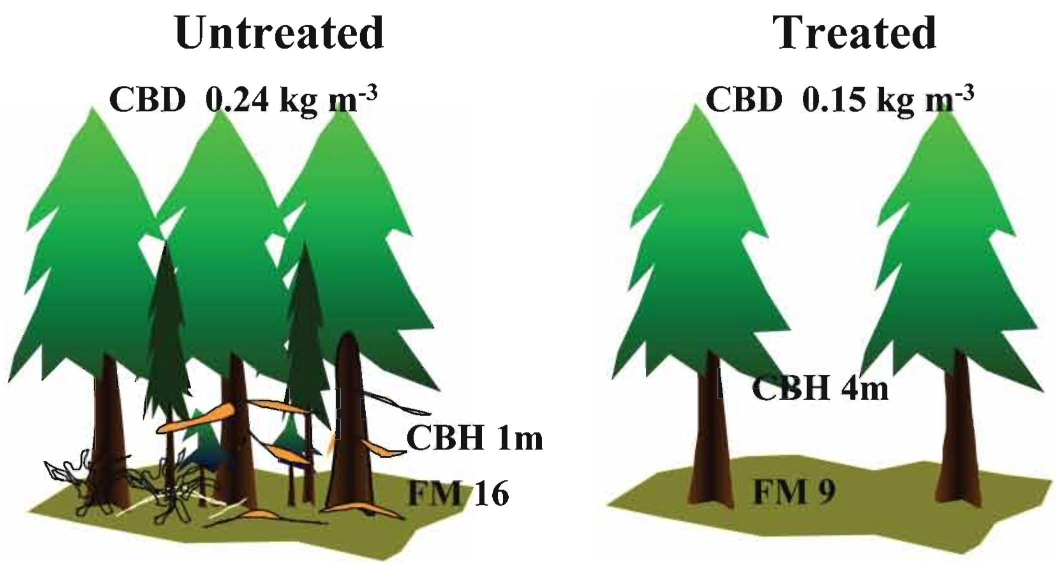


***Figure 2**. Illustration of fuel conditions in treated and untreated areas. Treatments thinned smaller trees to increase crown base height (m) and some larger trees to reduce crown bulk density (kg m^{-3}). Surface fuels were prescribed burned.*

***Table 1.** Costs and schedule of fuel treatments and maintenance for the Camp Creek Watershed example.*

Unit[1]	Size (ac)	Ownership	Initial treatment (years before present)	Maintenance treatment (years before present)	Present net cost of treatments[2]	Present cost of perpetual maintenance[3]	TOTAL
A	120	FS[4]	15	8, 1	$ 49,381	$ 17,686	**$ 67,067**
B	80	FS	13	6	$ 25,288	$ 11,791	**$ 37,079**
C	60	FS	10	4	$ 16,593	$ 8,843	**$ 25,436**
D	90	Private	9	2	$ 37,847	$ 22,108	**$ 59,865**
E	220	FS	8	1	$ 54,490	$ 32,424	**$ 86,914**
F	50	FS	6	--	$ 8,376	$ 7,369	**$ 15,745**
G	20	FS	5	--	$ 3,191	$ 2,948	**$ 6,139**
H	160	FS	3	--	$ 23,153	$ 23,581	**$ 46,734**
I	140	FS	1	--	$ 18,375	$ 20,634	**$ 39,009**
TOTAL	**940**				**$ 236,694**	**$147,384**	**$384,078**

[1] Unit locations on Figure 1.
[2] Based on 5% discount rate; costs for treatments discussed in text
3 Present value of a perpetual series of payments ($60/ac USDA Forest Service, $100/ac private) on a 7-year interval.
[4] UDSA Forest Service.

conditions, and fire timing. The fire was ignited by humans in the early evening (1800 hours) on August 3rd along one of the forest roads on the north side of Camp Creek. Weather for the following two days consisted of high temperatures of 95 ºF with lows of 70 ºF. Relative humidity varied from 35 percent in the morning to 10 percent by afternoon. Overstory winds became strong each afternoon (20-25 mph) and did not subside (10 mph) until about 0300.

Suppression resources arrived and began their attack beginning around 2000 hours with air support for the remaining 2 hours of daylight. Various line production rates were assumed for the different crew types (table 2). Retardant was assumed effective for 2 hours at coverage level 4. A moderate draw-down of regional suppression resources was assumed to somewhat limit resource availability. Direct and parallel attacks with helicopter support were initiated along the backing and rear-facing flanks, progressing toward the head of the fire. Indirect attacks were used along the east and south flanks (table 3).

To illustrate the potential of this kind of simulation, an economic analysis was conducted. Two relevant statistics were determined: the benefit-cost ratio of the treatments, and the positive benefit period (time during which fuel treatment expenses are economical). The benefits were calculated as the present net value of the difference between the costs of the two scenarios assuming a discount rate of 5 percent. The costs of fuel treatments used in the analysis was the combined present value of the treatments and the present value of the future maintenance costs. Because of the large difference between the suppression costs alone and the total of suppression costs plus damages, benefit-cost ratios were calculated for each separately.

Table 2. *Fireline production rates (chains/hour) for crew types by fuel model.*

	Fuel Model							
Crew Type	**1**	**2**	**5**	**8**	**9**	**10**	**16** Custom model, untreated fuels timber with shrub understory[2]	**26** Custom model, montane chaparral [2]
Hotshot crew[1]	20	20	4	15	15	6	6	5
CDF/CDC crew[1]	15	15	3	12	12	4	4	3
Type II dozer	100	100	40	90	85	15	15	40
Type III engine	5	5	2	4	4	2	2	2

[+]assumes helicopter support [++]see Sapsis and others 1996

Table 3. Chronology of suppression activities. Ground resources are cumulative. Aircraft usage is by 2-hour period

Date/Time	No Fuel Treatments		Proposed Fuel Treatments	
August 3rd				
1800	Fire Starts		Fire Starts	
2000	4 Type III engines 1CDF/CDC crew[1] 4 drops[2], 4 drops[3]	Direct and parallel attack on west flank and along ridge to the north	4 Type III engines 1CDF/CDC crew[+] 4 drops[2], 4 drops[3]	Direct and parallel attack on west flank and along ridge to the north through the fuel treatments
2200	4 CDF crews[1] 1 Hotshot crew[1] 1 dozer	dozer and 2 crews build line along ridge to north 2 crews begin parallel attack on south flank	4 CDF crews[+] 1 Hotshot crew[+] 1 dozer	dozer and 2 crews build line along ridge to north 2 crews begin parallel attack on south flank
August 4th				
0200	4 hotshot crews[1]	Addition crews to north flank, burnout from roads	4 hotshot crews[+]	Additional crews to north flank, burnout from roads
0400				
0600	8 CDF crews[1] 8 hotshot crews[1] 4 dozers 4 drops[2], 6 drops[3]	1 dozer to south ridge, indirect 4 crews parallel on south flank	7 CDF crews[+] 8 hotshot crews[+] 4 dozers 4 drops[2], 4 drops[3]	1 dozer to south ridge, indirect 4 crews parallel on south flank
0800	4 drops[2], 6 drops[3]		4 drops[2], 4 drops[3]	
1000	4 drops[2], 6 drops[3]		2 drops[2], 4 drops[3]	
1200	12 CDF crews[+] 4 drops[2], 8 drops[3]	Crews retreat to north and east flanks with high winds and extreme burning conditions	7 CDF crews[+] 2 drops[2], 6 drops[3]	Crews hold line on north and north-east flanks
1400	2 drops[2], 8 drops[3]		2 drops[2], 6 drops[3]	
1600	15 CDF crews[+] 2 drops[2], 8 drops[3]		2 drops[2], 6 drops[3]	
1800	12 Hotshot crews[+] 2 drops[2], 8 drops[3]	Winds subside and crews work north and east flanks	12 hotshot crews[+] 2 drops[2], 6 drops[3]	crews concentrate on south and south-east flanks
2000	2 drops[2], 8 drops[3]			
August 5th				
0400				
0600	2 drops[2], 8 drops[3]		2 drops[2], 5 drops[3]	
0800	Fire Contained		2 drops[2], 4 drops[3]	
1000			Fire Contained	
1	helicopter support			
2	800 gallon retardant drop			
3	3000 gallon retardant drop			

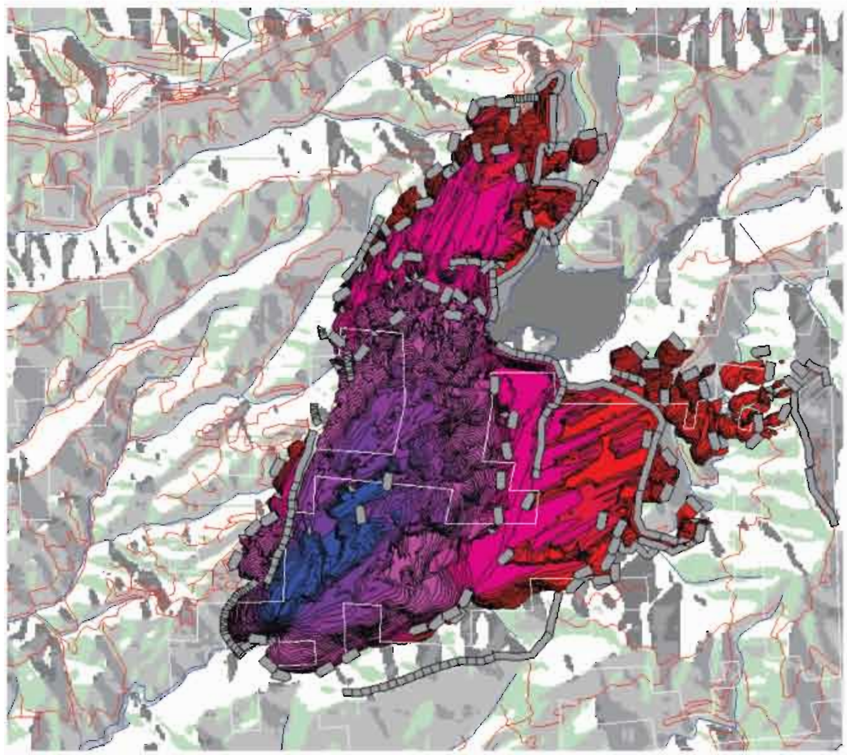
Results

The suppression module added to *FARSITE* was useful in representing an array of realistic tactics. Line production varied noticeably by fuel type and slope. Travel routes by direct and parallel attacks responded as intended to fire activity. Without automating these capabilities, it would have been impossible to effectuate suppression action in the fire simulation. Air attacks were effective at slowing head fire growth by forcing the fire to flank around retardant patterns. Additional benefit from retardant drops included relocation of ground forces to more active portions of the fire's perimeter, thus increasing the containment rate along the fire perimeter.

The two simulated fires grew to 3,440 acres with the fuel treatments and 6,460 acres with no fuel treatments. Both simulations showed fire growth and suppression were similar along the backing and flanking portions of the fires (fig. 3). The areas where fuels were treated, however,

A.

1 mile



B.

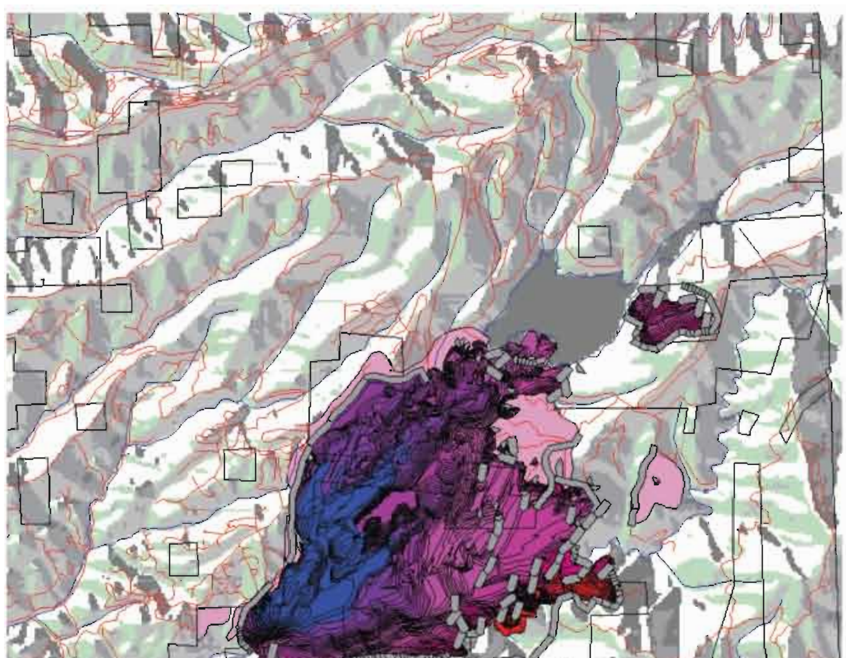


Figure 3. *Simulation results August 3rd-5th. Fire growth and suppression patterns with no fuel treatments (6,460 ac, perimeter 40 miles) (A), and with fuel treatments (3,440 ac, perimeter 23 miles) (B).*

required fewer resources for suppression because slower spread rates and lower intensities permitted line construction closer to the fire edge (ultimately requiring less line construction), and because lighter fuel loading facilitated faster line construction than in adjacent untreated areas. With fewer resources needed in the treated areas, the remaining resources were free to attack other portions of the fire front. This led to faster containment of the fire during the nighttime and morning hours because crews were directed to construct fire line to link the patches of treated areas. In general, the spatial arrangement of non-contiguous treatment areas was an effective asset to suppression because the method of suppression effort could be flexible about joining the most appropriate treatment units.

The fuel treatments showed a substantial benefit to the suppression effort at the head and forward flanks of the fire in both direct and indirect ways. First, the treated areas directly slowed the heading fire by restricting it to a surface fire with lower intensity than in unmanaged surface fuel. The mechanical removal of ladder fuels and thinned crowns also prevented wholesale torching and crowning in these areas and allowed suppression crews to perform parallel attacks rather than indirect attack. Second, the absence of crown fire activity in the treated areas indirectly aided suppression by limiting the generation of embers from torching trees. In the untreated units, these embers ignited subsequent spot fires down wind approximately ¼ to ½ mile and required longer times and more crews for their containment.

The fuels treatments were also apparently effective in helping to prevent losses of homes and private property in the developed subdivisions near the head of the fire. Many homes were assumed lost in the no-treatment scenario when weather conditions became more extreme during the burning period of the following day. High winds drove the fire over the containment lines to the north and east because holding actions in these areas were not completed by that time (in contrast to the treatment scenario). The escaped fire then caused spotting into the residential areas and resulted in an estimated loss of 240 homes compared to 8 homes lost with the fuel treatments. A total of 10 strike teams (5 Type I engines in each) were assigned to the subdivisions because of the imminent threat of uncontrolled fireline compared to 3 strike teams in the scenario with those treatment units.

Costs for the two situations suggested that the greatest differences occurred because of residential property, regardless of whether it was destroyed or merely threatened by the fires. The greatest losses occurred because high value residential property (homes, automobiles, outbuildings, land improvements) was destroyed in the subdivisions. Timber values came in second, primarily because conservative estimates of damages were used to account implicitly for legal and aesthetic proscription of salvage logging on some of the burned forest lands. Although property losses greatly exceeded the costs of suppression, suppression costs themselves were affected by the presence of residential areas. For example, the assignment of Type I engines for structural protection in residential areas was expensive in the no-treatment scenario (10 strike teams; table 4). Type I engines were also assigned in the treatment scenario, but only three strike teams were needed because wildland crews contained the fire before it arrived at the subdivisions.

The fuel treatments contributed to an estimated benefit-cost ratio of 1.47 to 2.94 for suppression costs alone (table 5). Including damages and losses, the benefit cost ratio was 29.8 to 59.6 (table 5). These figures assumed a 50- to 100-year average fire return period for calculating average annual savings (difference between treatment and no-treatment scenarios). Alternately, the positive benefit period was calculated as 147 years for suppression costs only and 2,977 years for combined suppression costs and damages.

Table 4. *Estimated fire costs by treatment scenario.*

Item/Action	**No fuel treatments**		**Proposed fuel treatments**	
Fuel treatments				
Thinning, burning	No acres treated	0	940 ac (present value, table 1)	236,694
Suppression costs				
Type I engines	**50 engines** (10 strike teams) 72 hours ($600/hr)	2,160,000	**15 engines** (3 strike teams) 72 hours ($600/hr)	648,000
Type III Engines	**25 engines** ($85/hr) 156 hrs line building 600 hrs travel 400 hrs logistics 2000 hrs mopup	 13,260 51,000 34,000 170,000	**20 engines** ($85/hr) 30 hrs line building 480 hrs travel 320 hrs logistics 960 hrs mopup	 2,550 40,800 27,200 58,650
Dozers	**4 dozers** ($50/hr) 50 hrs 96 hrs travel 64 hrs logistics	 2,500 4,800 3,200	**4 dozers** ($50/hr) 30 hrs 96 hrs travel 48 hrs logistics	 1,500 4,800 2,400
Hotshot	**12 crews** ($300/hr) 208 hrs line 144 hrs travel 192 hrs logistics 840 hrs mopup	 62,400 43,200 57,600 252,000	**12 crews** ($300/hr) 144 hrs line 144 hrs travel 144 hrs logistics 504 hrs mopup	 43,200 43,200 43,200 151,200
CDF/CDC	**15 crews** ($300/hr) 235 hrs line 120 hrs travel 240 hrs logistics 1050 hrs mopup	 70,500 36,000 72,000 315,000	**7 crews** ($300/hr) 78 hrs line 84 hrs travel 84 hrs logistics 336 hrs mopup	 23,400 25,200 25,200 100,800
Overhead	**8 days** ($150,000/day)	1,200,000	**6 days** ($100,000/day)	600,000
Water tenders	**8 days** ($1,800/day)	14,400	**6 days** ($1,800/day)	10,800
Aircraft 800 gal 3000 gal	 **30 loads** ($2,000/load) **68 loads** ($5,000/load)	 60,000 340,000	 **26 loads** ($2,000/load) **49 loads** ($5,000/load)	 52,000 245,000
Helicopters (1 Type III & 2 type II)	**5 days** ($13,800/day)	69,000	**4 days** ($13,800/day)	55,200
Suppression Sub-Total	**$5,030,860**		**$2,204,300**	
Property damage				
Timber	6,460 acres ($2000/ac)	12,900,000	3,440 acres ($2,000/ac)	6,880,000
Homes	240 homes ($160k/home)	38,400,000	8 homes ($160k/home)	1,280,000
Property	240 homes ($ 50k/home)	12,000,000	8 homes ($50k/home)	400,000
Burn Rehabilitation	6,460 acres ($10/ac) 40 miles perimeter	64,600	3,440 acres ($10/ac) = 23 miles perimeter	34,400
Property damage Sub-Total		**$63,384,600**		**$8,594,400**
TOTAL		**$68,451,460**		**$11,035,394**

Table 5. *Benefit cost analysis of fuel treatments for Camp Creek (discount rate 5 percent). Positive benefit period is the maximum fire interval over which a financial benefit is achieved by fuel treatment.*

A. Suppression costs only			
	Present value of fuel treatment costs[1]	**Present value of suppression cost difference (Benefit) [2]**	**Benefit/ Cost ratio**
Assumed 50 year fire return interval.	236,694+ 147,384= **$384,078**	$2,826,560*0.02 = **$1,130,624** 0.05	2.94
Assumed 100 year fire return interval.	236,694+ 147,384= **$384,078**	$2,826,560*0.01 = **$565,312** 0.05	1.47
Positive Benefit Period		**$2,826,560** **$384,078*0.05**	**147 yrs**
B. Combined damages and suppression costs			
Assumed 50 year fire return interval.	236,694+ 147,384= **$384,078**	$57,183,082*0.02 = **$22,873,232** 0.05	**59.55**
Assumed 100 year fire return interval.	236,694+ 147,384= **$384,078**	$57,183,082*0.01 = **$11,436,616** 0.05	**29.77**
Positive Benefit Period		**$57,183,082** **$384,078*0.05**	**2977 yrs**
	1. From table 1.	2. From table 4.	

Discussion

The addition of the suppression capabilities to *FARSITE* opens up the possibility for improving the analysis of fuel management effectiveness. Specific spatial arrangements of fuel modifications can be subjected to many simulated fire scenarios. When combined with estimates of the associated costs and fire losses, it has the potential for use in economic analysis of fire and fuel management alternatives. The application of these capabilities to the Camp Creek Watershed was our first attempt to use a mechanistic simulation for examining the effectiveness and economics of fuel management on a landscape basis. Obviously, more simulations for Camp Creek (e.g., fire locations, weather conditions) would be required to develop confidence in the results. However, the outcome of this work is easily interpretable and serves as a basis for further development and critique of the methods.

The economic analysis of fuel treatments, suppression costs, and fire damages suggested that for every dollar spent on fuel treatment in this urban-wildland intermix area, somewhere between $1.47 and $2.94 would have been saved in suppression costs alone (table 5). This assumed a 50- to 100-year fire free period and was intentionally shorter than the 185 year modern average fire rotation (1908-1992) for ponderosa pine (McKelvey and Bussy 1996). Non-randomness of human-caused ignitions and local fire experience suggest that Camp Creek would be at greater risk than reflected in the average fire rotation value. The actual fire interval at Camp Creek would have to be less than the 147 year positive benefit period to save on suppression costs. A greater potential savings, however, resulted when the benefit-cost figures were calculated for the combined suppression costs plus losses (table 5). The relatively huge losses contributed to much greater benefit cost ratios (29 to 59) and a positive benefit period of 2,977 years. Thus, if this analysis is correct, fuel treatments would almost always produce a financial benefit given the high value of the resources in this area and the near certainty that severe fires will happen. Fires in the simulated size range (3,440 to 6,460 acres) have been relatively common, occurring once every 5 to 10 years on a given National Forest since 1908 (Erman and Jones 1996).

The proposed treated areas were intended to be practical and proved to be effective in modifying the simulated fire behavior. First the dispersed pattern was probably the least expensive way to accomplish the treatments because the units were located along existing roads and situated on gentle topography so that efficient mechanized harvesting could be used. Second, the treatments were placed strategically in anticipation of threats to high value areas. The high value of residential subdivisions required that fuel treatments should occur between the identified hazard and the values at risk, yet primarily on Forest Service lands that were not contiguous on this landscape. Third, the dispersal of treatment units throughout an area increased their proximity to likely ignition locations. Having treated areas close to an ignition location is helpful in restricting initial spread along one or more flanks and improving the effectiveness of initial attack. Finally, the dispersal of treatment units did fragment the burning landscape and interrupt the potential routes of heading fire spread, which is the fastest and most intense portion. It was obvious in these simulations that the treatments served as localized impediments to the wind driven head fire and thus required the fire to flank around the slower-burning fuels. Although individual units smaller than a fire can and were bypassed (Dunn 1989, Weatherspoon and Skinner 1996), the collective effect of many such units slowed the overall forward fire spread rate. Regardless of their arrangement, the fuel treatments reduced spotting because torching and crowning was limited by the modifications to both surface and crown fuels.

The simulated fuel treatments also proved to be effective at assisting fire fighting operations. Even though the treatment areas were discontinuous and relatively small (the largest being about 300 acres), their strategic placement allowed suppression forces to dynamically connect these treatments by firelines. Faster line construction and burnout was possible in the treated areas; this freed resources for constructing line along other sectors of the fire front. The presence of treated areas reduced the distance and time spent constructing fire line between treated areas in more difficult untreated fuel types. The strategic use of different fuel types was similar to the common practice of using natural landscape features to assist line construction and fire containment (i.e., lakes, streams, ridges, rock outcrops). More importantly, because fuel treatments can be tailored to a particular management situation, it suggests a landscape-level pre-fire strategy that would involve arranging patches of managed fuels for use as links in a chain that suppression forces could join together by fireline at the time of a fire.

Although linear "fuel breaks" are being resurrected in discussions about landscape-level fuel management (Omi 1996, Weatherspoon and Skinner 1996), the dispersed pattern of treated areas could be more flexible in limiting the spread of fires. Assuming dispersed- and network-type fuel arrangements occupy the same fraction of a landscape, dispersed patterns can have shorter distances between the treatments. This increases the amount of treated area encountered at a given time by a random fire on the landscape. Proximity then becomes important because weather conditions typically determine when suppression efforts become effective on large fires and consequently where the fire front is located on a landscape at that time. By increasing the proximity of many treatment units to the fire, the dispersed pattern offers a spatial flexibility for opportunistic use by suppression crews. Multiple treatment units near the fire's edge can be connected. By contrast, the greater chance of weather affecting a fire somewhere between widely spaced fuel breaks means it must be controlled directly without the benefit of treatments or indirectly with large burnout operations. Further research, however, is badly needed for assessing the practical implications of these practices and for comparing the effectiveness of the many spatial arrangements of fuel treatments and their maintenance.

A primary assumption of the suppression simulation and this analysis was that the incident management team for the simulated fires were aware of the fuel situation, specifically the locations and condition of the treated areas with respect to fire behavior. This intelligence would be vital for incorporating treatments into suppression strategies. Without this information, the treated areas may be unknown to all but crews assigned to a particular sector of the fire perimeter.

Conclusions

These simulations showed that it is possible to begin assessing the effectiveness of an explicit fuel management program in terms of costs and benefits. More work is needed to replicate this kind of analysis with more potential fire scenarios and in other landscapes that have different values at risk. Ultimately a goal of this kind of mechanistic simulation is to identify and perhaps optimize appropriate landscape-level fuel arrangements that can be put into practice. This is made difficult by the many factors that cannot be predicted for a given fire, namely its start location, burning conditions, crew availability, and suppression strategy. However, it is hoped that the development of realistic tools for simulating the consequences of management activities can lead to better decisions regarding fuel and fire management.

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