

fire

Quantifying the Potential Impacts of Fuel Treatments on Wildfire Suppression Costs

Matthew P. Thompson, Nicole M. Vaillant, Jessica R. Haas, Krista M. Gebert, and Keith D. Stockmann

Modeling the impacts and effects of hazardous fuel reduction treatments is a pressing issue within the wildfire management community. Prospective evaluation of fuel treatment effectiveness allows for comparison of alternative treatment strategies in terms of socioeconomic and ecological impacts and facilitates analysis of tradeoffs across land-management objectives. Studies have yet to rigorously examine potential impacts to fire suppression expenditures associated with prior hazardous fuel reduction treatments. Such information would be helpful for federal land-management agencies struggling to contain escalating wildfire management costs. In this article we establish a methodology for estimating potential reductions in wildfire suppression costs. Our approach pairs wildfire simulation outputs with a regression cost model and quantifies the influence of fuel treatments on distributions of wildfire sizes and suppression costs. Our case study focuses on a landscape within the Deschutes National Forest in central Oregon that was selected to receive funding under the auspices of the Collaborative Forest Landscape Restoration Program. Results suggest substantial reductions in distributions of wildfire size and suppression cost on a per fire basis. Furthermore, because fewer ignitions become large fires on the treated landscape, distributions of annual area burned and annual suppression costs also shift downward because of fuel treatments. Results are contingent on four key factors: large-scale implementation of fuel treatments across the landscape, assumed treatment effectiveness over the duration of the analysis period, accuracy of wildfire and cost models, and accuracy of projected changes to fire behavior fuel models resulting from fuel treatments. We discuss strengths and limitations of the modeling approach and offer suggestions for future improvements and applications.

Keywords: wildfire management, hazardous fuels, suppression cost, risk assessment

Modeling the impacts and effects of hazardous fuel reduction treatments is a pressing issue within the wildfire management community. Prospective evaluation of fuel treatments allows for comparison of alternative treatment strategies in terms of socioeconomic and ecological impacts and facilitates analysis

of tradeoffs across land-management objectives (Stockmann et al. 2010). Although much attention has been focused on assessing how fuel treatments affect expected loss to highly valued resources and assets (e.g., Ager et al. 2007), some have also suggested benefits from fuel treatments in terms of avoided suppression costs (Snider et al.

2006). However, studies have yet to rigorously examine potential impacts to fire suppression expenditures associated with prior hazardous fuel reduction treatments.

In this article, we present a methodology for estimating potential reductions in wildfire suppression costs. Our approach pairs wildfire simulation outputs with a regression cost model and quantifies the influence of fuel treatments on distributions of wildfire sizes and suppression costs. Our framework is based on emerging applications of wildfire risk science to inform decisionmaking (Calkin et al. 2011a) and adopts wildfire cost modeling methods illustrated by Thompson et al. (2012a). Estimates of suppression cost reductions can ultimately be compared with treatment costs within a cost benefit framework.

Motivation for this study stems from four important sources. First, escalating USDA Forest Service wildfire management costs have and may continue to result in reduced budgets and potentially disruptive within-season borrowing to nonfire programs, challenging the ability of the agency to meet societal needs and maintain forest health (Thompson et al. 2012a). Recent legislative action has attempted to address this

Received March 29, 2012; accepted October 5, 2012; published online November 1, 2012.

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Acknowledgments: The authors thank Deschutes National Forest staff, especially Tom Mafera and Dave Owens. They are also grateful to Amy Waltz of The Nature Conservancy, who was helpful in the initial stages of this project, and Amy Steinke and Julie Gilbertson-Day for data analysis. Additionally, the National Fire Decision Support Center supported this effort.

fiscal problem, in part, by targeting proactive reduction of hazardous fuels. Title IV (Forest Landscape Restoration) of the Omnibus Public Land Management Act of 2009 established the US Forest Service Collaborative Forest Landscape Restoration Program, which funds up to 50% of fuel reduction and ecological restoration treatment implementation and monitoring costs for competitively selected proposals. Language in the act specifically calls for use of funds to “facilitate the reduction of wildfire management costs, including through reestablishing natural fire regimes and reducing the risk of uncharacteristic wildfire” and that selected projects will “affect wildfire activity and management costs.” Thus, there is significant interest in understanding how fuel treatments may provide opportunities to reduce future suppression costs.

Second, suppression costs are known to be positively and highly correlated with fire sizes and area burned. Calkin et al. (2005) reviewed trends in area burned and suppression expenditures across 1970–2002 and reported a positive correlation coefficient of 0.76. Liang et al. (2008) examined 16 potential nonmanagerial factors (representing fire size and shape, private properties, public land attributes, forest and fuel conditions, and geographic settings) and found that only fire size and private land had strong effects on suppression costs. All other things being equal, suppression costs were shown to increase monotonically with fire size. Thus, there is reason to believe that treating fuels to reduce fire sizes and annual area burned could lead to reduced suppression costs (although it should be said that reducing fire sizes may be neither desirable nor possible on many landscapes).

Third, modeling efforts and postfire analyses suggest that fuel treatments can significantly affect fire spread and final fire size (Stratton 2004, Finney 2007, Hudak et al. 2011). The composition and spatial configuration of fuels influence fire size distributions, which may be altered by modifying fuel availability and flammability (Cui and Perera 2008). Cochrane et al. (2012) examined the effects of actual landscape fuel treatments on likely fire spread and final fire size, focusing on 14 large wildfires that interacted with extant fuel treatments. In that study, the authors used the FARSITE fire modeling system (Finney 2004) to simulate observed wildfire progression and spread rates and, in addition, to simulate fire growth that would have occurrence in the absence of the

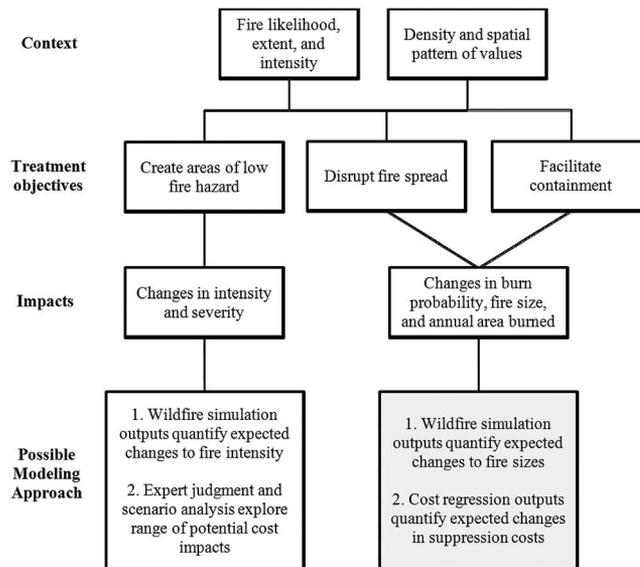


Figure 1. Conceptual framework for evaluating potential cost impacts of fuel treatments (our approach is highlighted in gray).

fuel treatments. Effects of fuel treatments on fire size were variable, although net size reductions caused by treatments were identified for 11 of the 14 wildfires, with a mean of 13.2% reduction in size. Collins et al. (2011) evaluated an actual landscape fuel treatment project on the Tahoe National Forest, and simulation results indicated substantial reductions in burn probabilities within and beyond treatment areas. Reductions in burn probabilities and fire sizes caused by fuel treatment were also reported by Ager et al. (2010), who found that increasing fuel treatment area decreased average wildfire size and intensity (see also Moghaddas et al. 2010). A critical variable influencing the effect of landscape fuel treatments on fire spread is the spatial extent of treatments (Collins et al. 2010).

Finally, fuel treatments can also lead to reductions in final fire size by providing

opportunities for enhanced suppression (Moghaddas and Craggs 2007, Graham et al. 2009, Hudak et al. 2011). In fact, in some cases fuel treatments were shown to be largely ineffective without suppression activities (Syphard et al. 2011). Reinhardt et al. (2008) caution, however, that under extreme weather conditions that often drive large fire events these mitigating effects may be overwhelmed.

Methods

Framework

The evaluation of potential cost impacts involves first modeling how treatments will impact fire behavior, and, in turn, modeling how altered fire behavior may impact suppression costs. Figure 1 provides a conceptual framework detailing how the biophysical and socioeconomic context, treat-

Management and Policy Implications

Controlling escalating wildfire management costs is a critical issue for federal land-management agencies. Fire and fuels managers can implement the modeling techniques illustrated here to better understand the likely financial impacts, in terms of changed suppression costs, of proposed fuel treatments intended to restrict fire growth, or enhance containment. Modeling results can also serve to help inform broader allocation and prioritization processes to see where fuel investments might be most effective, by comparing alternative treatment scenarios. Effective treatment implementation can result in reduced large fire sizes as well as reduced occurrence of large fires, which, in turn, can lead to suppression cost savings. Expected suppression savings (if applicable) can be compared with fuel treatment costs for financial cost–benefit analysis. Auxiliary analyses can consider how changes in fire behavior impact other socioeconomic and ecological objectives. Implementation of fuel treatments may, therefore, help achieve land and resource management goals, while simultaneously lessening future suppression cost impacts.

ment objectives, and treatment impacts relate to our modeling approach. The likelihood, extent, and intensity of fire, along with the density and spatial pattern of values at risk, jointly influence treatment strategies and design objectives (Calkin et al. 2011a). In some contexts, this may entail creating areas of low-fire intensity and hazard, and fire sizes might actually increase as part of restoring historical fire regimes. In other contexts, treatment strategies are oriented more toward resource protection and the inhibition of fire growth across the landscape.

Multiple mechanisms exist by which fuel treatments could affect suppression costs. Reduced intensity will in many contexts lead to reductions in burn severity (Martinson and Omi 2008, Wimberly et al. 2009), enabling opportunities for resource benefit and moderated suppression responses. These changes in wildfire management could in turn lead to suppression of cost reductions. However, Gebert and Black (2012) recently found that less aggressive protection strategies may ultimately lead to costs on par with or higher than more aggressive strategies, because of longer durations and increased acreages burned.

Another mechanism is the alternation of fire size distributions, which, to reiterate, are a major determinant of suppression costs. Here, we focus on fire size as a primary variable affecting suppression cost estimates (Figure 1). The foundation of our approach is the coupling of two peer-reviewed models used by the Forest Service and other federal land-management agencies: FSim (Finney et al. 2011a), a spatially explicit large fire occurrence and spread model, and a large fire cost model (Gebert et al. 2007). The use of a fire growth simulation model approach allows us to directly model disruptions in fire spread and subsequent impacts to fire size. Therefore, in our approach, all else being equal, treatments resulting in reduced fire spread will tend to decrease fire size, in turn reducing fire cost.

The effects of altered suppression strategies and containment likelihood are not well accounted for in our modeling approach. The FSim modeling system includes an algorithm that models the likelihood of containment largely as a function of fire weather. The algorithm is based on an earlier model presented by Finney et al. (2009) that also incorporates information on fuel type and fire spread, and so it is conceivable that future modeling efforts could account for modified containment likelihood as a func-

tion of reduced rate of spread. However, even this adjustment would be statistical, not mechanistic, and so it would not be possible to specifically assess potential impacts from alternative suppression tactics. Relying on expert judgment to identify where direct attack might be effective coupled with sensitivity analysis could explore a possible range of cost savings beyond those presented with our modeling approach.

Wildfire Simulation Modeling

The large fire simulation model, FSim (Finney et al. 2011a), relates to a family of fire modeling systems including FARSITE (Finney 2004), FlamMap (Finney 2006), and FSPro (Finney et al. 2011b). FSim uses the minimum travel time (MTT) fire spread algorithm (Finney 2002), producing fire growth by searching for the fastest travel paths from burning to unburned nodes. FSim combines a logistic model for ignition probability (Andrews et al. 2003) given en-

ergy release component (ERC) values, simulated temporal ERC streams with the same statistical properties as historical ERC streams, random draws of wind speed and direction given local weather history, fuel moisture conditions as a function of ERC, the MTT algorithm, and the containment algorithm, to simulate fire occurrence and spread for thousands of simulated “fire seasons.” The ensemble modeling method accounts for uncertainty surrounding multiple input variables and enables estimation of potential wildfire growth under weather conditions that may not have been observed in the limited historical record. A primary input to FSim is a landscape file containing spatial fuels and terrain information (elevation, slope, aspect, surface fuel model, canopy cover, canopy height, canopy base height, and canopy bulk density). Historical fire and weather from a representative remote automated weather station (RAWS) is also used

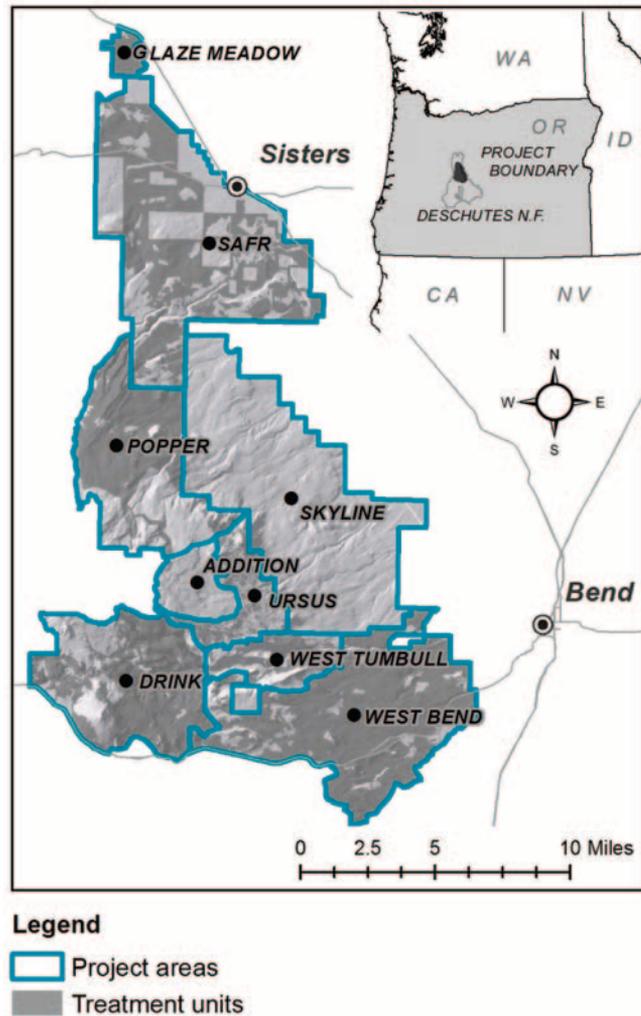


Figure 2. Map of DCFP study area, with project areas and treatment units highlighted.

Table 1. Modeled changes in burnable fire behavior fuel models (FBFM40; Scott and Burgan 2005) as a result of ongoing and planned fuel treatments.

EC fire behavior fuel model			PT fire behavior fuel model		
Block	Code	Name	Block	Code	Name
101	GR1	Short, sparse dry climate grass	101	GR1	Short, sparse dry climate grass
104	GR4	Moderate load, dry climate grass	101	GR1	Short, sparse dry climate grass
122	GS2	Moderate load, dry climate grass–shrub	121	GS1	Low load, dry climate grass–shrub
141	SH1	Low load, dry climate shrub	141	SH1	Low load, dry climate shrub
142	SH2	Moderate load, dry climate shrub	141	SH1	Low load, dry climate shrub
145	SH5	High load, dry climate shrub	141	SH1	Low load, dry climate shrub
161	TU1	Low load, dry climate timber–grass–shrub	161	TU1	Low load, dry climate timber–grass–shrub
162	TU2	Moderate load, humid climate timber–shrub	161	TU1	Low load, dry climate timber–grass–shrub
181	TL1	Low load, compact conifer litter	181	TL1	Low load, compact conifer litter
121	GS1	Low load, dry climate grass–shrub	183	TL3	Moderate load, conifer litter
165	TU5	Very high load, dry climate timber–shrub	183	TL3	Moderate load, conifer litter
183	TL3	Moderate load, conifer litter	183	TL3	Moderate load, conifer litter
185	TL5	High load, conifer litter	183	TL3	Moderate load, conifer litter
187	TL7	Large downed logs	183	TL3	Moderate load, conifer litter
188	TL8	Long-needle litter	183	TL3	Moderate load, conifer litter
184	TL4	Small downed logs	184	TL4	Small downed logs

FBFM40, Fire Behavior Fuel Model.

for time series analysis to generate synthetic weather streams and to parameterize the large fire occurrence model.

FSim produces raster format calculations of burn probability and flame length (in this case, 30-m pixel resolution), as well as vector format layers containing simulated wildfire perimeter and final fire size. Burn probability is an estimate of the likelihood of a pixel burning from a random ignition within the pixel or spread from adjacent pixels and is quantified as the number of times a given pixel burns divided by the number of simulated fire seasons. Validation efforts showed that FSim was able to successfully replicate historic patterns of fire occurrence, fire size distributions, and burn probabilities (Finney et al. 2011a). FSim outputs currently form the basis for large wildfire potential for the Fire Program Analysis System (National Interagency Fire Center 2012) and the Hazardous Fuels Priority Allocation System. Recent applications of FSim include national-scale wildfire risk assessment (Thompson et al. 2011), forest-level risk assessment (Thompson et al. 2012b), analysis of municipal watershed exposure to wildfire on the Beaverhead-Deerlodge National Forest (Scott et al. 2012), and related analyses on the Bridger-Teton National Forest and the Grand Teton National Park (M. Thompson, pers. comm., Rocky Mountain Research Station, March 2012).

Suppression Cost Modeling

The large fire cost model (Gebert et al. 2007) is a regression model built from historical fire cost data that estimates per acre

and final fire costs as a function of total fire size, fire environment variables (e.g., slope, aspect, and fire weather), and values at risk (e.g., distance to town and total housing value within 20 mi). For the purposes of the fire cost model, large fires are defined as fires greater than 300 ac in size. The cost model is embedded within the Wildland Fire Decision Support System for cost containment guidance and is used as a performance measure to identify extreme high-cost fires (Calkin et al. 2011b). We used the cost model to estimate suppression costs for all simulated large fires that grew to at least 300 ac.

Fuel Treatment Cost Impact Modeling

Simulating the occurrence and growth of wildfires across the current and hypothetically treated landscapes enables evaluation of changes in fire behavior and, therefore, treatment impacts. Fire size potential is jointly driven by the spatial continuity of fuels and temporal opportunities for spread. To compare simulation results with and without fuel treatments, we set up FSim runs to use identical ignition locations and weather conditions for both scenarios. Thus, weather conditions are controlled for and changes to modeled final fire size are attributed to treatment effects (although there is some stochasticity induced via the modeling of spotting and containment). Differences in estimated suppression costs (a function of changed fire sizes) reflect expected suppression cost differences due to treatment. With this approach, fuel treatments can also change suppression costs if the fuel

type (brush, grass, timber, etc.) at ignition is changed, in those relatively rare circumstances where ignitions occur in treated areas.

The following basic steps of the overall analysis procedure are outlined. Data needs include an up-to-date map of landscape fuels, spatially delineated fuel treatments, and projected fuel conditions after treatment:

1. Obtain or create up-to-date fuels data to represent existing conditions.
2. Obtain historical fire occurrence data, and identify appropriate RAWS for fire weather data.
3. Design and spatially lay out prospective fuel treatments.
4. Modify existing conditions fuels data to reflect fuel treatments.
5. Generate FSim wildfire simulation model outputs with and without fuel treatments.
6. Aggregate and feed variables output from FSim into the regression cost model to estimate the expected suppression cost for each simulated fire.
7. Compare expected suppression costs with and without fuel treatments, across fires and across simulated fire seasons.

Case Study: Deschutes Collaborative Forest Project

The Deschutes Skyline Project, commonly referred to as the Deschutes Collaborative Forest Project (DCFP), was one of the first 10 projects approved and funded under the Collaborative Forest Landscape Restoration Program and was selected as a

Table 2. Modeled changes in canopy characteristics as a result of ongoing and planned fuel treatments.

Canopy cover (%)		Canopy base height (ft)		Canopy bulk density (kg/m ³)	
EC	PT	EC	PT	EC	PT
40–45	40	1–5	10	0.00–0.07	No change
46–50	42	6–10	12	0.08–0.10	0.07
51–60	45	11–15	18	0.11–0.15	0.09
61–70	50	16–20	No change	0.16–0.20	0.10
71–75	55	20+	No change	0.21–0.30	0.11
76–80	60	—	—	0.31+	0.12
81–90	65	—	—	—	—
91–00	70	—	—	—	—

Table 3. DNF fire history across FY 2000–2011, US Forest Service costs only (exclusive of Department of Interior), for fires ≥300 ac, compiled from the NIFMID and the FFIS.

FY	Fire name	Size (ac)	Cost per acre (\$)	Fire cost (\$)
2000	Newberry II	552	2,367	1,306,522
2001	Crane Complex	650	3,621	2,353,443
2003	Davis Fire	21,135	382	8,066,561
2003	Booth	79,734	384	30,587,468
2003	Link	3,590	1,877	6,738,609
2003	18 Fire	3,800	464	1,763,364
2005	Cave Fire	652	389	253,343
2006	Lake George	5,550	1,866	10,357,841
2007	Woodside Ranch	589	1,203	708,281
2007	GW	7,357	917	6,744,132
2008	Royce Butte	381	4,142	1,578,028
2008	Snow Creek	389	6,461	2,513,437
2009	Blackbutte II	711	4,558	3,240,404
2011	Shadow Lake	10,000	1,016	10,161,226
Summary statistics				
Mean	—	9,649	2,117	6,169,476
Median	—	2,151	1,534	2,876,921
Minimum	—	381	382	253,343
25th percentile	—	604	577	1,624,362
75th percentile	—	6,905	3,307	7,735,954
Maximum	—	79,734	6,461	30,587,468

FY, fiscal year; NIFMID, National Interagency Fire Management Integrated Database; FFIS, Foundation Financial Information System.

pilot study for modeling the impacts of fuel treatments on expected suppression costs. Figure 2 provides a map of the analysis landscape (516,962 ac), as well as the DCFP project area, most of which is located within the Deschutes National Forest (DNF; 145,000 ac total; 112,000 ac of which is US Forest Service), in west central Oregon. Information presented here regarding DCFP landscape conditions and treatment plans can all be found in the original proposal document (USDA Forest Service 2012).

The DCFP has identified a total of seven areas that will be analyzed under project-level National Environmental Protection Act (NEPA) guidelines (alphabetically): Drink, Glaze Meadow, Popper, Sisters Area Fuels Reduction (SAFR), Ursus, West Bend, and West Tumbull. Identified in Figure 1

are the locations of all proposed fuel treatments within the DCFP. No treatments are planned within the Addition or Skyline areas, some of which is private land. The degree of implementation varies across project areas—as of this writing, in some areas fuels have already been or are currently being treated, and in other areas teams are in various stages of planning.

Most of the DCFP landscape is comprised of ponderosa pine (*Pinus ponderosa*) and dry mixed conifer forest types, characterized by frequent, low-severity fire. The western portions of the landscape, however, include wet mixed conifer forest types, with mixed severity and return intervals between 35 and 150 years. A multistakeholder collaborative effort identified the DCFP landscape as a priority landscape for restoration and wildfire hazard and risk reduction. The

broad treatment goals are restoring forest ecosystems, promoting resiliency, and protecting highly valued resources and assets.

Fuel treatment objectives vary according to forest type. In dry forests, efforts are aimed at restoring natural fire regimes and creating trajectories to late-successional stages, by reducing stand density, reducing ladder fuels, and favoring large fire-resilient trees. Areas prioritized for treatment are typified by closed-canopy and midsuccessional stand conditions (Glaze Meadow, SAFR, and West Tumbull). In wet forest types on the western edges of the landscape, strategically placed treatments may inhibit fire spread driven by westerly winds (Drink, Popper, and Ursus). Thinning from below (commercial and noncommercial) is the primary vegetation treatment, with surface fuels treated through a combination of hand piling and burning, mowing, and prescribed fire.

DNF staff provided data on vegetation and fuel layers reflecting existing conditions (EC), as well as treatment polygons and posttreatment (PT) fuel conditions. Table 1 details expected changes in fire behavior fuel models (Scott and Burgan 2005). Fire behavior fuel models are more of an expression of expected fire behavior than a true representation of the fuelbed, and thus modeled changes reflect expectations of future fire behavior based on local expert opinion and past fire observation. Table 2 provides additional details on expected changes to canopy characteristics (crown cover, crown base height, and canopy bulk density).

In total, 66,808 ac (~46% of the DCFP landscape) are projected to receive treatment,¹ during the planning period from 2010 to 2019. For modeling purposes, we used a single landscape to reflect the entire suite of fuel treatments; i.e., the PT modeling results represent the cumulative effect of all treatments on completion of implementation, rather than unique simulation results capturing individual treatment effects as they are implemented. The expected lifespan of treatments is 10 years, which should temper concerns over this modeling assumption. We set up FSim to simulate fire occurrence and growth for a total of 10,000 simulated fire seasons and included a buffer around the study area of width ranging from 2 to 3 mi to account for off-site ignitions that could affect onsite burn probabilities. To generate weather files for FSim, we used the Colgate RAWS with data from 1990 to 2010 and used fire history

information for all fires on the DNF over the same period.

Because of the large spatial extent of the treatments and the combination of mechanical treatments with surface and activity fuel treatment, we hypothesized reductions in fire sizes and expected suppression costs would occur within the study area. We further hypothesized that treatment effects would be more prominent for those ignitions occurring closer to treated areas. Therefore, we present modeling results for fires that ignited within three overlapping analysis areas of increasing size (within treated areas, within a 2-mi buffer of treated areas, and across the entire study area).

Results

Comparison of Historical and Simulated Results

Table 3 presents historic large fire data across fiscal years² 2000–2011, for the entire DNF. Note this is a different time period from that used to parameterize fire size distributions FSim, in large part to enable comparisons of suppression cost in addition to fire size. Fire occurrence data are compiled from the National Interagency Fire Management Integrated Database and financial data from the Foundation Financial Information System. The 14 large fires in the historic record evince substantial variability, with fire size ranging from 381 to 79,734 ac; cost per acre ranging from \$382 to 6,461/ac; and cost per fire ranging from \$253,343 to 30,587,468.

Simulation results generally agree with the range of historical observations. Across the entire study area the mean and median fire sizes are 9,541 and 2,955 ac, respectively, compared with historical values of 9,649 and 2,151 ac, respectively. The simulated mean and median per fire suppression cost are \$9,003,597 and 5,081,574, respectively. These modeled fire costs are higher than historical observations, a result not altogether unexpected given the proximity of the study area to the communities of Sisters and Bend (Figure 2) and the positive influence of housing value on suppression costs within the regression cost model. Historical fire cost data by contrast includes fires that ignited in more remote, less developed areas and in wilderness areas, where suppression costs are generally lower.

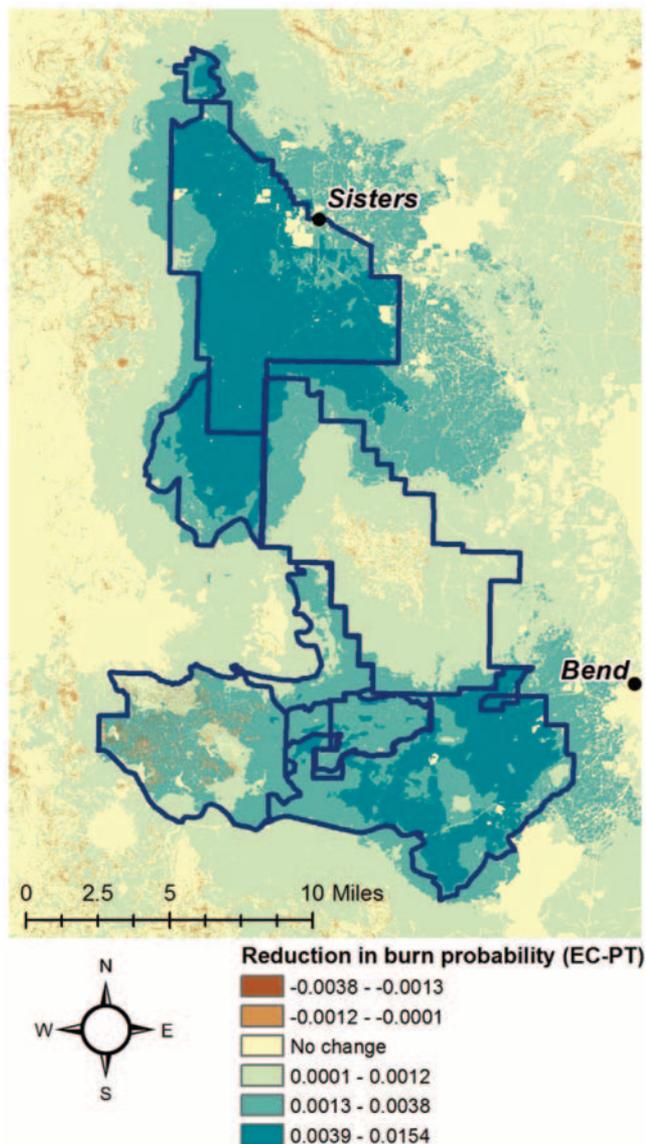


Figure 3. Reduction in landscape burn probabilities between the ECs and PT conditions, for the DCFP study area plus. Areas shaded in blue indicate reduced likelihood of burning due to fuel treatments. Areas of negative reduction correspond to areas of increased burn probability, which are rare on the landscape. Reductions in burn probability are evident within and beyond treatment locations.

Fuel Treatment Effects on Burn Probability, Fire Size, and Suppression Cost

Figure 3 presents simulated annual burn probabilities across the ECs and the PT landscapes. Reductions in burn probability are evident, especially in areas receiving fuel treatments (Figure 2), which stem from reductions in rate of spread and their final fire size. Burn probabilities do increase in some areas, although the magnitude of this increase is quite small relative to reductions elsewhere on the landscape. Causes for increased burn probability are not directly obvious, although given the stochasticity of fire spotting and containment within the wild-

fire model these results are not altogether unexpected. Furthermore, fuel treatments may in some circumstances increase surface fire spread rates because of enhanced understory growth and increased wind speeds (Hudak et al. 2011), although the occurrence of increased burn probabilities within treated areas is quite rare across the study area.

Table 4 presents summary statistics regarding percent reductions in fire size, cost per acre, and cost per fire resulting from treatment. With respect to size, reductions are most prominent within treated areas although off-site effects are discernible. Within treated areas, the mean and median

fire sizes decrease by 17.08 and 22.24%, respectively, and within the 2-mi buffer mean and median fire sizes decrease by 11.30 and 14.97%, respectively. Treatment effects dampen as the analysis area increases because of the increasing proportion of fires that do not interact with treatments.

Table 4 also indicates increasing cost per acre with decreasing fire size, consistent with both the cost regression model and historical Deschutes data, where smaller fires tend to cost more per acre. Overall per fire costs decrease, however, because the effects of the reductions in fire sizes overwhelm the effects of increases in per acre costs. Reductions in cost per fire also lessen as the analysis area increases and are generally comparable in magnitude with reductions in fire size. Within treated areas, the mean and median fire costs decrease by 15.86 and 17.58%, respectively, and within the 2-mi buffer mean and median fire sizes decrease by 10.78 and 10.63%, respectively.

Annual Area Burned and Annual Suppression Costs

Beyond per fire results, it is important to aggregate individual simulated fire results into unique fire seasons on an annualized basis. This approach captures both those fire seasons in which no large fires occur and those fire seasons in which multiple large fires occur. In the historical record, the DNF experienced at least one large fire during 11 of 14 years. The occurrence of large fires within the study area is likely to be less, because the study area comprises only a fraction of the acreage of the entire forest. Of a total of 10,000 unique fire seasons simulated, the EC landscape had the following number of seasons with at least one large fire: 3,620 (entire study area), 2,179 (2-mi buffer), and 1,371 (treated areas). Similarly, the PT landscape experienced 3,463 (entire study area), 1,926 (2-mi buffer), and 1,072 (treated areas) seasons with at least one large fire. Because we used the exact same set of simulated ignitions on the untreated (EC) and treated (PT) landscapes, the difference in the number of large fires reflects the effect of fuel treatments on limiting the growth of ignitions to below the 300-ac “large fire” threshold.

Tables 5–7 present results for annual area burned and annual suppression costs. Results in Table 5 are conditional on at least one large fire occurring, i.e., exclusive of simulated seasons in which a large fire did not ignite within the given geographic

Table 4. Percent reductions to fire size, cost per acre, and cost per fire resulting from treatment, across all large fires igniting within three overlapping landscape areas of increasing size (within treated areas, within a 2-mi buffer of treated areas, and across the entire study area).

	Treated areas	2-mi buffer	Entire study area
Size			
Mean	17.08%	11.30%	4.68%
Median	22.24%	14.97%	5.55%
Minimum	0.66%	0.66%	0.74%
25th percentile	12.12%	5.97%	2.78%
75th percentile	23.13%	13.20%	7.06%
Maximum	12.84%	3.78%	0.58%
Cost per acre			
Mean	-2.24%	-0.60%	0.53%
Median	0.26%	0.28%	1.00%
Minimum	-6.73%	-0.43%	-0.17%
25th percentile	-0.30%	1.40%	1.22%
75th percentile	-3.18%	-1.04%	0.35%
Maximum	-1.74%	0.00%	0.00%
Cost per fire			
Mean	15.86%	10.78%	6.71%
Median	17.58%	10.63%	5.21%
Minimum	-0.48%	0.25%	-0.78%
25th percentile	18.60%	11.30%	5.05%
75th percentile	20.57%	12.91%	7.04%
Maximum	5.64%	1.06%	2.72%

Treatment effects dampen as the area increases, because of the increasing proportion of fires that do not interact with treatments.

Table 5. Percent reductions to annual area burned and annual suppression costs resulting from treatment, across fires igniting within three overlapping landscape areas of increasing size (within treated areas, within a 2-mi buffer of treated areas, and across the entire study area).

	Treated areas	2-mi buffer	Entire study area
Annual area burned (conditional)			
Mean	18.47%	13.30%	7.05%
Median	21.96%	12.04%	8.91%
Minimum	1.24%	0.66%	0.74%
25th percentile	9.91%	5.58%	3.01%
75th percentile	23.90%	13.57%	8.06%
Maximum	26.71%	21.82%	9.12%
Annual suppression costs (conditional)			
Mean	17.26%	12.80%	9.03%
Median	16.96%	11.80%	8.24%
Minimum	0.00%	0.25%	0.25%
25th percentile	21.16%	11.14%	7.28%
75th percentile	22.62%	15.56%	8.33%
Maximum	27.33%	19.73%	19.73%

Results are conditional, meaning they are aggregated from only those simulated fire seasons with at least one large fire.

scope. Percent reductions in mean and median annual area burned and annual suppression costs are roughly on par with per fire reductions (Table 4) and suggest substantial treatment effects, especially within treated areas. Table 6, by contrast, presents unconditional results across all 10,000 simulated seasons. The 25th, 50th (median), and 75th percentiles are not presented because they are all equal to zero. The annual area burned and suppression costs increase as the size of the analysis area increases, simply because more fires are included in the

sample. Percent reductions, however, decrease, because a smaller fraction of fires interact with treatments, consistent with results presented in Tables 4 and 5. For fires igniting within treated areas, mean annual area burned and suppression costs drop by 36.25 and 35.30%, respectively, after treatment. Table 7 presents additional summary statistics of annualized results for just the 2-mi buffer analysis area. Area burned and suppression cost increase steeply going from the 90th to the 95th to the 100th (maximum) percentiles, suggestive of a long right

Table 6. Mean annual area burned and suppression costs across all 10,000 simulated fire seasons, across fires igniting within three overlapping landscape areas of increasing size (within treated areas, within a 2-mi buffer of treated areas, and across the entire study area).

	Treated areas			2-mi buffer			Entire study area		
	EC	PT	Reduction	EC	PT	Reduction	EC	PT	Reduction
Area burned (ac)	1,315	838	36.25%	2,494	1,911	23.37%	5,398	4,799	11.08%
Suppression cost (\$)	1,610,806	1,042,147	35.30%	2,848,653	2,195,551	22.93%	5,093,335	4,432,626	12.97%

EC, existing conditions; PT, posttreatment landscapes.

tail and potential for rare but highly damaging and expensive fire seasons.

Discussion and Concluding Remarks

Our analysis shows that planned fuel treatments within the DCFP study area are likely to reduce the number of large fires, fire sizes, and large fire suppression costs. In a broader sense, our analysis presents a possible method for estimating the impacts of fuel treatments on financial risk. Our analytical approach adopted wildfire simulation and burn probability modeling techniques, which are increasingly used to inform fire and fuels management decisions (Miller et al. 2008) and which are essential for estimating the likelihood that a given treatment will interact with a wildfire during its effective lifespan. Auxiliary analyses can couple wildfire simulation outputs with maps of values at risk to consider possible exposure and effects, to contemplate the broader socioeconomic and ecological impacts of fuel treatments, and to compare these impacts with the costs of fuel treatments. Sensitivity and scenario analyses can be used to examine a range of potential cost impacts, given uncertainty surrounding both future fire occurrence and cost modeling. One opportunity for integration with other decision support tools lies with use of the ArcFuels treatment planning and risk analysis system (Ager et al. 2011). ArcFuels integrates fire behavior models and spatial data within a geographic information system framework and can greatly facilitate development and testing of fuel treatment scenarios at stand and landscape scales. Use of ArcFuels could, therefore, help in the design of treatment strategies for further analysis and simulation modeling. The tools and approaches defined here could inform treatment design and strategy development across land-management agencies interested in better managing suppression costs.

It is recognized that the modeling approaches shown here entail several assump-

Table 7. Annual area burned and annual suppression costs across all 10,000 simulated fire seasons, for ignitions occurring within a 2-mi buffer of the treated area.

	EC	PT	Reduction
Annual area burned (ac)			
Mean	2,494	1,911	23.37%
90th percentile	4,398	2,960	32.69%
95th percentile	14,561	10,926	24.96%
Maximum	160,491	125,479	21.82%
Annual suppression costs (\$)			
Mean	2,848,653	2,195,551	22.93%
90th percentile	7,673,437	5,547,975	27.70%
95th percentile	17,714,613	13,501,278	23.78%
Maximum	188,746,521	151,510,191	19.73%

The 25th, 50th (median), and 75th percentiles are not presented because they are all equal to zero. EC, existing conditions; PT, posttreatment landscapes.

tions and limitations. In particular, four critical factors condition our results. First, nearly 50% of the DCFP project area will receive treatment. We might not expect similar impacts to fire sizes and costs on landscapes with lower treatment levels. In such cases strategic placement of treatments to interrupt predominant fire spread pathways (Finney 2007) can enhance the impact of fuel treatments on burn probabilities, if consistent with broader landscape objectives. Second, modeling all treatments as occurring at once through time may not adequately capture nonlinear relationships or temporal dynamics and could overestimate treatment longevity. For our purposes it is assumed that treatments are sufficiently intensive to remain effective over the duration of the analysis period and/or that maintenance treatments are applied as necessary. Third, results are dependent on the wildfire simulation and regression cost models used. Limitations of the FSim model relate to reliance on submodels with potential for propagated error, use of coarse weather data, and potential for crown fire underprediction bias (Cruz and Alexander 2010). Issues of scale also can be a limitation to consider, where as the size of the analysis area decreases so does the population of historical large fires available to parameterize the model. Questions remain as to the optimal spatial scope of

analysis for capturing historical fire variability, as well as the optimal spatial scope for capturing fire spread potential from remote ignitions. Validation efforts, however, have shown that FSim can replicate fire size distributions well for the continental United States (Finney et al. 2011a), as well as within this particular study area. Limitations of the regression cost model include a reliance on limited spatial fire information (e.g., ignition location versus fire perimeter), limited valuation of threatened nonmarket resources, and a limited ability to handle fire complexes. Fourth, changes in wildfire outputs are largely driven by projected changes in fire behavior fuel models. As is the case with many modeling systems, astute users could manipulate parameters and input variables to achieve desired outputs. If projected changes to fire behavior fuel models are optimistic, in a sense, reductions in fire sizes may be overstated.

Results of this demonstration should therefore be viewed through a critical lens, and future applications should focus on careful model calibration and validation. Particularly critical is the accuracy of projected fuel conditions before and after fuel treatments; Stratton (2009) provides guidance for critiquing and calibrating input fuels data (see also Scott et al. 2012). Validating simulated fire sizes and fire costs is

admittedly challenging, in large part because of a limited historical record. Seeking to closely replicate observed fire size distributions may be overfitting to an incomplete distribution and, furthermore, would ignore possibilities for statistically rare conditions not observed under which fires can grow beyond historical maxima. Comparing simulated and historical suppression costs is particularly difficult, because cost structures vary not only across biophysical settings and associated fire growth potential, but also according to the location and density of socioeconomic values.

Potential limitations of our modeling approach extend to real-world concerns as well. As Reinhardt et al. (2008) succinctly state, the only certain way to reduce suppression expenditures is to make a decision to spend less money, independent of potential changes to fire behavior from extant fuels treatments. Strong sociopolitical pressures and misaligned incentive structures could still encourage aggressive suppression irrespective of other considerations (Donovan and Brown 2005, Donovan et al. 2011). Additionally, for various reasons such as budget uncertainty and realities of NEPA planning, the treatment schedule designed during the proposal may differ from what is eventually implemented. Modeling future treatments necessarily involves some best guesses by local experts regarding location, extent, and intensity of treatment.

At present, this modeling technique only addresses cost impacts from changes to final fire size, not fire intensity. In earlier versions of the suppression cost model fire intensity was included as a dependent variable and was found to have a significant positive correlation with cost per acre. Questions over the reliability of subjective assessments of intensity, however, ultimately led to the removal of fire intensity from the model. Thus, modeling the cost impacts of reduced fire intensity will likely require the incorporation of local expertise and professional judgment coupled with scenario analysis. Here, FSim outputs, which include spatially resolved estimates of fire intensity (via flame length), should prove useful. Penman et al. (2011) and Plucinski et al. (2012) provide useful illustrations of reliance on expert judgment in the wildfire management context. Information on how suppression tactics might change with the presence of fuelbreaks could also inform future estimates of reduced suppression costs (Syphard et al. 2011).

Future work could seek to expand on the suppression cost modeling methods in a number of ways. Currently, the regression cost model is being updated to reflect a broader suite of spatial explanatory variables, which may enable refined suppression expenditure estimates in the future (Thompson et al. 2012a). It may also be possible to integrate information on suppression strategies and tactics into the regression model (e.g., Gebert and Black 2012) or to elicit expert judgment to capture how changes in suppression would likely affect fire size and cost. Future improvements could include the integration of structured processes for eliciting expert judgment to capture changes in future suppression tactics and to estimate impacts of reduced fire intensity on likely cost. Upcoming changes to the wildfire modeling system include use of finer-scale weather information, which could enable refined estimates of localized fire behavior and spread, and improved modeling of wildfire containment (M. Finney, pers. comm., Rocky Mountain Research Station, March 2012).

In summary, we believe we have identified a novel and unique methodology that should inform fuel treatment design and implementation and that ultimately will facilitate the reduction of wildfire management costs. Despite identified limitations, modeling results can provide useful information about the relative magnitude and direction of change resulting from strategic fuels management. Recommended applications include fuel treatment design where impacting fire sizes and suppression costs are explicit management objectives and analyses of projects moving forward under the Collaborative Forest Landscape Restoration Program and the National Cohesive Wildland Fire Strategy.

Endnotes

1. The initial proposal called for 52,000 treatment ac, but as treatment implementation continues this projection has increased.
2. In the United States a fiscal year extends from October 1 through September 30. The fiscal year largely overlaps with typical fire seasons for most regions of the country.

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