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The economics of alternative fuel reduction treatments in western United States dry forests: Financial and policy implications from the National Fire and Fire Surrogate Study

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Abstract

We collected data at seven sites in the western US, on the costs of fuel reduction operations (prescribed fire, mechanical treatment, mechanical plus fire), and measured the effects of these treatments on surface fuel and stand parameters. We also modeled the potential behavior of wildfire in the treated and control stands.

Gross costs of mechanical treatments were more expensive than those of prescribed fire, but net costs of mechanical treatments after deducting the values of harvested products were, on most sites, less than those of fire.

The fire-only treatment reduced surface fuels, while most mechanical treatments (with the probable exception of whole-tree removal) increased these loads. Most mechanical-plus-fire treatments had little net effect on surface fuels. All treatments reduced the number of live trees, on average by about 300, 500 and 700 stems per hectare respectively for fire-only, mechanical, and mechanical-plus-fire. As intended by prescription, the mechanical treatments reduced basal area per hectare significantly. In most cases the fires – either alone or following mechanical treatment – killed mostly small trees, having essentially no impact on basal area.

The mechanical-plus-fire treatment was the most effective, followed by fire-only, at reducing the modeled severity of wildfire effects under extreme weather conditions. The effectiveness of mechanical-only treatments depended on how much surface fuel remained on site. A whole-tree harvesting system removed the tops and limbs along with the felled trees, thereby reducing potential fire severity more than methods which left slash and/or masticated material within the stands.

The various treatments created different conditions, and therefore the treatment intervals needed to maintain desired fire resilience would probably differ as well, being shorter for fire-only than for mechanical-only or mechanical-plus-fire treatments.

Decisions about which treatments to prescribe, where, and when, will generally consider not only the financial costs and entry intervals, but other societal benefits and costs of the treatments and of wildfires as well.

Keywords: Fuel reduction; Mechanical treatment; Prescribed fire; Wildfire

1. Introduction

A team of scientists and land managers has established an integrated national network of long-term research sites known as the Fire and Fire Surrogates study (FFS) to address the need

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for better comparative information on alternative fuel reduction methods. With support from the USDI/USDA Joint Fire Science Program (http://www.nifc.gov/joint_fire_sci/index.html), the FFS study applied a common experimental design over 13 sites across the United States, with each site representing a forest that is at risk of uncharacteristically severe wildfire. This paper describes the financial aspects of fuel reduction treatments as applied to seven of the FFS sites in the western United States (Fig. 1); forests at each of these sites are dominated by conifer species that are adapted to frequent, low-intensity fire (Table 1). The western US is of particular concern because the majority of forests managed by the US Forest Service in this region have experienced a significant increase in area burned by wildfire from 1940–2000 (Stephens, 2005).

The FFS study compares the costs and consequences of alternative fuel reduction methods in these seasonally dry forests nationwide. Fuel reduction has become a high priority in dry forests, because of changes that have occurred in forest structure over the past 100 years. Current seasonally dry forests are more spatially uniform, have more small trees and fewer large trees, and have greater quantities of forest fuels compared to pre-European settlement times (Parsons and DeBenedetti, 1979; Bonnicksen and Stone, 1982; Parker, 1984; Chang, 1996; McIver et al., 2001; Stephens and Ruth, 2005). Causes of these changes include fire suppression, past livestock grazing and timber harvests, and changes in climate (Parsons and DeBenedetti, 1979; Skinner and Chang, 1996; Weatherspoon and Skinner, 1996; Arno et al., 1997; Westerling et al., 2006). These changes in forest ecosystem integrity increase the probability of large, high-severity wildfires that damage difficult-to-obtain older forest structures such as large old trees (Weatherspoon and Skinner, 1996; Dahms and Geils, 1997; Stephens, 1998). Reports from the Blue Mountains of Oregon and Washington (Everett, 1993), the Columbia River Basin (Quigley and Cole, 1997), and the Sierra Nevada Ecosystem Project (SNEP, 1996; Weatherspoon and Skinner, 1996) have highlighted these problems and have explained the need for large-scale and strategically-located thinning (especially of small trees) and/or other fuel treatments, and the use of prescribed fire.

While the need for widespread use of methods to increase resilience to disturbance by creating structural conditions that promote non-lethal fire behavior is clear (e.g., Hardy and Arno, 1996), less clear is the appropriate balance among mechanical fuel treatments (cuttings and/or mastication), and prescribed fire

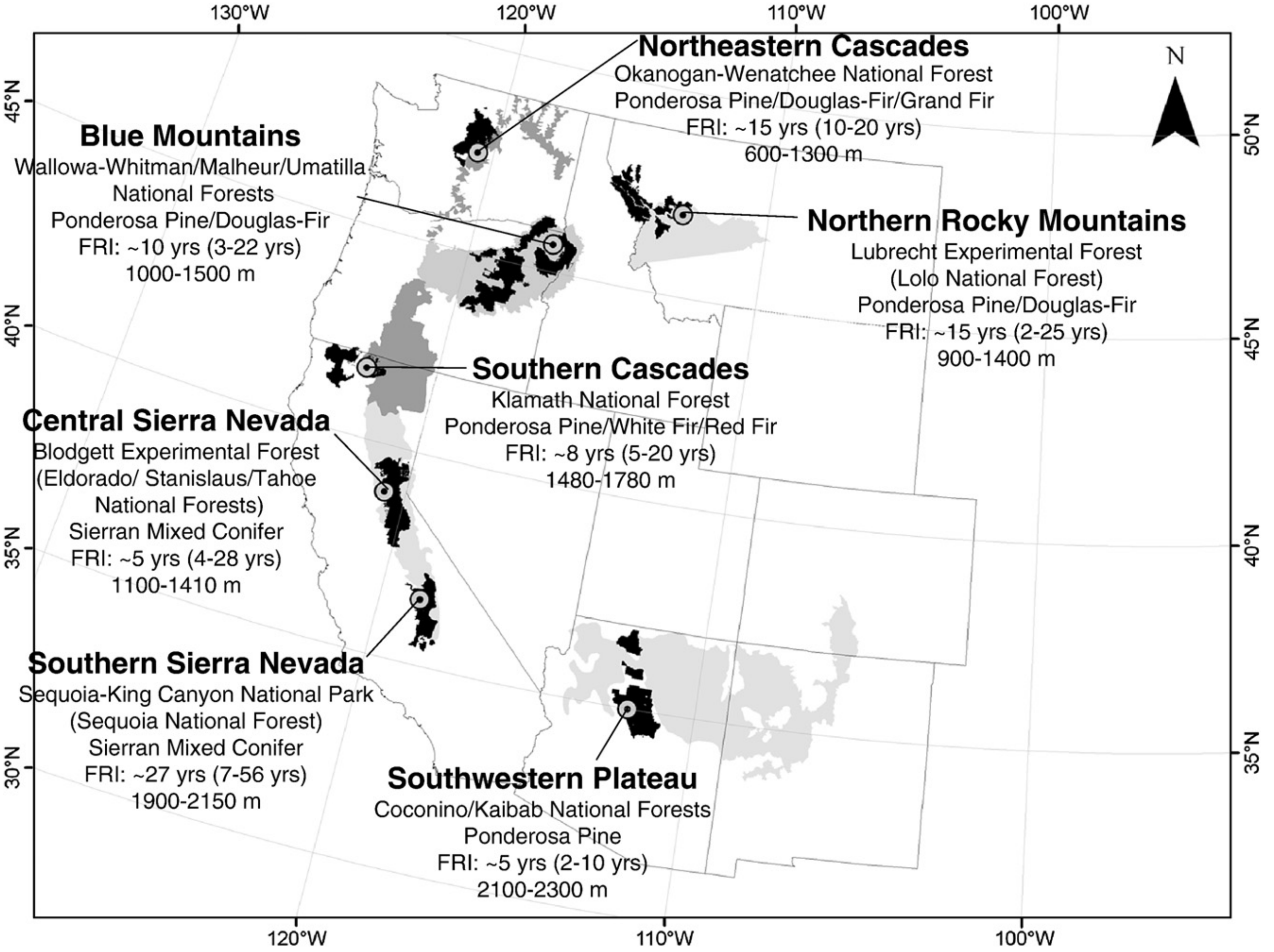

Fig. 1. Names and locations of the seven western Fire and Fire Surrogate (FFS) sites, showing relevant national forests (black shaded areas), forest type, fire return interval (FRI), and elevational range (meters). Lighter shading indicates 'representative land base', or the area to which FFS results can be most directly applied for each site. Representative land bases are derived from EPA Type III Ecoregions: www.epa.gov/wed/pages/ecoregions/level_iii.htm.

Table 1
Fire and fire surrogate site descriptions including past management and treatment methods

Site name and location	Past management history	Mechanical FFS treatment	Burn FFS Trtmt	Source
Northeastern Cascades, Mission Creek, WA		Fell, limb and buck with chainsaws; yard with helicopter; leave residue on site		
Northern Rocky Mountains, Lubrecht Experimental Forest, MT	Logging in early 20th century and fire suppression resulting in 80–90 year old stand; Grazing over last 100 years	Fell, limb and buck with tracked single-grip harvesters; forward logs with rubber-tired forwarders; leave all harvest residue on site	Spring under burn using a strip head fire	Metlen et al., 2006
Blue Mountains, Hungry Bob Forest, OR	Partial overstory removal in early 20th century; at least two entries within the past several decades; fire suppression since early 1900s; active grazing for the past 20 years	Fell, limb and buck with tracked or rubber-tired single-grip harvesters; forward logs with rubber-tired forwarders; leave all harvest residue on site	Fall underburn	Heyerdahl et al., 2001; Metlen et al., 2004
Southern Cascades, Goosenest Experimental Forest, CA	Railroad logging in 1920s; various sanitation and salvage since	Fell with tracked feller-bunchers; skid whole trees with rubber-tired or tracked skidders	Fall underburn	Zack et al., 1999; Ritchie, 2005; Ritchie and Harcksen, 2005
Central Sierra Nevada, Blodgett Forest Research Station, CA	Railroad logging in early 20th century; sanitation salvage mid-1970s; commercial harvest using various methods to present	Fell, limb and buck trees > 25 cm dbh with chainsaws; lop and scatter tops and limbs; skid logs with rubber tired or tracked skidders; post-harvest masticate 70% of trees < 25 cm DBH	Fall underburn using a combination of backing and strip head fires	Dunning, 1942; Olson and Helms, 1996; Stephens and Collins, 2004; Kobziar et al., 2006
Southern Sierra Nevada, Sequoia National Park, CA	Fire suppression since early 20th century	No mechanical treatment	Fall and spring underburn, each replicated 3 times	Knapp and Keeley, 2006
Southwestern Plateau, Northern AZ	Past harvesting; grazing; limited low thinning in early 1990s	Fell, limb, and buck trees > 13 cm dbh with chainsaws; skid logs with rubber-tired skidders; fell and lop trees < 13 cm to waste with chainsaws; pile harvest residues and small trees with tracked dozer	Fall underburns with a combination of backing and strip head fires	Larson, 2004

(SNEP, 1996; van Wagtendonk, 1996; Weatherspoon, 1996; Stephens, 1998; Stephens and Moghaddas, 2005a). To achieve goals for ecosystem integrity and sustainability, we need better information about the ecological consequences and tradeoffs of alternative fuel reduction practices. Likewise, we need better comparative information on the finances and technical feasibility of various fuel reduction treatments because managers will inevitably have to address these factors as they consider the tradeoffs associated with selecting different treatment alternatives. While there is considerable information on the costs of both prescribed fire and thinning treatments in western US forest ecosystems (e.g., Cleaves et al., 2000; González-Cabán, 1997; González-Cabán and McKetta, 1986; Hartsough et al., 1997; Walsted et al., 1990), no studies have directly compared the finances or economics of these two methods in the same place and at the same time, especially with experimental sites located over a broad range of the western US.

2. Methodology

2.1. Treatments and costs

The over-riding goal of the FFS fuel treatments was to increase resilience of stands to wildfire rather than to necessarily emulate historical, pre-European settlement conditions. The primary fuel treatment objective was to alter stand conditions in ways that were projected to reduce fire severity to the extent that 80% of the dominant and co-dominant trees would survive a wildfire under the 80th percentile fire weather conditions (the 80–80 rule). The specific treatment design for each site in the FFS network varied but the 80–80 rule was common throughout the network. At each site, staff members consulted with local fire management professionals to create the 80–80 prescription parameters while incorporating various treatment tools such as masticators that were available locally. Some sites, such as the Central Sierra, modeled fire behavior at the stand scale using Fuel Management Analysis Plus (FMA; Carlton 2004) to assist in prescription development.

The extent to which this objective was achieved varied with stand conditions, type of treatment, and regional conditions such as the locally appropriate timing of burning or type of mechanical treatment. This standard (80–80 rule) was only a minimum requirement and stricter agency or local standards were commonly integrated across sites. In reality the fuels reduction treatments achieved a much higher resilience to wildfire, approaching 80% of dominant and co-dominate trees surviving a wildfire of 90th or 97.5th percentile (Stephens, in preparation).

Prescribed fire treatments were conducted at all seven western FFS sites. The burn units across all treatment sites were smaller (8–83 ha, averaging 24 ha) than those designated for operational prescribed burning which typically vary from 10–1000 ha. Costs per unit area have been shown to decrease with size of the unit (González-Cabán, 1997; González-Cabán and McKetta, 1986). In addition, prescribed burns were not always implemented by crews equivalent to those used in operational prescribed burns by most federal land management agencies in the US. Because of these and other factors, the study team anticipated that the experienced costs of the fire treatments in this study would be higher than those expected under operational conditions.

Although some sites collected empirical data on prescribed fire costs, we recognized these potential problems as we designed the financial analysis for the FFS study and included expert opinions rather than empirical data in the original study design for developing cost estimates for the fire treatments on most sites. An expert in prescribed fire planning and implementation associated with each site was asked to provide information for prescribed fires of units that they considered to be of small, medium and large areas for their specific operating regions. The sizes ranged from 4–40 ha on the small end, to 20–280 ha for medium-sized units, to 400–600 ha on the large end. Experts provided information in different ways. Some gave detailed information on the crew and equipment configurations and required times for each scenario. Others provided holistic costs per unit area, based primarily on experience with contracting for prescribed burns. Still others provided estimates for different options (such as hand or aerial ignition) commonly used in the region. Where crew and equipment times were provided, current wage rates and equipment replacement costs were used to develop hourly costs. In some cases, expert opinions consistent with the study criteria could not be obtained, therefore site personnel provided standard burning costs, i.e., those typically experienced in the local region, or we used the observed costs for the study units were used.

As noted in Table 1, all mechanical treatments included some harvesting, either of whole trees or logs. Sub-merchantable trees were masticated on one site (Central Sierra) and cut and piled on another (Southwestern Plateau). Only on the whole-tree units (Southern Cascades) were the tops and limbs removed from the stand. Helicopter logging was carried out at the Northeastern Cascades site, but this method was considered atypical of fuel reduction operations, so data on mechanical treatments was not collected at this site.

For mechanical treatments, costs were derived from empirical data from the study sites. Productive hours of machine operation were recorded on most study units, and scheduled hours on the others. Purchase prices for similar new equipment were obtained, and then hourly costs were estimated using the machine rate approach (Miyata, 1980) together with realistic assumptions for equipment life and operating costs. All on-site activities were accounted for. Transport costs were also included for materials such as sawlogs that were removed from the sites. In most cases the transport costs were based on actual average load size, estimated round-trip time per load based on the distances and road conditions to the actual mills, and estimated hourly costs. The actual contract hauling cost per delivered volume was used for one site, and an estimated cost per mile, transport distance and load size for another.

On those sites where harvesting took place, the amount of sawlog and/or biomass material removed was estimated from truck-load records, as were values of those materials at processing facilities such as sawmills. For both treatment costs and revenue, total values for each unit were divided by actual area of the unit to derive values per hectare.

2.2. Changes in fuel conditions

Vegetation and fuels measurements were recorded in plots referenced to a set of points established on a grid in the interior of each unit. Gridpoints were set 40 m, 50 m, or 60 m apart. Depending on the size of the experimental unit, this grid was comprised of between 35 and 70 gridpoints. To minimize edge effects, the grid system was surrounded by a 30–100 m buffer that also received the same treatment as the interior region.

Tree survival data and measurements of forest structure were generally collected within 20 × 50 m (0.1 ha) modified Whittaker plots, 6–20 of which were established per unit, with two sites (Central Sierra and Blue Mountains) using a systematic grid of 0.04 ha circular plots. Within plots, all trees with a DBH > 10 cm were labeled with a uniquely numbered tag. Smaller diameter trees were not permanently tagged but were included in understory cover estimates in subplots. Tree species and status (alive, standing dead, dead and down) were noted, and DBH was recorded. As an indicator of ladder fuels, height to base of live or dead crown was also recorded. Units were sampled prior to and following treatment.

Mass of surface fuel (dead and down woody fuels plus litter and duff) was estimated both prior to and following treatment using Brown's planar intercept method (Brown, 1974). Sampling intensity within an experimental unit differed by site, with between 60 and 150 transects per unit. In each transect, the number of intersecting downed woody stems in different time lag size classes was recorded (1-hour fuel: 0–6 mm, 10-hour fuel: >6–25 mm, 100-hour fuel: >25–76 mm, and 1000–hour+ fuel: >76 mm). For the 1000-hour+fuel size category, the diameter and decay class (sound or rotten) of each log were recorded.

2.3. Post-treatment fire risk reductions

In western US coniferous forests, fire managers often use a stricter standard than the FFS 80th percentile weather conditions for designing fuels treatments (i.e., 90% or 97.5% percentile). Therefore, we simulated fire behavior and effects of the FFS treatments under upper 80th (moderate), 90th (high), and 97.5th (extreme) percentile fire weather conditions based on archived Remote Access Weather Station (RAWS) weather data. Weather data from the RAWS station closest to each FFS site were analyzed with Fire Family Plus (Main et al., 1990) to determine percentile fire weather conditions (data not shown). Each RAWS station had a weather record of at least 25 years and these data were used to generate percentile fire weather.

Fuels Management Analyst Plus (FMA; Carlton 2004) was used to estimate potential fire behavior, crowning index, torching index, scorch height, and tree mortality. Torching and crowning indices are the wind speeds (measured at 6.1 m above ground) required to initiate torching (passive crown fire) and sustain a crown fire (active crown fire) within a stand, respectively. FMA uses information from field measurements (tree species, DBH, tree crown ratio, tree crown position, percentage canopy cover, surface and ground fuel loads), slope, and fire weather to simulate fire behavior and fire effects at the stand scale. FMA incorporates published methodologies for

Table 2
Costs and revenues per hectare for the study sites, 2004–2005 United States dollars

Site	Prescribed burning		Mechanical treatment		
	Expert cost (\$/ha)[a]	Actual cost (\$/ha)[b]	Cost (\$/ha)[c]	Revenue (\$/ha)[c]	Net cost (\$/ha)[c]
Northeastern Cascades, WA	2200 (600–2400)	Not available	Not available	Not available	Not available
Northern Rocky Mts., MT	990 (300–4700)	600 (320–760)	2560 (2300–3200)	1610 (800–3000)	950 (200–1500)
Blue Mountains, OR	150 (70–330)	320 (140–470)	3620 (2500–5600)	3360 (1900–5200)	260 (−700–2200)
Southern Cascades, CA	Not available	460 (440–470)	5150 (3500–6400)	8080 (5500–10700)	−2930 (−4300 – −2000)
Central Sierra Nevada, CA	740 (680–820)	1210 (890–2280)	2570 (1200–3900)	5440 (2100–7500)	−2870(−3800 – −1000)
Southern Sierra Nevada, CA	520 (350–880)	1020 (910–1140)	Not applicable	Not applicable	Not applicable
Southwestern Plateau, AZ	Not available	310 (250–380)	1730 (1900–2100)	1740 (1200–2400)	−10 (−400–300)

[a] Expert opinion estimates for units of medium size (and range for small to large sizes). Medium size as specified by the experts for operational units varied from 20–280 ha across the regions.

[b] Mean (range) of standard or actual/reported costs for study units.

[c] Mean (range) of observed values for study unit.

computing crown bulk density, height to live crown base, fire behavior, and predicted mortality by species. Stephens and Moghaddas (2005a, c) summarize the methodologies used for these computations. Similar approaches were applied to evaluate the wildfire performance of the treatments at five other sites (all except Northeastern Cascades; S. Stephens personal communication 2007).

3. Results

3.1. Treatment costs

The costs of prescribed burning and the costs, revenues and net costs of mechanical treatments are shown in Table 2. The experienced costs for burning are included for illustration purposes only, and due to the reasons mentioned previously are not considered valid for operational settings. As anticipated, the actual costs were generally higher than the expected costs derived from expert opinion.

A *t*-test of results across all sites found that costs of mechanical treatments (ignoring revenues) were substantially higher ($P < 0.0001$) than the expert point estimates for medium-sized burns. Burning, however, will always have an operational cost and no immediate revenue, while mechanized fuel reduction – if it involves some product recovery as did all of the mechanical treatments considered in this paper – may have net cost or net revenue. The net mechanical treatment costs (total cost less product value) were significantly less than the burn costs ($P = 0.004$).

Costs for combined mechanical/burn treatments under the study conditions were higher than for mechanical-only operations because the mechanical treatments were carried out in the same manner without regard to whether they would be followed by prescribed fire. Costs of burning after mechanical treatment may be somewhat higher or lower than the cost of burning untreated units, depending on the net effects of mechanical treatment on fuel mass and distribution. All the mechanical treatments used at the study sites were intended to reduce ladder fuels by removing trees from the understory, but most treatments also created activity fuels, i.e. tree tops, limbs and other harvest debris and any masticated material, that increased surface loads. The amount of activity fuel varied from system to system; whole-tree harvesting with feller-bunchers and skidders (Southern Cascades) generally produced little activity fuel because most of the tops and limbs were removed intact with the tree boles. (Breakage during felling and skidding does produce some surface fuel.) In contrast, when chainsaws or mechanized harvesters are used to fell, limb and top trees in the stand, the tops and limbs remain on site. Harvesters and forwarders generally compact the residues on the forwarding trails, while residues left after chainsaw processing tend to be dispersed and uncompacted. Two treatment methods – mastication and felling to waste – leave all the material they treat as surface fuels and therefore can generate high surface loads. Mastication,

Table 3
Total mass (mean Mg/ha +/− S.D.) of 1-, 10-, 100-, and 1000-h fuels, pre-treatment and one-year post-treatment

Site	Treatment							
	Control		Burn-only		Mechanical		Mechanical + burn	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Northeastern Cascades, WA	14.86 ± 6.53	11.92 ± 6.53	16.92 ± 9.44	7.15 ± 1.40	18.45 ± 5.23	29.83 ± 1.04	22.98 ± 1.12	20.27 ± 7.69
Northern Rocky Mts., MT	11.65 ± 3.12	NA	8.26 ± 4.08	4.24 ± 1.28	7.76 ± 1.45	24.25 ± 0.44	8.06 ± 2.85	12.23 ± 1.16
Blue Mountains, OR	16.30 ± 8.91	12.94 ± 0.82	5.70 ± 2.03	3.51 ± 0.95	8.13 ± 4.036	13.49 ± 5.78	7.97 ± 3.70	6.04 ± 1.61
Central Sierra Nevada, CA	19.72 ± 7.44	27.57 ± 7.82	18.30 ± 6.73	9.33 ± 3.34	20.56 ± 9.47	30.08 ± 4.52	25.15 ± 2.08	10.68 ± 1.90
Southern Sierra Nevada, CA	52.05 ± 28.78	41.70 ± 8.86	33.48 ± 5.48	15.39 ± 5.55	NA	NA	NA	NA
Southwestern Plateau, AZ	8.63 ± 3.37	NA	10.59 ± 4.36	5.24 ± 0.42	11.79 ± 4.85	18.62 ± 2.85	9.69 ± 4.86	9.39 ± 1.52

1000-h rotten fuels excluded.

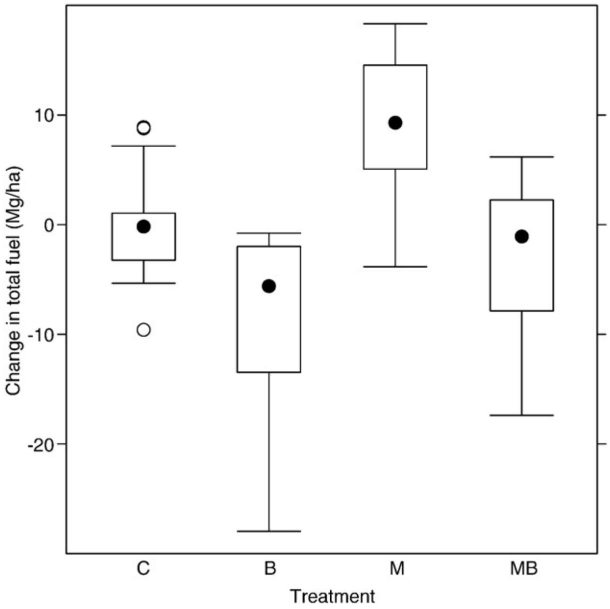

Fig. 2. Change in total surface fuel by treatment across all sites, one year post-treatment (C = Control; B = Prescribed Burn; M = Mechanical, MB = Mechanical + Burn). Dots indicate medians, boxes show first to third quartiles, and capped lines show ranges excluding outliers (black circles) outside 1.5 times the first-to-third interquartile range.

conducted at the Central Sierra site, converted ladder fuels and taller surface fuels into smaller pieces, generally in contact with the ground. Chainsaw felling and lopping of small trees (Southwest Plateau) generally produced larger pieces than did mastication, but piling of the lopped material and harvest residues concentrated the fuel and thereby reduced prescribed burning costs.

3.2. *Changes in fuel conditions*

Table 3 presents pre- and post-treatment surface fuel loadings for each site, and Fig. 2 displays the changes in loadings across sites. The burn-only treatments reduced surface fuels across all six sites where pre- and post-treatment data were collected. The reductions averaged about 8 Mg/ha. In contrast, the mechanical-only treatments increased surface fuel loadings, by an average of approximately 10 Mg/ha for the five sites on which mechanical treatments were conducted and on which pre- and post-treatment information was available. Unfortunately, no pre-treatment data was available on the one site (Southern Cascades) where whole trees were removed. As noted previously, the whole-tree system should have the least impact of the mechanical treatments on total surface fuel loadings.

The combination of mechanical treatment followed by burning had little net impact on most sites. Increases in fuel loads caused by the mechanical treatments were mostly offset by the effects of the subsequent burns. The one notable exception was the Central Sierra site, where the masticated fuel bed produced by the mechanical treatment was efficiently consumed by the subsequent burn, reducing the pre-treatment loading by 14 Mg/ha versus only 9 Mg/ha for the burn-only treatment.

Pre- and post-treatment values for live stems and basal area per hectare are shown in Tables 4 and 5 respectively. All treatments reduced the numbers of live trees per hectare across sites, by averages of 10–60% for burning, 35–60% for mechanical treatment, and 60–80% for combined mechanical-burn treatment. The trees killed or eliminated by prescribed burning, however, were mostly of small diameter, so the burn-only treatment had essentially no impact on live tree basal area. As would be expected, mechanical and mechanical-plus-fire treatments both reduced basal area, by between 30 and 60% of pre-treatment values. At most sites, there was little difference between the basal area impacts of these two treatments, again reflecting the tendency of the prescribed burns to kill primarily the smallest trees. At the Central Sierra site, however, the heavy fuel bed created by mastication of the understory resulted in some mortality to larger trees during the subsequent burn.

3.3. *Post-treatment fire risk reductions*

Results from the six study sites on which modeling with Fuels Management Analyst Plus have been conducted indicate that all three active treatments mitigated potential fire severity to some degree. Stephens and Moghaddas (2005a) report modeled results for the Central Sierra FFS site; those for the other five sites will be published shortly (Stephens, in preparation). Mechanical treatment followed by prescribed fire was most effective, followed by fire only. The effectiveness of mechanical-only treatments varied: whole-tree harvesting removed the tops and limbs of the felled trees from the site and therefore reduced potential fire severity more than did treatments which

Table 4
Tree density (mean stems/ha +/− S.D.), pre- and post-treatment, of all live trees taller than 1.4 m

Site	Treatment							
	Control		Burn-only		Mechanical		Mechanical + burn	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Northeastern Cascades, WA	754 ± 452	748 ± 486	696 ± 178	643 ± 97	788 ± 418	335 ± 254	902 ± 318	283 ± 158
Northern Rocky Mts., MT	2387 ± 684	2581 ± 661	2620 ± 1867	2125 ± 1400	1719 ± 378	1143 ± 229	1407 ± 539	299 ± 157
Blue Mountains, OR	466 ± 69	513 ± 66	282 ± 62	253 ± 49	683 ± 212	426 ± 123	394 ± 197	168 ± 58
Central Sierra Nevada, CA	1579 ± 437	1677 ± 585	1261 ± 298	524 ± 59	1342 ± 544	552 ± 331	1153 ± 456	255 ± 50
Southern Sierra Nevada, CA	461 ± 71	456 ± 79	584 ± 72	336 ± 125	NA	NA	NA	NA
Southwestern Plateau, AZ	NA	654 ± 258	NA	562 ± 285	NA	189 ± 41	NA	140 ± 31

Table 5
Live tree basal area (mean m^2/ha +/− S.D.), pre- and post-treatment

Site	Treatment							
	Control		Burn-only		Mechanical		Mechanical + Burn	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Northeastern Cascades, WA	30.51 ± 5.49	31.85 ± 5.51	36.45 ± 8.46	36.88 ± 8.46	33.21 ± 4.87	16.66 ± 7.70	35.11 ± 1.47	20.20 + 2.52
Northern Rocky Mts., MT	23.93 ± 7.64	23.89 ± 7.61	22.80 ± 8.03	21.70 ± 2.79	20.59 ± 1.17	10.89 ± 1.47	21.03 ± 4.23	9.49 ± 0.27
Blue Mountains, OR	20.31 ± 6.44	21.27 ± 4.04	15.43 ± 3.41	15.50 ± 3.53	21.96 ± 6.88	14.83 ± 1.42	16.53 ± 3.10	10.55 ± 2.29
Central Sierra Nevada, CA	50.74 ± 4.97	56.85 ± 5.41	45.47 ± 3.49	47.92 ± 4.34	47.77 ± 3.25	41.21 ± 1.45	50.72 ± 2.34	39.44 ± 4.36
Southern Sierra Nevada, CA	61.78 ± 2.23	61.02 ± 1.45	68.79 ± 5.49	62.61 ± 7.34	NA	NA	NA	NA
Southwestern Plateau, AZ	28.89 ± 6.06	30.69 + 4.33	32.28 ± 6.82	29.31 ± 3.02	27.60 ± 2.16	14.26 ± 1.54	30.20 ± 4.33	12.57 ± 3.47

left activity fuels or biomass on site in the form of slash and/or masticated material.

The modeling emphasized that reduction in surface fuels is critical in the production of forest structures that are resistant to wildfire, although reducing ladder fuels is also very important. At the Central Sierra site, for example, the large reduction in surface fuels due to prescribed fire significantly altered modeled behavior of wildfires in both mechanical-plus-fire and fire-only treatments. These two treatments reduced fireline intensities, rate of spread, and predicted mortality relative to the control treatment. The mechanical-only treatment, which at this site left masticated small trees and limbs and tops of larger trees, was an improvement over the control, but resulted in higher predicted tree mortality than did the two treatments that included prescribed fire (Stephens and Moghaddas, 2005a).

4. Discussion

4.1. Financial aspects

The net cost results for mechanical treatment are highly sensitive to the values of the products generated by the operation. Stumpage prices in the western US vary considerably over time; Haynes (1998) found that for the ten-year period from 1986 to 1996 stumpage prices for national forests in the coastal Pacific Northwest varied from about 100 dollars per thousand board feet (mbf) to almost 600 dollars per mbf, changing by 200 dollars or more from year to year. Stumpage prices for national forests in the interior of the Pacific Northwest (east of the Cascade Mountains) were generally lower than for the coastal forests but no less volatile. In 1996, stumpage prices for the interior national forests ranged from about \$50/mbf to almost \$220/mbf while the average for the coastal national forests was about \$380/mbf.

For all of the study sites, most of the harvested trees could be utilized for relatively high-value products such as dimensional lumber. Ideally, from a financial prospective, dirty chips (a combination of wood, bark, and foliage) produced from woody materials that are not needed on the site for ecological purposes would be utilized to produce energy or converted to other products. Due to high delivered costs and low value of small material or lack of local facilities that accept dirty chips, only one site – Southern Cascades – provided material to the energy market. At that site, biomass accounted for 20% of the total material removed. Using this type of material is almost always a challenge for land managers; the volatility of markets, particularly for low value material, must be carefully considered in decisions to require removal of small trees (often considered trees less than about 18 cm at breast height). In situations where the removals are all of low value, mechanical treatments will generally have net costs. If managers understand the financial uncertainty associated with removing and selling this type of material they can work with contractors to evaluate whether it makes more sense to remove small trees and activity fuels or to treat them in place with combinations of mastication and prescribed fire (Fight and Barbour 2005). On national forests, giving contract officers and administrators flexibility in these types of decisions allows them to decide when it is better from a cost prospective to remove small trees or to treat on-site.

If management objectives require a combination of mechanical treatment and burning to adequately reduce potential fire behavior and effects, it may be possible to eliminate part of the mechanical treatment and thereby reduce its cost. For example, felling to waste or mastication of the smallest trees was carried out prior to burning at some of the study sites. Prescribed fire, after mechanized thinning of the merchantable and possibly some of the larger submerchantable trees, might achieve much of the same effect on ladder fuels as did felling to waste or mastication of all the submerch material.

Our results indicate that, in the western US, prescribed fire has relatively high costs due to the terrain and stand conditions, high fuel loads and the need to ensure that prescribed fires do not escape, especially near inhabited areas. Costs are generally higher in the western US than in other parts of the country. For example, in the USDA Forest Service Southern Region, management-ignited burn costs were reported to average only \$74 per hectare (Cleaves et al., 2000; adjusted to 2005 dollars). Currently, the incentives for line officers within the USDA Forest Service to treat specified target areas result in prescribed burning being allocated towards the lower cost, lower risk areas where these targets can be met (USDA, 2006).

As indicated by previous research cited above, burn costs per hectare are higher on small areas. In fact, unit size can be the primary factor in determining these costs. Small units may, based on burn complexity, still require the same amount of contingency resources (i.e. people and equipment) as larger units, increasing the per hectare cost. Unit size can be influenced by the local and regional tolerance for smoke emissions: as this tolerance decreases, so does corresponding unit size and/or area burned per burning period. In addition, as unit size decreases, it is more difficult to use existing roads and natural barriers as control lines, which increases burn prep cost.

Managerial decisions – such as placing high priorities on preventing escapes or minimizing smoke – influence burn unit costs (González-Cabán, 1997). Other factors affecting costs include overall stand condition, fuel type, burn complexity, and season of burning. Initial entry in untreated stands with excessive surface and ladder fuels can be more expensive than in stands which have been previously thinned and/or underburned. Prescribed fires in long-needle fuel types are typically easier to ignite and maintain higher rates of spread than short-needle-dominated units. In addition, short-needle stands are typically dominated by true firs (*Abies* species) which can suffer higher rates of mortality due to cambium char and crown injury (Ryan and Reinhardt, 1988; Ryan et al., 1988; Stephens and Finney, 2002).

Burn complexity typically increases depending on resources at risk and/or number of personnel needed to implement the prescribed fire. Increased burn complexity due to proximity to the Wildland–Urban Interface (WUI) can increase burn costs adjacent to communities. In addition, close proximity to the WUI may decrease unit size due to lower tolerance for smoke. In many areas mechanical-only methods are preferred in the WUI because they don't generate smoke and can't "escape." Finally, the costs of spring burning can be approximately 30% higher than fall burns due to additional holding and surveillance activity. Typically, spring burns must be completely (100%) mopped up due to approaching summer weather. Spring burns must be patrolled until they can be called "out." Units burned in fall can be partially mopped up and then extinguished with winter rains and snow. In addition, the probability of ignition decreases later in fall, requiring less frequent patrols.

4.2. Residual stand conditions

Agee and Skinner (2005) described basic principles for producing fire-resilient stands: reduce surface fuels, increase height to the live crown, decrease crown density, and retain large, fire-resistant trees. All four treatments (including control) achieved the last principle, the fire-only treatment met the first, and the two mechanical treatments were best at modifying crown characteristics. While all active treatments changed the conditions, the results were not the same. This has implications immediately, but also over time: burning produces an immediate reduction in surface fuels, while mechanical treatment has a bigger effect on ladder fuels and long-term effect on surface fuels. Mechanical-plus-fire provides both benefits.

For example, prescribed fire-only will normally produce an increase in small, standing snags (Stephens and Moghaddas, 2005b), which will eventually fall to the ground and become new surface fuels. Therefore, prescribed fire-only treatments will require follow-up treatments to maintain stands in a low-hazard condition. Mechanical-plus-fire treatments will produce longer intervals where fire hazards remain low because they remove small diameter trees from the site.

Only the Southern Cascades site employed the mechanized whole tree harvesting system, which leaves less activity fuel than do others (Agee and Skinner, 2005). This system is very competitive from the financial standpoint with the others employed in the FFS study, if tree sizes and other conditions allow its use (Hartsough et al., 1997).

4.3. Economic considerations

The costs presented here represent financial analyses, i.e. cash flows in essentially one time period. But the money spent on the treatments (including control) buys different results, and the return intervals for the active treatments would be different. Some effects occur immediately after treatment and diminish over time. Others, such as delayed mortality after fire and differences in understory vegetation, may appear after long and variable periods. Society needs to judge which residual conditions and other effects have more value, and consider the strings of benefits and costs over time, applying the social discount rate. Some of the values are easier to quantify (in dollars) than others. For example, it is relatively easy to track the operational costs of each of the active treatments. We can also make educated guesses as to how frequently to repeat the treatments, and future data from the FFS sites will improve these estimates.

The tougher issues relate to the social benefits and costs. What is a more fire-resilient stand worth? What are the health and other costs of smoke produced by prescribed burns versus smoke generated from these same stands if they are burned by wildfires? What is the benefit of using a relatively predictable mechanical treatment versus prescribed burning with associated risks of escape and uncertainty about changes in stand structure? What is the value of substituting harvested material for fossil fuel and thereby reducing net emissions of carbon dioxide? Each treatment (and wildfire) has different effects on soil, habitat and other site conditions. The lack of established markets for many of the benefits and costs makes it difficult to assign agreed-upon dollar values. Accepted econometric methods such as contingent valuation can provide estimates, but the values are controversial. Non-economic issues will continue to be a part of, and in many cases even dominate, the debate about what treatments are "best" to achieve a specific set of desired conditions. Clearly, treatments can't be compared on the basis of the financial costs alone.

The FFS treatments described in this paper produced stand structures that were relatively open and (when fire was incorporated) had low levels of surface fuel. The stands were, therefore, more resilient to fire than those generated by traditional silvicultural systems which favored retention of biomass and little or no secondary treatment of surface fuels (Stephens and Moghaddas, 2005c). Managing forests for increased fire resiliency can decrease potential suppression costs (Moghaddas, 2006) and help provide long term protection of wildlife habitat, recreation areas, watershed, and wood fiber, along with other values, on both public and private lands (Mason et al., 2006). Most analyses have indicated that the ecological effects of pre-emptive fuel reduction are subtle and transient. In contrast, the impacts of most large wildfires are much more severe. Decision processes for pre-emptive treatments must include expected future savings in suppression costs and decreased risk of loss of forest assets from fire due to large-scale implementation of fuel treatments on public and private lands.

4.4. Implications for management

Prescribed fire is a blunt tool: managers can choose when to apply it, but the results are variable. If pre-fire fuel loadings are high, it may be difficult or risky to achieve an 80–80 condition with fire alone in a single operation. Mechanical treatment can rather precisely achieve any prescribed removal of standing trees. Combined mechanical-fire treatments appear to have the best potential for transforming dense stands into fire-resilient ones.

Typically, the total acreage that managers have been able to treat in any given year with various fuel reduction methods has been small when compared to the acreage burned in most recent years by wildfire and suppression efforts. Some of the constraints are associated with the problems of managing prescribed burning: fires are risky, they generate smoke and are permitted only during rather narrow time windows. Others relate to actual or perceived negative impacts of mechanical treatments, especially the concern that fuel reduction is just an excuse to harvest more timber. Lastly, budgets for pre-emptive treatments are limited.

Due to the high value of human improvements (homes, etc.), pre-emptive fuel reduction in the WUI is clearly a high priority (US Congress, 2003). Given budgetary and other restrictions, it would be easy to concentrate all the efforts there. But much is sacrificed when extensive areas of untreated lands outside the WUI are exposed to wildfires.

Can substantially larger areas be treated? The potential for expanding the use of prescribed fire is somewhat limited by the narrow operating windows. Developing a large, capable workforce for this demanding, largely manual-labor activity would require opportunities for year-round employment.

Mechanical operations have longer seasons, can break even or better under many conditions, and probably need to be repeated less frequently than prescribed fires, so they have the potential to be scaled up. There is, however, the issue of surface fuels, which are not easily addressed by existing mechanical systems. Although a number of equipment-development efforts have focused on the collection of logging residues, new initiatives would be needed to address surface fuels in fuel reduction treatments. Obvious first steps are to utilize the whole tree system so that surface fuels are not increased, and to avoid mastication where surface fuels are an issue and the mechanical treatment will not be followed by prescribed fire.

One unanswered question is whether the forest products industry could absorb materials generated from a large-scale thinning program. Today, federal managers are concerned that they cannot offer sufficient volumes to interest wood processing firms, but if a large thinning program were instituted the opposite problem could occur. Abt and Prestemon (2006) have conducted an analysis that suggests that rapid additions of materials from fire-hazard-reduction treatments could depress raw material prices, at least in the short term, and also cause marginal private timberlands to go out of production.

For lands outside the WUI, we’re in a bit of a Catch-22. If not for current fuel loadings, natural fire could be utilized to a greater degree in place of active treatments. Pre-emptive reduction is needed on a large scale to allow the use of wildland fires. The doctrine of “Appropriate Management Response” allows fire managers to select a range of responses to fire events based on local management objectives, site specific fire behavior, and predicted fire weather (USDA, 2005). Appropriate Management Response includes the full range of actions from complete fire suppression to wildland fire use. Recently, National Parks and National Forests in the western US have begun expanding the use of fire as a management tool beyond designated Wilderness Areas and into areas previously managed by fire suppression only.

This shift in management philosophy has resulted in the use of wildland fire where fire has been excluded for several decades, in areas that have previously been harvested, are roaded, and are often closer to the WUI or developed recreation sites than Wilderness Areas where wildland fire has been used in the past. Therefore, it is not unlikely that many of these areas may have forest structure conditions similar to the pre-treatment/control conditions in this study. As quantified in this paper, the use of FFS treatments is likely to reduce the potential for high fire severity. Having forest structures which help reduce fire severity at a landscape level may decrease the need for immediate suppression. This would expand the range of appropriate responses for fire managers, allowing them to more easily apply the tool of wildland fire for beneficial use.

5. Conclusion

Implementing fuel treatments will remain a high priority for public land management agencies in the United States for the foreseeable future. Our results indicate that costs for treatments incorporating prescribed fire are generally higher in the west than published costs for other regions of the US. Treatments costs can be offset in some cases by the value of harvested material, although this may not be true where either product value per ton or amount of product removed is low.

Investments in fuel treatments should reflect the net gain in resource protection, whether those resources are human developments, water quality, scenic value, wildlife habitat, etc. These benefits, however, have not yet translated into equivalent operating budgets to carry out such treatments. Until this happens, managers might try to prescribe and package fuel treatments (including mechanical and prescribed burn-only) to reduce the cost of the combination.

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