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Fuel Reduction in Residential and Scenic Forests: a Comparison of Three Treatments in a Western Montana Ponderosa Pine Stand

Joe H. Scott

The Author

Joe H. Scott is a Forester with Systems for Environmental Management (P.O. Box 8868, Missoula, MT 59807) and a Consulting Forester specializing in fuel treatments for the wildland and urban interface. He received a B.S. degree in forestry and resource management at the University of California at Berkeley in 1990. He completed this study while pursuing an M.S. degree in forestry at the University of Montana.

Research Summary

Three contrasting thinning treatments to reduce fire hazard were implemented in a 100-year-old ponderosa pine/Douglas-fir (*Pinus ponderosa/Pseudotsuga menzesii*) stand on the Lolo National Forest, MT. All treatments included a commercial thinning designed to reduce crown fuels and provide revenue to offset costs. The treatments are outlined as follows:

1. **Minimum impact**: light commercial thinning from below, with slash hand-piled and burned.
2. **Revenue production**: moderate commercial thinning from above, whole-tree harvest.
3. **Forest restoration**: moderate commercial thinning from below, with broadcast burn.

Total surface fuel loadings were reduced slightly by all treatments, but fine fuel load increased except in Treatment 3. All treatments raised crown base height and reduced crown bulk density, making crown fires less likely.

All treatments generated income in excess of treatment cost. Treatment 2 produced a net income of $832 per acre treated, Treatment 3 earned a net income of $222 per acre, and Treatment 1 generated a net income of $156 per acre in 1996 dollars.

Analysis of the aesthetic quality of treated stands revealed that Treatment 1 was the most preferred, even over the untreated stand, and Treatment 3 the least preferred. Transitivity of preferences indicates that the preferences were not strong, indicating that the treatments actually have similar aesthetic value. A severely burned but otherwise untreated stand, when included in the analysis, was preferred even less than Treatment 3.

All treatments used in this demonstration were effective at reducing forest fuels and cost-feasible while maintaining or improving aesthetic quality. Individual preference, suitability for a particular site, or compatibility with other resource objectives may guide the choice of treatment.

Acknowledgments

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Contents

On the cover: an untreated second-growth ponderosa pine/Douglas-fir stand (left), and the same stand after a moderate thinning followed by prescribed underburn (right).

Rocky Mountain Research Station
324 25th Street
Ogden, UT 84401

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Introduction

Forests dominated by ponderosa pine (*Pinus ponderosa*) occupy roughly 40 million acres in the Western United States (Van Hooser and Keegan 1988), more than any other forest type. On roughly half of these acres, ponderosa pine is a climax species that forms pure stands. As a result of fire exclusion, many climax pine forests have become overstocked and have developed thickets of seedlings and saplings. However, they do not exhibit a shift in species composition over time in the absence of fire. On the other half of its range, ponderosa pine is a seral species that can be successionally replaced by more tolerant species such as Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and grand fir (*Abies grandis*). In the past, pine-dominated forests persisted in a "fire climax" state despite this successional pressure because of the species' ability to survive frequent, low-intensity surface fires better than its would-be successors. In the absence of fire, seral pine forests also become overstocked. In addition, they often develop an understory of shade-tolerant conifers. Seral pine forests may also exhibit a compositional shift in favor of the more tolerant associates of ponderosa pine, making restoration more difficult.

Although many old-growth ponderosa pine and Douglas-fir stands were uneven-aged (Arno and others 1995), most second-growth stands are even-aged. Logging in the late 19th century, which removed nearly all merchantable trees from a stand, created ideal conditions for regeneration of even-aged stands. The subsequent suppression of fire altered the disturbance regime of frequent, low-intensity fires responsible for creating the uneven-aged, pine-dominated condition in the old growth forests (Arno and others 1995). Many pine forests have not experienced a fire in the last 75 to 100 years, whereas under a "natural" regime they would have experienced several during that time.

These forests are flammable during the warm, dry summer months, and also burn under dry conditions during the spring and fall. The fires of past centuries were characteristically of low intensity and severity in pine forests due to their high frequency. Today, in contrast, fires in pine forests are much less frequent but exhibit higher intensity and may become crown fires. This change in fire regime (frequency and intensity of fires) can be partially attributed to changes in fuel loading and stand structure resulting from historic logging and fire suppression. The quantity of dead and down fuels has increased, leading to greater surface fire intensity and rate of spread. Stand density has increased, leading to increased likelihood of crown fire and making the trees more susceptible to fire damage. Also, the thickets of small trees provide a fuel ladder that allows a fire to burn from the surface into the tree crowns. These changes in fuels and stand structure lead to fires that cause more severe effects than in the past.

The ponderosa pine forest type is not only the most extensive and most altered by fire exclusion, but also one of the most used for residential and recreational development. Ponderosa pine forests are valued for their scenic quality and proximity to urban centers. Thinning in ponderosa pine forests will be necessary to reduce fire hazard and improve tree vigor. Because there are few documented demonstration studies that have applied hazard reduction treatments for residential and recreational settings, it is difficult to gain the public support necessary to successfully implement such treatments.

Fire hazard in ponderosa pine stands can be lessened by prescribed burning, removing understory fuels, pruning lower branches of small conifers, and thinning the stand to lessen the likelihood of a crown fire (Schmidt and Wakimoto 1988). In many cases in the Western United States, severe wildfires have exhibited reduced fire intensity and severity when they burned into areas treated with prescribed fire (Biswell 1963; Clark 1990) or thinning with fuel removal (McLean 1993). Such treatments generally keep the fire from spreading into tree crowns, thereby reducing fire damage and making fire suppression more effective.

Whether such a treatment is proposed for a residential property or in a recreation area, its effect on visual quality is of great concern. The scenic quality of a stand is usually directly related to tree size and inversely related to the amount of woody fuel, the presence of stumps, and other indicators of logging activities (Daniel and Boster 1976). These factors can be affected by hazard reduction treatments.

Many homeowners are aware of the need to manage fuels on their forest properties, but fail to act on this need because of their concerns about the cost of reducing fuels and negative effects on aesthetics. Hazard reduction treatments such as ladder fuel removal, pile or broadcast burning, and pruning can be costly. If combined with a commercial thinning, however, revenue from the sale of forest products could offset most or all of the cost of other noncommercial treatments. Other potential benefits of a silvicultural thinning to reduce fire hazard can include a more insect- and disease-resistant stand, increased growth rate, reduced tree mortality in case of a fire, and perhaps increased residential property value.

To effectively manage visually sensitive ponderosa pine forests, Forest Service managers and wildland homeowners need basic descriptive information and a demonstration of example thinning treatments to reduce fire hazard. This study was undertaken to provide such a demonstration and document outcome in terms of (1) the degree of hazard reduction, (2) any difference in visual preference, and (3) the cost feasibility of conducting the treatments.

Study Area

The study area is located in the Sixmile Creek drainage on the Lolo National Forest, about 20 miles northwest of Missoula, MT. The area is covered by a dense stand of second-growth ponderosa pine and interior Douglas-fir, with the fir constituting a minority of the total basal area but a majority of the understory trees. A few western larch (*Larix occidentalis*) are present in some of the treatment units. The main overstory cohort is 95 to 100 years old, and the oldest trees in the stand are widely scattered pines about 150 years old.

The study area is located near an area that historically received heavy Indian use. Prior to 1900, fires occurred at an average interval of about 8 years, more frequent than if the area had been more remote from Indian use (Barrett 1981). Fire records and the lack of fire scars on trees that became established following the early logging in the 1890's indicate that there have been no fires in this stand since its creation.

Slopes within the study area are generally south-facing and incline 5 to 20 percent. The area is located at about 4,000 feet elevation. Habitat type (Pfister and others 1977) over most of the study area is *Pseudotsuga menziesii/Physocarpus malvaceus, Calamagrostis rubescens* phase—Douglas-fir/ninebark, pinegrass. This habitat type falls in Fire Group Four: the warm, dry Douglas-fir habitat types (Fischer and Bradley 1987). Ponderosa pine is a seral species on these habitat types, but frequent fires prevented succession toward a Douglas-fir forest. However, in the absence of disturbance these stands will in theory succeed toward a Douglas-fir climax as the ponderosa pine overstory dies out and is replaced by advanced regeneration of Douglas-fir. From a practical standpoint, a severe wildfire is likely to intervene. Unlike a low-intensity fire, a severe wildfire may lead to an increase in Douglas-fir in the postfire community (Arno and others 1985).

The stands in the study area are even-aged and relatively even-sized. Average stand diameter at breast height is approximately 10 inches (fig. 1). Maximum tree diameter is 23 inches for both ponderosa pine and Douglas-fir. The stands in the study area support a basal area of roughly 140 ft^2 per acre. Understory vegetation is composed mainly of grasses (dominated by pinegrass [*Calamagrostis rubescens*]), the low woody plant kinnikinnick (*Arctostaphylos uva-ursi*), shrubs such as snowberry (*Symphoricarpos albus*), ninebark (*Physocarpus malvaceus*), and an occasional serviceberry (*Amelanchier alnifolia*). Douglas-fir regeneration occurs as individuals and in clumps throughout the study area. There are an average of 427 Douglas-fir established seedlings per acre (1 to 4.5 feet tall), but only 15 of ponderosa pine.

Methods

Treatments

The treatments were designed around three contrasting "themes", each with the overall goal of reducing fire hazard and improving forest health (table 1). The three alternatives emphasize: (1) minimum impact, (2) revenue production, and (3) forest restoration. Four rectangular 6 acre treatment units were established, one for each treatment, plus an untreated control. A principal requirement of any forest fire hazard reduction treatment is to increase crown base height, reduce crown fuel load (and bulk density), and remove ladder fuels to prevent a fire from spreading into the crowns. If possible, a treatment should generate enough revenue to offset its costs so that widespread application is more feasible. Therefore, the treatments in this demonstration involve a commercial thinning to reduce crown fuels and improve tree vigor by reducing stand density, as well as to produce revenue. Treatments varied in the harvesting method, slash disposal method, basal area of the post-harvest stand, and thinning method (for example, from below or from above).

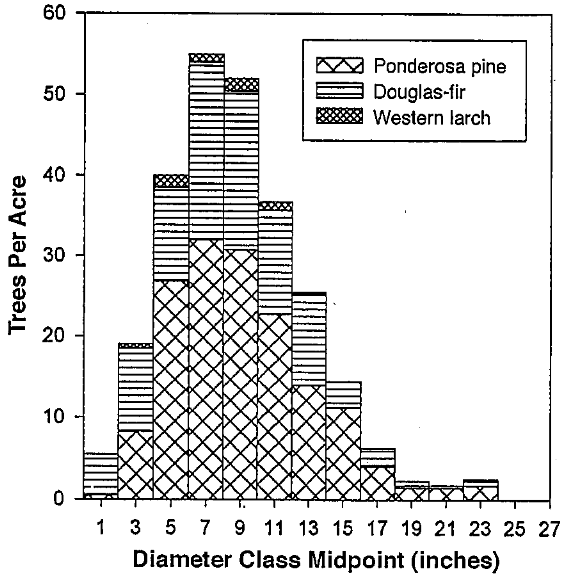


Figure 1—Diameter distribution of trees taller than 4.5 feet in the study area, before treatment. There are an additional 427 Douglas-fir and 15 ponderosa pine established seedlings (between 1 and 4.5 feet tall) per acre.

A thinning from below (or low thinning) removes the smaller, weaker trees to favor the larger dominant and codominant trees. A thinning from above—also called crown thinning and high thinning—favors dominant and codominant trees by removing competing trees in these same crown classes. Selection thinning is the removal of large, dominant trees to release vigorous trees of lower crown classes. The "Revenue production" treatment (unit 2) was primarily a crown thinning, but also included elements of low and selection thinning. In such a hybrid treatment, the average stand diameter can increase or decrease depending on the relative number of dominant and small low-vigor trees harvested. Treatments that did not involve a commercial thinning component (such as understory removal, pruning, or prescribed burning alone) were not considered because of the importance of reducing crown fuels to minimize crown fire risk and the high cost of conducting these treatments.

Harvesting took place in the spring of 1993. Pile burning and firewood removal in Unit 1 occurred through fall. The broadcast burn in Unit 3 took place in September 1993. The burn unit was approximately 8 acres in size, including a buffer of about 50 feet around the unit. Low temperature on the morning of the burn was 33 °F, and the high was near 70 °F. Minimum relative humidity was 35 percent. Ignition began at 1:00 p.m. and was completed by 5:00 p.m. Eye-level winds were less than 1 mph. Strip- and spot-headfire ignition patterns were used. The fire spread slowly through the slash fuels and not at all through the natural fuelbed, which was still green with pinegrass. Flame lengths averaged 2 to 3 ft, with occasional flareups of 5 to 6 ft. The fire covered approximately 85 to 90 percent of the unit; 94 percent of the sample trees had some degree of bark char.

Fuels and Vegetation

Ten permanent sampling points were located systematically within each treatment unit to measure stand structure and fuel loading. Each sample point consisted of: a $\frac{1}{10}$ acre circular plot for inventory of trees taller than 4.5 ft, a $\frac{1}{300}$ acre circular plot for tallying the number of trees between 1 and 4.5 feet tall by species, a planar-intercept transect for estimating dead, down fuel loading by size class, three

Table 1—Summary of treatment specifications.

	Unit		
	1	2	3
Treatment	Minimum impact	Revenue production	Forest restoration
Residual basal area	100 ft^2/acre	75 ft^2/acre	75 ft^2/acre
Thinning type	From below	From above (crown)	From below
Harvest method	Trees were hand-felled, limbed and bucked into logs, then skidded to a roadside deck using a modified farm tractor with logging winch.	Fully-mechanized tree-length logging using a track-mounted feller-buncher, rubber-tired grapple skidder and slide-boom delimber.	Same as Treatment 2, but most of the slash was "back-hauled" and distributed over the unit with the grapple skidder.
Slash disposal	Slash, some understory conifers, and jackpots of existing fuels were burned in small hand-built piles.	Slash was burned in one large landing pile. No further treatment took place in the unit.	The unit was broadcast burned in the fall under mild weather conditions.

point-samples of duff depth, four 1-foot square quadrats for estimation of needle litter, and herbaceous and shrub fuels (Brown and others 1982).

Visual Quality

Five forest conditions were evaluated for visual preference. Four conditions are simply the three treatments and the untreated control at the study site. The fifth condition was a stand of ponderosa pine and Douglas-fir, similar to those in the study area, that experienced a severe surface fire in the spring of 1995, causing heavy mortality in the overstory (80 to 100 percent in some areas). After the fire, some trees were salvaged for sawlogs and firewood, and the undergrowth recovered well. This condition was added to the analysis because it represents a possible condition of an untreated pine forest after a wildfire.

Several methods of evaluating forest aesthetics are available. Most are based on viewers judging scenes (either on-site or in photographs) and recording either a preference, numerical rating, or a word descriptor for the scene. Benson (1996) notes that the treated stands in this study are similar in appearance and have few differentiating features. Numerical rating systems such as the Scenic Beauty Estimation method (Daniel and Boster 1976) would require a large number of viewers to find statistically significant differences among such areas. The limited resources for this study did not permit an intensive evaluation using Scenic Beauty Estimation ratings. Instead, an alternative method using photo triads (sets of three photos) was used to obtain preferences directly (Benson 1996).

Six color photos were taken at representative locations in each unit in June 1996, during the third growing season of recovery. A total of 28 viewers were shown 10 sets of photos, three photos per set. (A few viewers had education or experience in natural resource management, but most were laymen.) Viewers were asked to view each set and indicate which scene they preferred most and which they preferred least (TRIAD method). The viewers were allowed to use their own criteria for determining preference. A photo judged "most preferred" was given a score of 3, the intermediate scene a score of 2, and the least preferred a score of 1. The treatments were ranked by summing the scores over all viewers and sets, providing a Total Vote Count (Coombs 1964). This method ranks the treatments by viewer preference, but does not measure the magnitude (or strength) of the preference. This photo preference analysis was conducted as a separate study (Benson 1996).

As mentioned earlier, the treatments were similar in appearance. This similarity could result in viewers not making sharp preference distinctions. This was examined by computing the "transitivity" of the rankings (how often individual preferences did not agree with the overall rank). For example, let's say that an overall ranking (by the Total Vote Count) indicates that area A is preferred over area B. The transitivity is how often the viewers ranked area B higher than area A in the triads. It is not possible to test for statistically significant differences among triad rankings.

It should be noted that in Treatments 1 and 3 the slash disposal takes place within the unit (either pile or broadcast burning), so its effect on visual quality is recorded in the photos. In Unit 2, however, the slash is piled and burned at the landing that is located some distance from the unit. Therefore, the visual impact of slash disposal in this treatment is not fully reflected in the photo preference survey results.

Potential Fire Behavior

Wildland fire behavior is a function of fuels, weather, and topography. Assessing changes in potential fire behavior involves examining how a treatment affects these three factors. Topography (slope and aspect) is not modified by hazard reduction treatments. The general weather pattern is not affected by hazard reduction treatments, but thinning can change how the general weather (20-foot windspeed, ambient temperature, and humidity) affects conditions at the fuel bed level (midflame windspeed, and fuel moisture) if the reduced canopy cover allows increased midflame windspeed or solar radiation. In general, thinning will make the surface fire environment more windy and perhaps drier for a dry, midsummer weather pattern. The fire hazard reduction potential of these treatments arises primarily from modification of surface and crown fuels. This modification must offset the "worsening" of burning conditions to be effective in reducing fire hazard.

The loading of crown fuels (Brown 1978), crown base height, and loading of surface fuels by size class and component (Brown and others 1982) were measured before treatment. This inventory was repeated two growing seasons after treatment (as opposed to immediately after treatment). The delay in post-treatment sampling was to allow needle fall from scorched needles and any change in herbaceous load to be measured.

Surface Fire—The fuel inventory provides the data needed to build custom fuel models (Burgan and Rothermel 1984) for input into the BEHAVE fire behavior prediction system (Andrews 1986). However, the mathematical model underlying BEHAVE is sensitive to fuel parameters that are very difficult to measure in the field (for example, fuel bed depth). Therefore, custom models must be calibrated by comparison with actual spread rate observations by adjusting model inputs such as bulk density and heat content (Burgan 1987). Because this adjustment is not possible in small treatment units, a method of predicting fire behavior that combines a fuel inventory with a standard fire behavior fuel model (Anderson 1982) must be employed.

For this study, surface fire rate of spread is predicted from the most appropriate standard fire behavior fuel model for each unit. Fireline intensity for the standard model is "adjusted" to reflect the actual fine fuel load in the treatment unit. The fireline intensity predicted for the standard fuel model is multiplied by the ratio of fine fuel load in the custom model to that of the standard model to obtain an estimate of the fireline intensity for the treatment units. This adjustment is made to maintain consistency in computing fireline intensity. The fraction of the total fine fuel load consumed in the flaming front for the custom model is assumed to be the same as the standard model. This method results in fire behavior predictions that respond reasonably to environmental conditions, yet are also sensitive to subtle differences among the treatments. These surface fire predictions alone are useful indicators of fire potential, but are also used in conjunction with crown fuel descriptors to determine crown fire potential.

Crown Fire—Several models and guides exist to help in making crown fire hazard assessments. Fahnestock (1970) produced a dichotomous key to rate crowning potential on a scale of 0 to 10 from characteristics such as foliage type, moisture and flammability, canopy closure, and abundance of ladder fuels. However, the ordinal ratings do not consider the contribution of surface fuels to crowning and do not permit determination of environmental conditions that lead to crowning. Van Wagner (1977) presented theoretical models to determine critical fire behavior that leads to crown fire initiation and sustained crown fire spread. He used these critical values to classify crown fires as passive or active. Rothermel (1983) provided a rule-of-thumb for predicting crown fire spread rate from the predicted spread rate of the surface fire. He later refined this rule by a linear regression of predicted surface fire spread rate (using Fuel Model 10 and wind reduction factor 0.4) with observed crown fire spread rate for several documented fires (Rothermel 1991). Albini and Stocks (1985) present a promising but not yet fully developed model of crown fire rate of spread based on a radiation-driven fire spread model (Albini 1985a,b). Van Wagner (1993) suggests a method of predicting the rate of spread and intensity of a crown fire making the transition from passive to active spread, based on the proportion of crown fuel consumed.

Van Wagner's (1977) crown fire criteria help managers make hazard assessments (Alexander 1988) and design silvicultural treatments to create crown-fire safe forests. With currently available technology, crown fire hazard assessments can also be made by linking models of surface fire behavior (Albini 1976; Rothermel 1972), crown fire rate of spread (Rothermel 1991), and crown fire initiation (Van Wagner 1977) to solve for the environmental conditions that lead to crown fire activity. Linking these models not only permits detailed assessment of crown fire potential of a particular site, but is also useful in demonstrating how different factors affect crown fire initiation and spread.

1. *Conditions for crown fire initiation*

Briefly, Van Wagner (1977) theorizes that crown fuels will ignite when the heat supplied by the surface fire raises crown fuels to ignition temperature (after first driving off moisture). He identifies the critical (minimum) fireline intensity, I_c, that will ignite foliage of a given heat of ignition and height above ground.

$$I_c = (C\,z\,h)^{3/2} \tag{1}$$

where C is an empirical constant, z is the crown base height, and h is the heat of ignition of crown foliage. In the original SI units, Van Wagner (1977) empirically determined C to be 0.010 and

$$h = 460 + 26\,m \tag{2}$$

where m is the foliar moisture content, percent. Combining equations (1) and (2) yields

$$I_c = (0.010\,z\,(460 + 26\,m))^{3/2} \tag{3}$$

with intensity in kW/m and crown base height in meters. The English unit version of equation (3) is

$$I_c = (0.0030976\,z\,(197.90 + 11.186\,m))^{3/2} \tag{4}$$

with intensity in BTU/(ft·s) and crown base height in feet (Alexander 1988). The crown fire initiation model is not as sensitive to changes in foliar moisture content as it is to crown base height and surface fire intensity. For this analysis, foliar moisture content will be held constant at 100 percent for all treatments (Philpot and Mutch 1971).

2. *Conditions for sustained crown fire spread*

By rearranging a basic heat balance equation applicable to fire spread in any fuel complex, Van Wagner (1977) theorized that solid flames would form in the crowns if a critical mass flow was met. His empirically determined value (3.0 kg/(m^2·min)) compares favorably with the minimum value given for experimental fuel beds by Thomas (1963). Thus, the critical rate of spread is

$$R_c = 3.0/d \tag{5}$$

where R is the after-crowning spread rate (m/min) and d is the crown bulk density (kg/m^3). The English unit version of this criterion is

$$R_c = 0.55861/d \tag{6}$$

where R_c is in chains/hr and d is in lb/ft^3. Fire spread rate after crowning can be predicted using the method described by Rothermel (1991). Briefly, Rothermel's estimate of crown fire rate of spread is 3.34 times the rate of spread predicted for surface fuel model 10 using a 0.4 wind reduction factor, regardless of the actual surface fuels or wind reduction factor. Some authors (Bessie and Johnson 1995) have incorrectly multiplied the predicted surface fire rate of spread for the actual surface fuels and wind reduction factor by 3.34 to obtain an estimate of crown fire rate of spread.

These criteria for initiation and sustained spread are used to classify a fire as follows:

Crown fire classification		Predicted crown fire spread rate	
		Less than critical spread rate	Greater than critical spread rate
Predicted surface fire intensity	Less than critical intensity	Surface fire	Surface fire
	Greater than critical intensity	Passive crown fire	Active crown fire

where a passive crown fire is one in which individual trees (or small groups) torch out but the overall rate of spread is controlled mainly by the surface fire, and an active crown fire is one that advances as a wall of solid flame extending from the surface to above the tree canopy (Alexander 1988). The overall rate of spread of an active crown fire can be much greater than that of a surface fire alone, and is predicted by Rothermel (1991).

Van Wagner (1977) further supposes that an independent crown fire would result if the crown fuel layer could provide all of the heat flux required for solid flame propagation, but does not provide any criteria for identifying when, or if, this phenomenon might occur. An independent crown fire is one that advances in the crown fuel well ahead of (or in the absence of) the surface fire, requiring none of the surface fire's energy for sustained spread in the crowns. If such a fire can indeed occur in a forest canopy, it surely would be short-lived (Van Wagner 1993) and require a combination of steep slope, high windspeed, high crown bulk density, and low foliar moisture content. Given the dubious and fleeting nature of independent crown fires, they will not be discussed further.

The next step in making crown fire hazard assessments is to determine the environmental conditions (wind and moisture) that produce the critical fire intensity and rate of spread for a given set of surface and crown fuel characteristics. In this study, the potential fire hazard of the treated areas was determined from the predicted surface and crown fire behavior and the measured crown fuel parameters. Because crown fires generally take place during dry weather, surface fuels can be assumed to be dry, and the critical 20-foot windspeeds that correspond to initiation and sustained spread of crown fire can be used to compare the treatments. Canopy cover after treatment varies among the different treatments, therefore, the wind reduction factor also varies (see table 5 in results). The midflame windspeed, therefore, varies from treatment to treatment according to its assigned wind reduction factor.

Economic Feasibility

The net cost (or revenue) of conducting each treatment was estimated by subtracting the cost of implementing the treatment (sale planning and administration, harvesting, and slash disposal) from the revenue (sale of sawlogs) that each treatment produced. Some treatment costs are incurred per unit of volume harvested (for example, harvesting cost), while others are incurred per acre treated (for example, broadcast burning, planting, and herbicide application). Some costs are commonly reported on a per-acre basis but are more accurately estimated from the volume harvested (for example, hand-pile burning). Lastly, some costs are reported on a unit volume basis but have significant per-acre and fixed cost components (for example, sale planning and administration). Before computing the net cost or revenue, the various costs and revenues must be converted to a common unit of measure. Because these treatments have different per-acre harvest volumes but identical treatment area, the net cost or revenue is ultimately expressed on a per-acre basis. Changing the size of the treated area or the unit volume harvested could affect the net per-acre cost or revenue.

Future monetary (residual stand value and reduced fire suppression cost) or nonmonetary benefits (improved wildlife habitat, reduced suppression cost, and reduced wildfire damage) were not evaluated and must be considered separately. This study reports only the immediate-term monetary costs and revenue.

Revenue—At the time these stands were treated, pulplog prices were roughly equal to the cost of treatment, so the harvest of this small material did not materially affect the net cost or revenue. Because of the relatively small number of pulplog purchasers in the region, no agency monitors pulplog prices. In addition, pulpwood volume accounted for only a small fraction of the total volume in this demonstration. Therefore, the pulplog price and volume have not been used in this study. However, treatment of some ponderosa pine stands will require removal of a much higher proportion of pulpwood. In those cases, the pulplog price may significantly affect the economic feasibility of the treatments.

Revenue was estimated by multiplying the unit volume of harvest in thousands of board feet per acre (MBF/acre) in each unit (determined from the pre-sale timber cruise) by the average log price for the species and product mix harvested ($/MBF) to arrive at the revenue per acre ($/acre). Log prices were taken from the quarterly Montana Sawlog and Veneer Log Price Report published by the Bureau of Business and Economic Research at the University of Montana. Log prices can fluctuate considerably, so the average log price was computed quarterly for the past 10 years to calculate cost-feasibility over this time.

Costs—Keegan and others (1996) reported timber management costs for several land ownership types in Idaho and Montana. Their accounting divided management costs into the following categories:

Sale design and administration
Reforestation
Road construction
Long-range planning
Timber stand improvement

Not all of these costs will apply when estimating the cost-feasibility of a particular treatment. For instance, the treatments applied in this demonstration did not require reforestation or road construction. (Second-growth forests in residential and recreational areas often have sufficient access even without additional road construction.) Many long-range planning costs (such as research and development, inventory, managing public use, and fire protection) apply to a whole land management program rather than to any individual project, so can be ignored when determining cost feasibility. Timber stand improvement costs (such as ladder fuel removal or broadcast burning) are based on their actual costs in the demonstration treatments. Sale design and administration costs (including surveying, prescription writing, environmental analysis and documentation, litigation, sale preparation, and administration) total $52/MBF for National Forests but only $13/MBF for private industry lands (Keegan and others 1996). Nonindustrial private land management costs (often through a consulting forester) are not reported, but probably are similar to those of private industry. Because of this difference in sale design and administration costs between ownerships, cost-feasibility is reported for both National Forest and private land.

Additional costs to consider are harvesting and slash disposal. Harvesting costs were estimated from Keegan and others (1995) and from contractor estimates. Slash disposal costs were reported by the contractors and in the timber sale documentation.

Results and Discussion

Representative photographs of each unit after treatment are shown in color plates 1 through 4. While the untreated control had more basal area than the other units before treatment, it was similar enough to provide a good demonstration of initial stand conditions. The average stand diameter was increased after treatment in all units (table 2), because all treatments removed a large number of small trees relative to the number of larger trees (including Treatment 2). The smallest increase in average stand diameter was in Unit 2, which was thinned from above. Even though thinned from above, enough small (poor quality) trees were harvested to increase the average stand diameter. Treatment 3 showed the largest increase in average stand diameter (10.4 to 13.3 inches) because it was thinned from below with moderate intensity.

Visual Quality

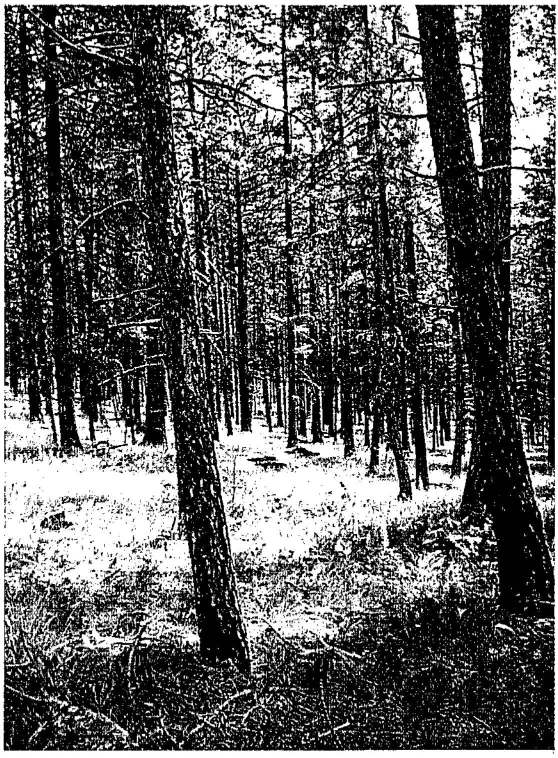
Using the TRIAD method of analyzing scenic beauty, the treatments were ranked by Total Vote Count (TVC) as follows (Benson 1996):

Rank	Treatment	Total vote count
1	Treatment 1 (minimum impact)	384
2	Treatment 2 (revenue production)	345
3	Treatment 4 (untreated)	332
4	Treatment 3 (forest restoration)	317
5	Treatment 5 (untreated; burned control)	302

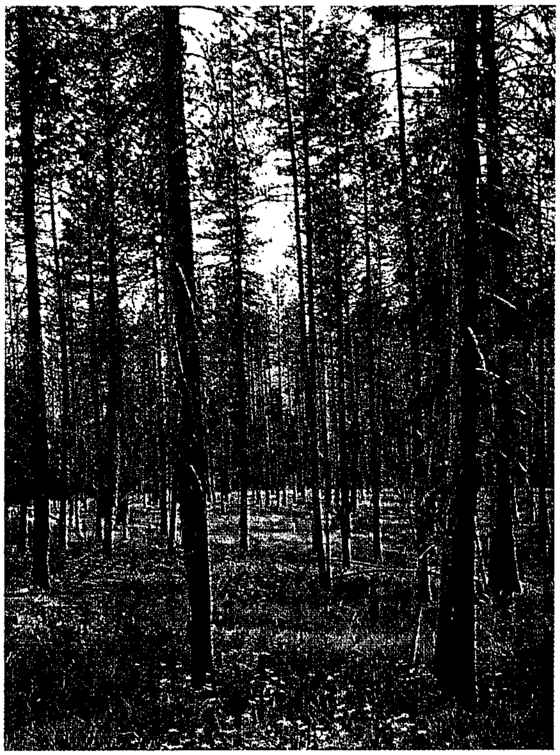
Table 2—Measures of stand density and tree size before ("pre") and after ("post") treatment.

Treatment	Basal area (ft^2/acre)		Density (trees/acre)		Average d.b.h.[a] (inches)	
	Pre	Post	Pre	Post	Pre	Post
1 Minimum impact	137	94	266	125	9.6	11.8
2 Revenue production	137	69	263	99	10.2	11.4
3 Forest restoration	145	76	266	78	10.4	13.3
4 Untreated	150		249		10.5	

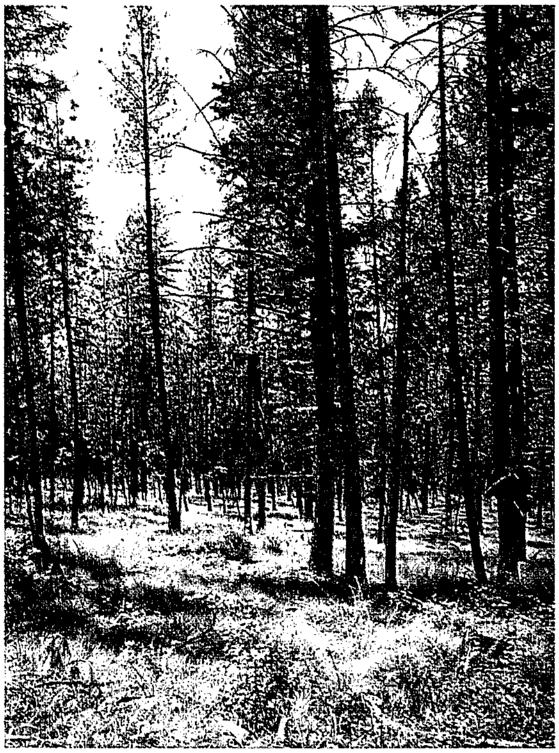
[a]Diameter at breast height.



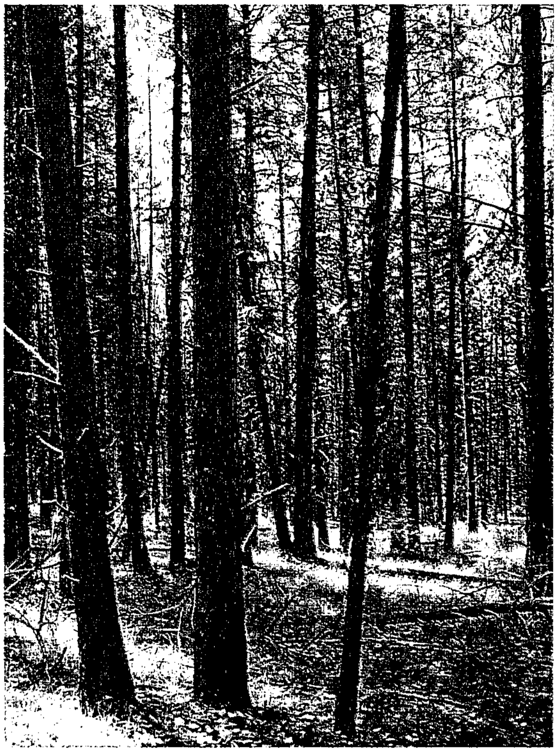
Color plate 1—Representative photograph of the **Minimum impact** treatment (Unit 1), 2 years after treatment. Photo by author in June 1995.



Color plate 3—Representative photograph of the **Forest restoration** treatment (Unit 3), 2 years after treatment. Photo by author in June 1995.



Color plate 2—Representative photograph of the **Revenue Production** treatment (Unit 2), 2 years after treatment. Photo by author in June 1995.



Color plate 4—Representative photograph of the **untreated stand** (Unit 4). Photo by author in June 1995.

Table 3—Transitivity between pairs of preferences. Source: Benson (1996). Note: ">" indicates preference, for example, 1 > 2 Treatment 1 preferred over Treatment 2.

Agrees with overall rank		Reverse of overall rank	
Treatment pair	Percent	Treatment pair	Percent
1 > 2	54	2 > 1	46
1 > 3	70	3 > 1	30
1 > 4	57	4 > 1	43
1 > 5	76	5 > 1	24
2 > 3	54	3 > 2	46
2 > 4	52	4 > 2	48
2 > 5	60	5 > 2	40
4 > 3	56	3 > 4	44
4 > 5	50	5 > 4	50
3 > 5	57	5 > 3	43

When examined by the TVC, the treatments appear to be very similar in preference (scores ranging only from 302 to 384). However, this scale does not start at zero. Because even the least-preferred scene in a triad set is given a score of 1, the minimum TVC possible is 168 (for example, all 28 viewers judge all six photos of a treatment as being the least preferred [one point] when compared with the others in the triad set). Similarly, the maximum TVC is 504.

By TVC, Treatment 1 was most preferred, whereas Treatment 5, the severely burned area, was ranked the lowest. There is some similarity in TVC among the different treatments, indicating that viewers might not have made sharp preference distinctions. This was tested by examining the transitivity of the preferences, or how often the individual preferences were "reversed" from the overall ranking. For example, although Treatment 1 was ranked higher than Treatment 2 in the overall ranking, sometimes (for some viewers and triad sets) Treatment 2 was preferred over Treatment 1. Of all individual preferences made, 59 percent were in agreement with the overall ranking shown above while 41 percent were intransitive. This indicates that there were not sharp differences in preference, reinforcing the notion that treatments were aesthetically similar. Preference among all pairs of treatments is shown in table 3.

The triad results show a slight preference for Treatment 1, probably due to the nearly complete cleanup of slash and the retention of large trees after harvest. Treatment 5, the untreated pine stand that was burned intensely then salvage-logged, was ranked lowest in visual quality. Interestingly, both Treatments 1 and 2 were preferred over the unharvested stand, contrary to the perception that untreated stands are most preferred. The treatments that involved broadcast fire (Treatments 3 and 5) were the least preferred, suggesting the viewers did not like the immediate effects of fire.

However, the intransitivity of the preferences indicates that preferences are not strong (especially between treatments of neighboring rank) and that differences between treatments of neighboring rank may not be significant. In an analysis of these treatments, Benson (1996) concludes that the treatments were similar in appearance, and apparently viewers did not detect any features that strongly influenced their preference.

Potential Fire Behavior

Surface Fire—In all units, both before and after treatment, surface fuels are best represented by Fuel Model 9 (Anderson 1982). Fire spread in Fuel Model 9 is controlled by a relatively compact layer of fine fuels, mainly pine needles in the present case. To adjust the standard model to conditions in each of the treatment units it is necessary to know the fine fuel load. Custom fuel models were created using the NEWMDL program of BEHAVE (Burgan and Rothermel 1984). Shrub fuels were sparse and small trees were scattered on all units, so their loading was not included in the custom fuel models. These widely scattered shrub patches would probably not affect the average surface fire behavior, but provide a "ladder" from the surface fuels to the tree crowns. Pre- and post-treatment surface fuel loading of individual classes is summarized in table 4. Note that most of the changes in fuel load are not statistically significant. However, the fuel inventory was designed to only characterize fuels for use in fuel modeling, not to test for significant differences, which would require a much larger sample size given the high degree of variability in fuel loading from point-to-point in a wildland fuel complex. Moreover, the significant differences apply only to the particular unit and not to the treatment in general, because the treatments were not replicated. Fine fuel load and other inputs needed to compute fireline intensity from the standard model rate of spread are summarized in table 5. The crown fuel characteristics required for assessing crown fire potential are shown in table 6.

Surface fire behavior was predicted using the Rothermel (1972) spread model, as modified by Albini (1976) using a PC-based spreadsheet, so that the predictions could be linked with crown fire initiation and spread models. Predictions were based on the "drought summer" fuel moisture conditions outlined by Rothermel (1991):

Fuel class	Fuel moisture
	percent
Dead 1-hour	4
Dead 10-hour	5
Dead 100-hour	7
Live	78

Table 4—Surface fuel loading by component (tons/acre).

	Unit (treatment)									
	1 (minimum impact)			2 (revenue production)			3 (forest restoration)			4
Class/component	Pre	Post	Change	Pre	Post	Change	Pre	Post	Change	(untreated)
			Percent			*Percent*			*Percent*	
Litter	1.25	1.11	–11	1.18	0.95	–19	1.18	0.69[a]	–42	1.16
Herbaceous	0.19	0.17	–11	.22	.26	18	.31	.37	19	.10
1 Hour	.23	.17	–26	.42	.19[a]	–55	.41	.06[a]	–85	.27
10 Hour	.89	1.19	34	1.13	2.23[a]	97	1.53	.98	–36	.92
100 Hour	1.02	1.31	28	1.46	1.02	–30	1.03	1.46	42	.58
Total fine fuels	3.6	4.0	10	4.4	4.7	5	4.5	3.6	–20	3.0
1,000 Hour sound	5.3	1.6	–69	4.0	.8[a]	–80	6.2	4.7	–24	3.8
1,000 Hour rotten	1.7	.7	–59	1.5	.9	–40	2.8	.3	–88	3.5
Duff	17.1	18.2	6	15.9	21.3	34	17.7	15.0	–15	17.7
Small trees	.11	.02[a]	–82	.11	.05	–55	.07	.0[a]	–100	.1
Total load	27.8	24.5	–12	25.9	27.7	7	31.2	23.6	–24	28.1

[a] Statistically significant difference from pretreatment at the 10 percent level significance.

Table 5—Surface fuel characteristics and wind reduction factor.

	Unit				
	1	2	3	4	
Treatment	Minimum impact	Revenue production	Forest restoration	Untreated	All
Load (t/acre)					
1 Hour	1.45	1.40	1.12	1.63	
10 Hour	1.19	2.23	.98	1.12	
100 Hour	1.31	1.02	1.46	1.02	
Herb	.08	.13	.18	.10	
Depth (ft)	.23	.27	.21	.22	
Wind reduction factor	.20	.25	.20	.15	
SAV[a] (1/ft)					
1 Hour					2,500
Live					3,000
Bulk density (lb/ft^3)					.803
Heat yield (BTU/lb)					8,000

[a] Surface-area-to-volume ratio.

Table 6—Crown fuel characteristics.

	Unit				
	1	2	3	4	
Treatment	Minimum impact	Revenue production	Forest restoration	Untreated	All
Crown base height (ft)	34	32	36	20	
Crown bulk density (kg/m^3)	0.064	0.045	0.051	0.082	
Canopy closure (percent)	70	50	60	80	
Stand height (ft)					70
Foliar moisture content (percent)					100

The predicted intensity and flame length for the units is plotted as a function of 20-foot windspeed (fig. 2). The 20-foot wind is used because there are different wind reduction factors for the treated and untreated stands (table 5) as a result of a change in canopy closure, and because weather forecasts predict this value rather than the eye-level or midflame wind.

These predictions are for level terrain. If desired, the effect of slope could be simulated by computing the effective midflame windspeed. This is done by combining the wind and slope coefficients of the model (as in BEHAVE [Andrews 1986]) and then dividing by the wind reduction factor to get the effective 20-foot windspeed. Unfortunately, there is no simple rule for adding slope and wind effects, because the additional wind speed represented by a given slope depends on the actual windspeed. For example, assume a fire burning in fuels represented by Fuel Model 9 on a 50 percent slope with no wind and a wind reduction factor of 0.2. The slope is equivalent to adding a 15 mph 20-foot wind. However, if there were already a 20 mph 20-foot wind blowing directly up slope, the slope now represents only 6 mph additional wind. Wind and slope effects are further complicated by cross-slope winds. The pertinent features of fire hazard assessment can be demonstrated without considering slope. Therefore, to simplify the discussion, slope is assumed to be zero.

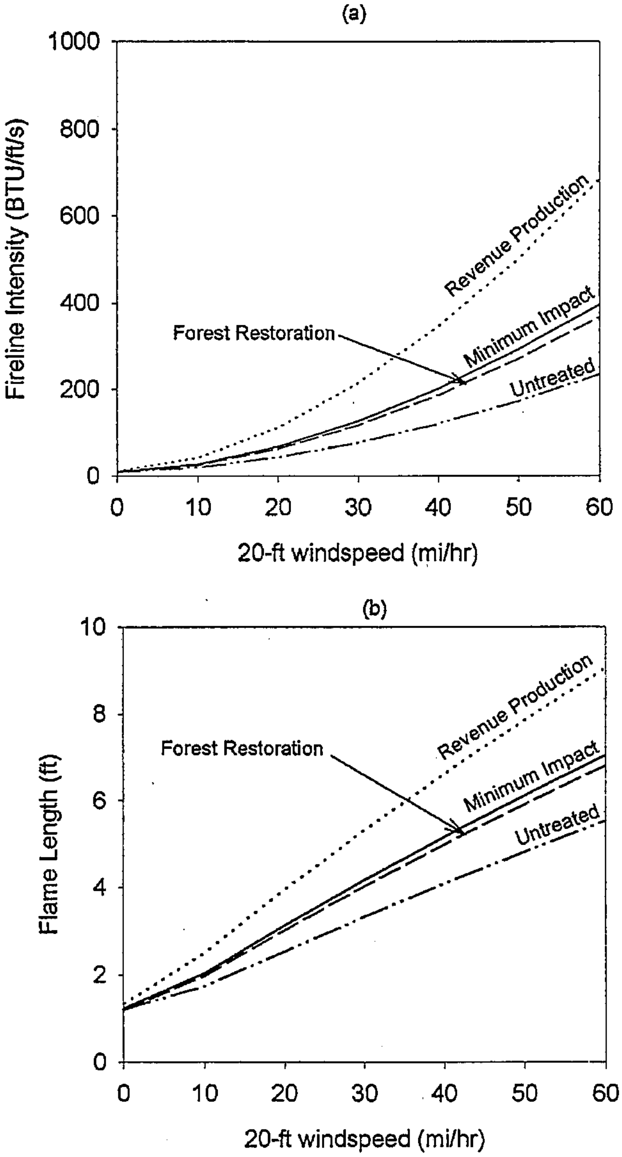


Figure 2—Predicted surface fire intensity (a) and flame length (b) for the treatment units. See tables 5 and 6 for input values.

Surface fire behavior is predicted to be higher in the treated stands because the more open stand conditions lead to higher midflame winds and possibly lower fuel moistures. The fuel load reduction did not offset these changes in the fire environment in the immediate post-treatment stand. However, fuel loads in the thinned stands may decrease over time due to reduced litterfall and decreased mortality. Despite the predicted increase in surface fire intensity, the post-thinning stands consist of larger, more fire-resistant trees than the unthinned stand, so fire severity may be lower in the treated stands. Lastly, crown fire potential may still be reduced even though the surface fire intensity increased.

Crown Fire—One way to determine the critical windspeeds for initiation and sustained spread of a crown fire is a graphical technique in which critical and predicted rates of spread are plotted against 20-foot windspeed (to allow for different wind reduction factors). The point where these lines cross indicates the critical windspeed for the specified surface and crown fuels (fig. 3). However, the critical parameter for crown fire initiation is fireline intensity, so it must be converted to an equivalent rate of spread. This conversion is made using Byram's (1959) equation defining fireline intensity, I

$$I = h\ w\ R \tag{7}$$

where h is the heat yield, w is the weight of fuel consumed in the flaming front, and R is the rate of spread. Rearranging to solve for R, we have

$$R_c = I_c \,/\, (h\ w) \tag{8}$$

where the h is the low heat of combustion and w is the weight of fuel consumed in the flaming fire front. Bessie and Johnson (1995) have incorrectly assumed that the weight of fuel consumed in the flaming front is the W_n parameter from Rothermel's fire spread model, but this is not the case. The W_n model parameter is the total fine fuel load reduced by only the mineral fraction. Not all of this fuel is consumed in the flaming front, especially in coarser fuelbeds. The

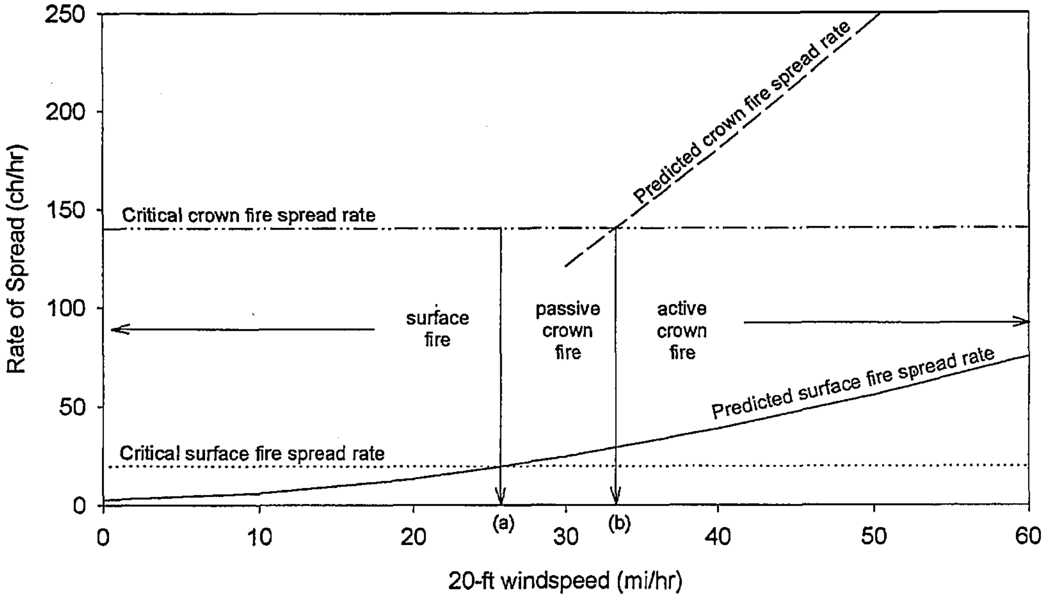


Figure 3—Graphical solution to finding critical windspeeds for the initiation (a) and sustained spread (b) of a crown fire for a hypothetical site.

problem of estimating the quantity of fuel consumed in the flaming front can be avoided by treating the quantity *h w* in equation (8) as one variable, heat per unit area (HPA). Heat per unit area is a standard output of the BEHAVE fire behavior prediction system. Although it is not a standard output of the model, the weight of fuel consumed in the flaming front, *w*, can be estimated by dividing the HPA by *h*. During "drought summer" fuel moisture conditions, the models predict that only 33 percent of the fine fuels in Fuel Model 9 are consumed in the flaming front (regardless of wind or slope).

The critical windspeed for crown fire initiation under the specified conditions of fuel load, moisture, and crown base height is determined from the intersection of the predicted and critical surface fire rate of spread. Next, we determine the critical windspeed that corresponds to sustained crown fire spread by plotting the critical rate of spread for solid flame (Van Wagner 1977, 1993) and the predicted crown fire rate of spread (Rothermel 1991). The intersection of these two lines gives the critical windspeed corresponding to the onset of active crown fire spread. Thus, a fire may remain a surface fire or become a passive or active crown fire depending on the windspeed (fig. 3). The dynamics of these transitions to crown fire can be further described as follows:

1. *Crown fire initiation*

A more accurate solution requires rearranging equations in the mathematical fire spread model to solve for these critical windspeeds explicitly (Scott and Reinhardt, in preparation) rather than relying on a graph. The critical 20-foot windspeed to initiate crowning for each of the treatments during "drought summer" fuel moisture conditions is shown below:

Unit	Treatment	Critical 20-foot windspeed for crown fire initiation ("drought summer" fuel moistures)
		mph
1	Minimum impact	216
2	Revenue production	135
3	Forest restoration	256
4	Untreated	188

Despite the increased surface fire intensity as a result of opening the canopy, the critical windspeed for initiating a crown fire was increased by Treatments 1 and 3 because the crown base was raised by the low thinning (Treatment 1) and broadcast burn (Treatment 3). In other words, Treatments 1 and 3 are less prone to initiating crown fires than the untreated stand. Treatment 2, however, is more prone to initiating crown fires because the crown bases were not raised as much, and that stand was the most open after treatment. This criterion refers to the initiation of a crown fire. Whether the crown fire is simply torching individual trees or an active crown fire is determined by a second criterion for sustained crown fire spread.

The very high windspeeds theoretically necessary to initiate crown fire in these stands indicate there is little risk of crown fire initiation even in the untreated stand. This is due to the relatively high crown base and low surface fuel load of the study area stands. Many ponderosa pine stands have lower crown base heights and heavier surface fuel loads, making crown fire initiation much more likely. One very important factor in determining whether ponderosa pine stands will crown is the presence of a conifer understory. In many pine stands, shade-tolerant conifers have invaded the understory and grown tall enough to create nearly continuous crown fuels from their base to the top of the main overstory trees. In such cases the effective crown base height becomes that of the understory trees, as low as a few feet, and initiation of crown fire can occur at 20-foot windspeeds as low as 22 miles per hr with surface fuels characterized by Fuel Model 9. The stands in this study currently have a conifer understory of seedlings mainly less than 4.5 ft tall. In this state, the understory does not pose a significant threat. However, as this understory grows, the "effective" crown base height will be reduced, making the crown fire hazard much greater. Therefore, treating stands at this stage should be viewed as a proactive measure to forestall the increasing crown fire initiation hazard.

The critical windspeeds for crown fire initiation are based on average surface fire intensity and average crown base height within a given area. In some portions of this area, the surface fire will be more intense than average and the crown base lower than average. Windspeeds much lower than the critical values may initiate crowning in these portions of the stand. Although these models may not accurately predict the exact windspeed at which crowning will begin, they do permit us to rank the treatments by the critical 20-foot windspeed required to initiate crowning so we can compare the effects of the different treatments.

Lastly, recall that this analysis does not include the effect of slope on the critical windspeed for crown fire initiation. If the wind is blowing up a steep slope, a lower windspeed than that computed for level ground can initiate a crown fire. However, at high windspeeds the marginal effect of slope is small and can safely be ignored.

2. *Sustained crown fire spread*

The critical windspeed for sustained crown fire spread, should such a fire be possible, is a function of crown bulk density and the after-crowning rate of spread. Because Rothermel's method for estimating crown fire rate of spread uses a wind reduction factor of 0.4 regardless of the actual wind reduction factor, predicted crown fire rate of spread is the same for each treatment. Therefore, the difference in critical windspeed among treatments results solely from differences in crown bulk density. Critical 20-foot windspeeds for sustained crown fire spread are shown below:

Unit	Treatment	Critical 20-foot windspeed for sustained crown fire spread ("drought summer" fuel moistures)
		mph
1	Minimum impact	33
2	Revenue production	43
3	Forest restoration	39
4	Untreated	27

Thinning reduces the crown bulk density in rough proportion to the volume removed, so the highest critical windspeed (most crown fire resistant) for active crown fire spread comes from the most heavily harvested treatment (revenue production), and the lowest value (most susceptible) come from the untreated stand.

In these cases, the critical conditions for sustained crown fire spread are less severe (lower windspeed) than the conditions for crown fire initiation. Thus, if the actual windspeed is greater than critical required for crown fire initiation, the fire would be classified as active; passive crown fire would not occur. This situation occurs where the crown bulk density is high enough to sustain crown fire spread at relatively low windspeeds but the crown base is too high for initiation unless the windspeed is greater.

It is desirable that a treatment both prevents crown fires from initiating within the treated area, and brings an active crown fire back to the surface. The importance of the crown fire initiation parameter is reduced if an active crown fire is burning toward a treated stand—the crown fire has already initiated. However, the sustained crown fire spread parameter provides a good indicator of the relative fire-stopping potential of different treatments. Thus, all three treatments were effective at reducing the active crown fire potential by reducing crown bulk density.

Reduced crown bulk density probably has an even greater effect on crown fire potential than indicated by the critical windspeed. Although Rothermel's method of predicting crown fire rate of spread is insensitive to crown bulk density, in reality the bulk density of crown fuels probably affects rate of spread just as in surface fires (Burgan and Rothermel 1984). Because crown fuels are so loosely packed, increasing its bulk density would likely lead to increased rate of spread. Therefore, thinning to decrease crown bulk density not only increased the critical rate of spread for sustained crown fire spread but probably also decreases the potential crown fire rate of spread, further increasing the critical windspeed at which sustained active crowning could occur.

Lastly, interpretation of the meaning behind differences in critical windspeeds (for either initiation or sustained active spread) requires some knowledge of the temporal distribution of windspeed. Even more important than the critical windspeed itself is how often that windspeed is exceeded. Higher windspeeds are exceeded much less frequently than low or moderate windspeeds. Therefore, a treatment's effect on how often crowning is possible is greater than the simple difference in windspeed indicates. For example, winds in excess of 40 mi per hr probably occur much less than half as frequently as winds in excess of 20 mi per hr.

Economics

One objective of this study was to determine the economic feasibility of the treatments—that is, whether the treatments will generate enough revenue to cover the costs of treatment design, administration, and implementation.

Revenue—The source of revenue from these treatments was the sale of logs to local sawmills. Only ponderosa pine and Douglas-fir were harvested in these units. The Bureau of Business and Economic Research at the University of Montana has tracked the price of delivered logs in Montana since 1990 without interruption. They report prices by species and product (sawlog versus veneer log). Veneer logs are larger (often ≥9 inch small-end log diameter, inside bark) than sawlogs, and must be cut to specific lengths (roughly 9-foot multiples) rather than random lengths for sawlogs (2-foot multiples). The sawlog price of ponderosa pine depends on the wood quality. The younger "bull pine" has wider growth rings, smaller diameter, and lower proportion of heartwood compared to the more valuable "yellow pine". The prices reported here are for second-growth "bull pine". The fourth quarter 1996 Montana Sawlog and Veneer Log Price Report indicates the following prices ($/MBF) for ponderosa pine (PP) and Douglas-fir (DF) logs delivered to western Montana mills:

	Product	
Species	**Sawlogs**	**Veneer logs**
PP	$359	$350
DF	$390	$493

Source: Bureau of Business and Economic Research, University of Montana, Fourth Quarter 1996 Montana Log Price Report.

To determine the total revenue generated by each treatment it is necessary to estimate the distribution of volume harvested among these species and product classes. Because the treatments differed in thinning type and intensity, product mix varied among treatments. The distribution of harvested volume in each of the units is as follows:

	Sawlogs		Peelers		
Treatment	**PP**	**DF**	**PP**	**DF**	**Total**
	percent				
1	16	16	34	35	100
2	8	14	39	39	100
3	16	30	36	18	100

Source: USFS preharvest timber cruise. Note: numbers may not total 100 due to rounding.

Finally, the weighted average log price ($/MBF) for each treatment is:

Treatment	Log price
1	$403
2	$412
3	$389

Costs—Total volume harvested per acre, average log price, logging cost, treatment design and administration costs, and additional costs such as slash treatment are shown in table 7. All costs are reported on a unit volume basis so they can be summed. Net revenue is reported in both $/MBF and $/acre. Treatment design and administration costs for Idaho and western Montana National Forests (Keegan and others 1996) is shown. (Sale costs for private land are only $13/MBF; compared with $52/MBF for National Forests.) Sale design and administration costs used here include: surveying, prescriptions, environmental analysis, appeals, timber cruising, marking, and harvest administration.

Table 7—Treatment costs and revenue.

		Unit		
		1	2	3
Treatment		Minimum impact	Revenue production	Forest restoration
(A) Harvest volume[a]	(MBF/acre)	1.71	5.23	3.56
(B) Logging cost[b]	($/MBF)	215	200	200
(C) Slash disposal[c]	($/MBF)	45	1	75
(D) Planning cost[d]	($/MBF)	52	52	52
(E) Total cost (B+C+D)	($/MBF)	312	253	327
(F) Total revenue[e]	($/MBF)	403	412	389
(G) Net revenue (F-E)	($/MBF)	91	159	62
(H) Net revenue (GxA)	($/acre)	156	832	222

[a] Source: presale timber cruise.
[b] Source: Keegan and others (1995) and contractor estimates.
[c] Source: Contractor estimates and timber sale report.
[d] Source: Keegan and others (1996).
[e] Source: fourth quarter 1996 Log Price Report, Bureau of Business and Economic Research, University of Montana.

Logging cost includes the costs of felling, limbing, bucking into log lengths, skidding logs to a landing, and hauling the logs 40 miles to the mill. In Treatments 2 and 3 the logging cost includes the cost of machine-piling slash at the landing or back-hauling. Logging cost in Units 2 and 3 were identical because the same harvest method was used. These harvest costs were estimated from data in Keegan and others (1995). Logging cost in Unit 1 was higher because a more labor-intensive method was used. The contractor provided the information on logging cost in Treatment 1.

Each treatment had additional costs, mostly relating to slash disposal. These costs were estimated by the contractor (hand-pile burning in Unit 1) or from the USDA Forest Service timber sale documentation (landing-pile burning in Unit 2; broadcast burn in Unit 3). The slash, some existing dead and down fuels, and some ladder fuels on Unit 1 were disposed of by burning in small hand-built piles at a cost of $462, or $45/MBF. (This works out to only $77 per acre, which may seem quite low. However, the reader should note that this treatment was a very light thinning from below, so very little slash was created.) The landing slash pile on treatment Unit 2 was burned at a cost of $20, or $3.33 per acre. Treatment Unit 3 was broadcast burned in the fall to reduce logging slash, remove Douglas-fir regeneration, and restore a vigorous understory. The burn was conducted by the USDA Forest Service Ninemile Ranger District (in cooperation with the University of Montana and the Intermountain Fire Sciences Laboratory) at a cost of $1600, or $75 per MBF ($267 per acre).

Net Revenue—As indicated in table 7, all treatments are cost-feasible since they are expected to generate more income than expenses at the reported level of log prices. Treatment costs are relatively stable, gradually inflating each year as the cost of labor, capital, and fuel increases. The price of logs, however, fluctuates widely with shifting supply and demand for lumber and logs. Figure 4 shows net revenue for the treatments over the last several years for both National Forest and private lands. Due to the lower sale design and administration costs, the net revenue from private land is consistently larger than for the National Forests.

In judging the revenue producing quality of the three treatments one can rank them based on the expected net revenue per acre. Treatment 2 generates the highest net revenue per acre because it has the highest volume harvested, the cheapest slash treatment, an inexpensive logging method, and no additional treatments. Treatment 2 produces more

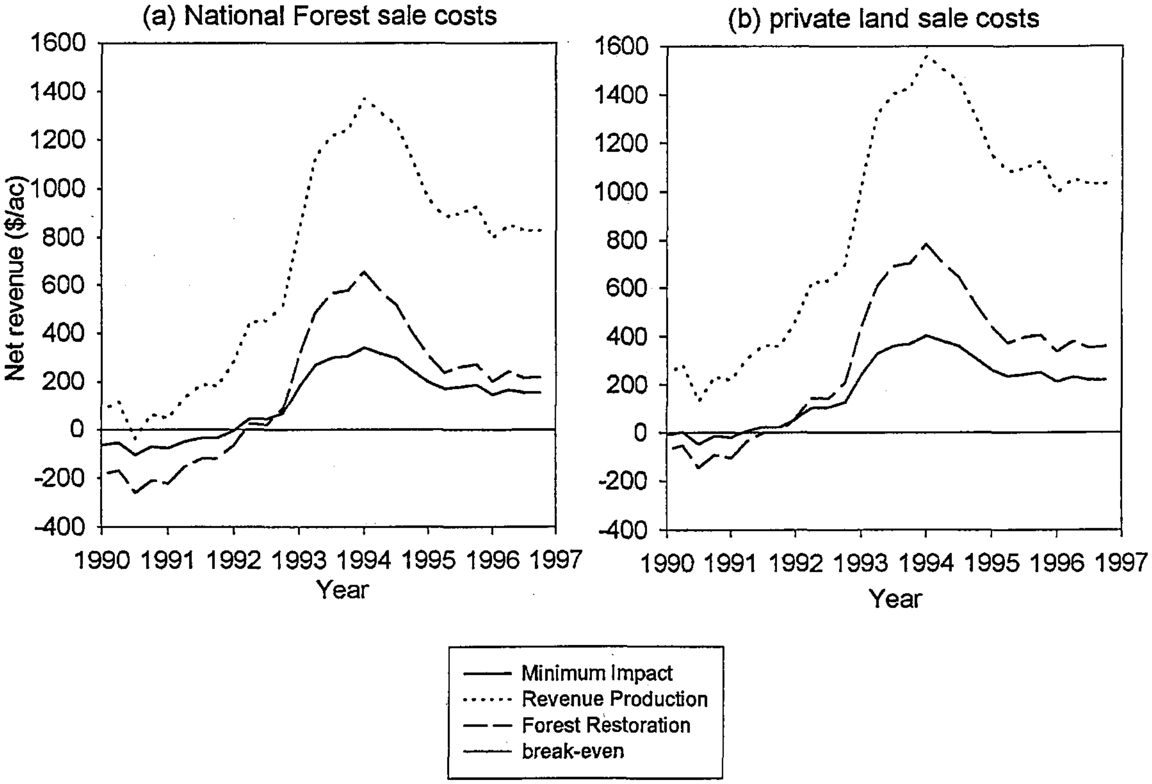


Figure 4—Net revenue (nominal-year dollars) over time for National Forest sale preparation and administration costs (a), and for private land sale costs (b). Treatment costs were discounted 3 percent annually to adjust for inflation.

than five times as much net revenue as Treatment 1 because Treatment 1 has a very low harvest volume, a more expensive logging method, and a moderately expensive slash disposal method. Treatment 2 produces 3.75 times as much net revenue as Treatment 3, because Treatment 3 has less volume per acre and a very expensive slash treatment. The cost of the broadcast burn is high largely due to the relatively small (6 acre) unit. Larger units with similar fuels can be burned at a much lower cost per acre.

It should be restated that the net revenue reported in table 7 and fig. 4 represents only immediate-term monetary benefits. Treatments 1 and 3 removed less volume in this entry and, therefore, have more residual growing stock than Treatment 2. Therefore, the value of the residual timber stand on Treatment 2 will be less than that of the other treatments. Moreover, the lighter treatments, especially Treatment 1, can be retreated sooner and more frequently than Treatment 2. Comparing the present value of these periodically retreated units is a subject for future research.

In summary, all of the treatments would generate more income than expenses at levels of log prices in the recent past. Through a simple economic analysis, Fiedler and others (1997) also concluded that restoration treatments could produce positive cash flow. Shifts in the supply and demand for lumber will largely determine the future level of log prices, and thus whether these treatments will remain financially feasible.

Review of Treatments

Table 8 summarizes important features of the treatments and indicates each treatment's relative rank in terms of potential fire behavior, aesthetics, and economics. All of the treatments developed in this study are appropriate for reducing fire hazard in an aesthetically pleasing and cost-feasible manner. Although the treatments are similar in design and implementation, there are differences among the treatments, both obvious and subtle, which make them appropriate in different situations.

Treatment 1: Minimum Impact

This treatment is favored for its aesthetic preference, being preferred over not only the other treatments, but over the untreated stand as well. The treatment was moderately effective in reducing fire hazard by reducing fine fuels, raising the LCBH, removing ladder fuels, and spacing tree crowns. Although this treatment produced less net income than the others, it nonetheless more than paid for itself, providing a return of $156 per acre to the landowner. This treatment is well-suited for small private residential properties where aesthetic values are high. This approach may also be useful as an initial thinning treatment that could be followed in a few years by additional thinning to enhance tree health. Such a two-stage treatment might also reduce wind or snow damage and make the transition to an open stand more gradual and acceptable to the public. The USDA Forest Service and other land management agencies may find such a treatment useful in areas with high recreational values where there is public concern over harvest impacts.

Without further treatment, this stand would eventually redevelop a Douglas-fir understory. Successful regeneration of ponderosa pine is unlikely at this high level of basal area. Surface fuels will accumulate as mortality of the weakest overstory trees continues. Crown fuels should remain low until the understory grows into the overstory crown space, which would take many decades. To maintain the open structure of this stand today, retreatment should be considered on a 10 to 20 year cycle. Broadcast burning could be easily applied at similar intervals to maintain low fuel loads and to keep the Douglas-fir regeneration in check.

A possible change to this treatment includes a lower residual stand density (perhaps about 85 ft^2 per acre) if the thinning is still done from below, leaving the largest, healthiest trees. The aesthetic acceptance of this treatment probably results from the nature of the thinning (from below) and the low-impact logging and slash disposal methods. A broadcast burn could probably be implemented in this treatment without significant degradation of aesthetic quality if it is conducted after the slash fuels have been eliminated. A burn conducted in slash fuels would likely result in too much bark char or mortality. The additional cost of the burn may make the treatment unable to pay for itself.

Treatment 2: Revenue Production

This treatment was effective at its emphasis of providing income. It produced more immediate-term income than the other treatments ($832 per acre), was effective at reducing the fire hazard by reducing crown fuel, and ranked high in visual preference. This type of treatment would be appropriate on a wide range of public and private land.

Over time, this stand will redevelop a conifer understory. Douglas-fir will dominate the understory, but successful regeneration of ponderosa pine is possible in the larger openings within the stand. Advanced regeneration of Douglas-fir that was not killed in this treatment will likely respond to the increased growing space and grow quickly. Broadcast burning could be used to control the composition of the regenerating conifers, favoring the more fire-tolerant ponderosa pine. Crown fuels should remain low for several decades, until the understory grows into the overstory crown space. Surface fuel loadings will remain low because of the reduced input of litter, and because

Table 8—Summary of results for all treatments. Overall rank is indicated in parentheses ().

<table>
<tr><th></th><th colspan="4">Unit</th></tr>
<tr><th>Treatment</th><th>1
Minimum impact</th><th>2
Revenue production</th><th>3
Forest restoration</th><th>4
Untreated</th></tr>
<tr><td rowspan="2">Surface fire (predicted intensity)</td><td>(3)
Predicted fire intensity increased slightly over the untreated (Unit 4) due mainly to the change in wind reduction factor resulting from the reduced canopy cover.</td><td>(4)
Slight changes in fine fuel loading and an increase in midflame windspeed resulting from the more open canopy lead to increased surface fire intensity.</td><td>(2)
Reduced surface fuels reduce hazard but the increased windspeed resulting from a more open canopy results in a slight increase in predicted fire intensity.</td><td>(1).
Surface fire hazard is low because fuels are not excessively heavy and the dense canopy reduces midflame windspeed considerably.</td></tr>
<tr><td colspan="4">Overall, surface fire behavior during drought summer conditions is predicted to be within the limits of mechanical control (flame lengths less than 11 feet) for all treatments, including the untreated control. However, significant mortality could result from consumption of duff and large woody debris. The thinned stands will add less litterfall to the surface than the untreated stand so should eventually have a reduced duff load. Repeated broadcast burning will accelerate this fuel reduction.</td></tr>
<tr><td rowspan="2">Crown fire initiation (critical 20-foot wind)</td><td>(2)
Low thinning raised the crown base, increasing the windspeed required to initiate crowning despite the increased surface fire intensity.</td><td>(4)
The high thinning did not raise crown as much as the other treatments and allowed increased windspeeds.</td><td>(1)
Low thinning and broadcast burning raised the crown base significantly. These factors overcome the slightly increased surface fire intensity to reduce the likelihood of crown fire initiation.</td><td>(3)
Despite the low predicted surface fire intensity, the low crown base height make crown fire initiation more likely than in Treatments 1 and 3.</td></tr>
<tr><td colspan="4">Based on average fuel loading and crown base height crowning is very unlikely to be initiated in any of these areas. However, some areas of these stands will have higher-than-average fire intensity and lower-than-average crown base, making crown fire initiation possible at these locations. Therefore, despite the high windspeeds required to initiate crowning in these stands based on average fuel characteristics, crown fire initiation cannot be ruled out completely.

Moreover, the effective crown base height will be lowering over time as the Douglas-fir understory (more than 400 trees per acre) grows into the main canopy. When the understory approaches the main canopy the effective crown base height will be the crown base of the understory, just a few feet. Crown fires can initiate under nearly any wind and fuel moisture condition is such a situation.</td></tr>
<tr><td rowspan="2">Sustained crown fire spread (critical 20-foot wind)</td><td>(3)
This lightly thinned stand reduced the crown bulk density only slightly.</td><td>(1)
This more heavily thinned stand has the lowest crown bulk density.</td><td>(2)
Thinning was moderate so crown bulk density, hence active crown fire hazard, falls between Treatments 1 and 2.</td><td>(4)
The unthinned stand will nearly always have the highest crown bulk density, therefore, the most susceptible to sustained crown fire spread.</td></tr>
<tr><td colspan="4">Sustained crown fire spread is a function solely of crown bulk density, so the unharvested stand will be the most susceptible and the most heavily harvested stand the least. Crown bulk density is difficult to estimate accurately, so the absolute critical values may not be accurate but the ranking correct.</td></tr>
<tr><td rowspan="2">Aesthetics (triad rank)</td><td>(1)
Viewers preferred this light, low-impact thinning over all other stands, even the untreated stand.</td><td>(2)
Despite the removal of some larger trees, viewers apparently liked the result of this whole-tree harvest unit.</td><td>(4)
This was the least preferred of the three treatments, because of the char and dead trees left by the burn.</td><td>(3)
The untreated stand is crowded with small trees and downed logs.</td></tr>
<tr><td colspan="4">Since 1990, these treatments have produced a positive net revenue a majority of the time. Only the immediate term monetary costs and revenue are considered. Longer-term cost and revenue will be the subject of further research.</td></tr>
</table>

little mortality is expected in the vigorous overstory. Retreatment of this stand should not be necessary for 20 to 30 years.

There is little that could be changed in this treatment to improve its effectiveness. Additional slash treatments such as a broadcast burn could not be justified in light of the income-producing short-term emphasis. Mechanized logging equipment should consistently provide the most cost-effective harvesting in this forest type. Further reduction in basal area would probably produce an unacceptable aesthetic condition, especially since the thinning is from above.

Treatment 3: Forest Restoration

This treatment represents a unique ecological restoration emphasis that balances aesthetics, income production, and forest health—an "ecosystem management" treatment with broad applicability. This treatment was the most effective in reducing fire hazard. Indeed, any treatment that couples a low thinning with a broadcast burn will significantly reduce wildfire hazard; the data show that. Even with the high cost of the broadcast burn, this treatment showed a modest return per acre. Burning would be more economical when applied to larger units. Unfortunately, aesthetic quality suffers for a few years whenever a broadcast burn chars the boles of trees. However, periodic application of this treatment would lead to an open-structured forest of large trees, which has high aesthetic value. This type of thinning and burning treatment has broad applicability on public and increasingly on private lands in the pine type.

As in Unit 2, an understory will redevelop. Ponderosa pine regeneration is aided by the broadcast burn, but probably requires more available growing space for successful regeneration. Surface and crown fuel dynamics should be similar to Unit 2. Retreatment of this stand should be considered at 15 to 20 year intervals, with future treatments aimed at reducing basal area enough to encourage successful ponderosa pine regeneration.

Some changes could be made to improve this treatment. In this implementation, slash was back-hauled from the landing and spread with the grapple skidder in order to retain as much of the nutrient base on the forest floor as possible. While this practice may have long-term benefits for forest productivity, when coupled with a prescribed burn the additional fuel can lead to increased bark char, crown scorch, and fire-caused mortality. It may be more practical to dispose of the slash in a landing pile and broadcast burn the natural fuel bed with the small amount of slash left after a mechanized logging operation. The residual basal area could probably also be reduced slightly, bringing in more income and helping create more "natural" conditions, without adversely affecting stand aesthetics.

Conclusions

Fuel reduction and ecological restoration treatments must ultimately be implemented at the landscape level for maximum effectiveness (Mutch and others 1993). Indeed, the Ninemile Ranger District of the Lolo National Forest is planning several large-scale timber sales that include low-impact partial-harvests like those implemented here. As land managers move toward landscape-level implementation, these treatments should be used first in the places where they can be expected to have the most benefit. The wildland and urban interface is a logical place to begin—there are high property and amenity values requiring protection from wildfire, the public recognizes this need and generally supports ecosystem restoration treatments in these areas, and an established road system will keep cost and controversy to a minimum. Managers may be able to increase the scope of application on the landscape as their experience in applying these treatments grows. Increasing the scope of application should reduce the cost of implementing these treatments, especially those involving the use of fire.

This study demonstrates that there are many viable approaches for accomplishing forest fire hazard reduction at the stand level, which in many cases will be self-financing. However, commercial thinning treatments will become more difficult on steeper slopes, where logging and road-building costs are higher. On sites where these treatments become difficult to implement because of steep slopes or lack of marketable wood products, managers should explore the use of prescribed fire alone as a means of maintaining low fire hazard and controlling species until market or technological changes makes complete restoration of these sites possible

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Three alternative thinning treatments for reducing fire hazard and improving forest health in scenic ponderosa pine forests of the Intermountain West are compared. Treatment cost and revenue, surface and crown fuel reduction, and aesthetic preference of the treatments are analyzed. The application of these ecosystem restoration treatments may have far reaching implications.

Keywords: fire hazard reduction, forest restoration, aesthetics, wildland/urban interface, ponderosa pine (*Pinus ponderosa*)

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