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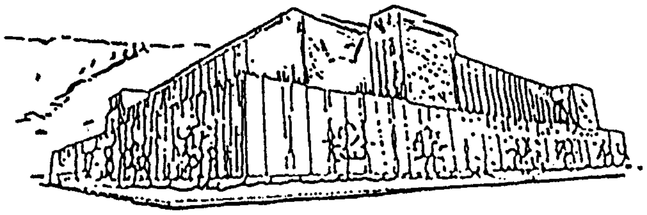

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DEVELOPMENT OF TWO INDICES OF CROWN FIRE HAZARD AND THEIR APPLICATION IN A WESTERN MONTANA PONDEROSA PINE STAND

by

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Development of two indices of crown fire hazard and their application in a western Montana ponderosa pine stand (75 pp.)

Advisor: Professor Ronald H. Wakimoto

Quantitative assessment of surface fire potential is possible with Rothermel's mathematical fire spread model. However, no quantitative means of comparing crown fire potential is available. In this thesis, two ordinal indices of crown fire potential, the Torching Index and the Crowning Index, have been developed for comparing the relative susceptibility of different stands to crown fire. The indices are derived from links among Van Wagner's transition criteria and Rothermel's models of surface and crown fire spread rate.

The indices are then used to compare the effectiveness of hazard reduction treatments in a western Montana ponderosa pine stand. 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, Montana. All treatments included a commercial thinning designed to reduce crown fuels and provide revenue to offset costs.

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.

The potential for passive crown fire was reduced by all treatments except treatment 2. Torching Index values for the treated stands ranged from 135 to 256, while the untreated stand was 188. The Crowning Index increased to 33-43 in the treated stands from a base of 28 in the untreated stand, indicating a reduced potential for active crown fire.

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

All treatments were both effective at reducing forest fuels and financially feasible. Individual preference, suitability for a particular site, or compatibility with other resource objectives may guide the choice of treatment.

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PREFACE

In 1991, representatives of the U.S. Forest Service Intermountain Fire Sciences Lab (IFSL) and Ninemile Ranger District identified a common desire for a demonstration of alternative silvicultural practices that reduce fire hazard and improve forest health in an aesthetically-pleasing way. The Ninemile Ranger District wanted such a demonstration to encourage public acceptance of similar proposed Forest Service activities in areas near residences, as well as to provide information that may help landowners undertake such treatments on their own land within the district. The IFSL desired the demonstration to show all land management agencies, developers, landowners, and county planners the feasibility of conducting such fuel treatments.

As a result of this mutual interest, the IFSL entered into a Research Joint Venture Agreement with the University of Montana School of Forestry (RJVA #92-685) to collaborate in the design and implementation of this demonstration.

The objectives of this project were to design three alternative treatments, implement the treatments in a uniform forest, and compare the effects of each treatment on fuel loading, potential fire behavior, and net cost (or revenue) of conducting the treatments. To rate the potential for crown fires, two indices of crown fire potential were developed. Each treatment consists of a combination of many treatment factors, such as residual basal area, logging method, or type of burning used. This demonstration study was not designed to identify how these individual factors affect the fuel loading, potential fire behavior or treatment cost.

The assistance of Professor Ronald Wakimoto at the University of Montana, Steve Slaughter and Risa Lange-Navarro of the Ninemile Ranger District, Elizabeth Reinhardt and Steve Arno of the Intermountain Fire Sciences Lab, and Robert Benson of Systems for Environmental Management has been greatly appreciated.

INTRODUCTION

Crown fires present special problems to managers. Crown fires are more difficult to control than surface fires. Their rate of spread is at least 2-4 times as fast as surface fires (Rothermel 1983), and spotting is frequent. Structures are more difficult to defend from crown fire than from surface fire. Effects of crown fire may also be more severe and lasting than surface fire.

Crown fire occurrence may be increasing in some forest types of the western U.S., due to management practices including fire suppression and selective timber harvest. When forest types prone to crown fire lie in proximity to residential or recreational development, a significant risk to life and property exists. Assessing the susceptibility of forest stands to crown fire and designing fuel and silvicultural treatments to reduce susceptibility have become priorities for many land management agencies.

In the U.S., there are separate methods for predicting surface fire behavior (Rothermel 1972) and crown fire behavior (Rothermel 1991), but not the transition between them. In this thesis I explore the use of Van Wagner's crown fire transition criteria (Van Wagner 1977, 1989, 1993), elements of which are used in the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), to link Rothermel's separate surface and crown fire behavior models. By linking these models, two indices of crown fire potential can be derived for comparing the susceptibility of different forest stands to the onset and sustained spread of crown fire. The indices will be used to compare alternative hazard reduction treatments in a ponderosa pine stand.

Forests dominated by ponderosa pine (*Pinus ponderòsa*) 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 which forms pure stands. As a result of fire exclusion, many climax pine forests have become overstocked and have developed thickets of seedlings and saplings (Arno and others 1985). 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 menzesii* var *glauca*) and grand fir (*Abies grandis*) (see, for example, Smith and Fischer 1997). 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/Douglas-fir stands were uneven-aged (Arno and others 1995), most second-growth stands are even-aged. Logging in the late 1800s and early 1900s, 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 75-100 years, whereas under a "natural" regime they would have experienced several during that time.

These forests are quite 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 (Arno 1996). 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 which allows a fire to burn from the surface into the tree crowns (Alexander 1988). These changes in fuels and stand structure lead to fires which 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 utilized 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.

Many homeowners are aware of the potential fire hazard on their forest properties, but fail to act, possibly because of their concerns about the cost of reducing fuels and potential negative effects on aesthetics. Hazard reduction treatments such as ladder fuel removal, pile or broadcast burning, and pruning can be quite 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 non-commercial 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 ponderosa pine forests, Forest Service managers and wildland homeowners need basic descriptive information and a demonstration of thinning treatments to reduce fire hazard. This study was undertaken to provide such a demonstration and document outcome in terms of the degree of fire hazard reduction and financial feasibility of conducting the treatments.

OBJECTIVES

(1) Develop quantitative indices of crown fire potential.

(2) Develop and implement three contrasting silvicultural prescriptions to reduce fire hazard and improve forest health in second-growth ponderosa pine forests.

(3) Quantitatively compare the three treatments in terms of fire hazard (potential fire behavior) and financial feasibility.

The general objective of this study is to develop, demonstrate and compare three contrasting techniques for reducing fire hazard in ponderosa pine stands in residential, recreational and scenic areas of western Montana. The on-the-ground demonstration and related descriptive information will allow fire officials, land use planners, forestland developers, public land managers and wildland homeowners to compare stands that have been treated in different ways to reduce the threat of a wildfire.

Due to limited area of homogeneous stand conditions in the study area it was not possible to replicate the treatments. Therefore, it is not possible to statistically compare the different treatments in terms of potential fire behavior or treatment costs. However, for the purpose of providing a demonstration, descriptive statistics suffice. Also, because the three treatments will vary in more than one factor (residual basal area, thinning method, equipment type and slash treatment), this research should be viewed as a case study rather than a traditional experiment involving the investigation of individual factors. This case study is designed to demonstrate viable (realistic) treatment alternatives to professionals and to the general public, not to determine how each individual treatment factor affects potential fire behavior or economic feasibility.

Potential surface fire behavior can be assessed using Rothermel's (1972) mathematical model. However, there are no quantitative methods for assessing the potential for crown fires. Therefore, the first section of this thesis is the derivation of two quantitative indices of crown fire potential. These indices will then be used to compare the treatments implemented in the ponderosa pine stand.

PART I. CROWN FIRE HAZARD ASSESSMENT

In the U.S., there are separate methods for predicting surface fire behavior (Rothermel 1972) and crown fire behavior (Rothermel 1991), but not the transition between them. In this part I explore the use of Van Wagner's crown fire transition criteria (Van Wagner 1977, 1989, 1993), elements of which are used in the Canadian Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992), to link Rothermel's separate surface and crown fire behavior models. By coupling these models we can derive indices of crown fire hazard and simulate the full range of fire behavior possible in a forest stand.

Although the coupled model produces estimates of overall fire behavior (surface through active crown), its main purpose is to compare the relative susceptibility of different stands to crown fire, not to predict the behavior of an actual fire. The derived indices allow direct, quantitative comparison of different stands or alternative fuel treatments from a description of surface fuels, crown fuels, site characteristics, and environmental conditions. Although Rothermel's (1991) crown fire model has limited geographic applicability, the concepts we present can be used with more broadly applicable models as they become available (Albini 1996, Catchpole and others 1998).

This part consists of two sections. In the first part I review the pertinent fire behavior models and transition criteria that are used to derive the coupled model. The second part contains the derivation of two indices of crown fire potential from existing mathematical models.

Fire Behavior Models

The behavior of both surface and crown fires can be described by fireline intensity (I), forward rate of spread (R) and heat (release) per unit area (HPA). A complete list of symbols used in this section appears in the appendix. Fireline intensity is the rate of heat release in the flaming front per unit length of fire front (flame depth may vary). Byram (1959) defines fireline intensity, I, as

$$I = \frac{HW_f R}{60} \tag{1}$$

where H is the heat yield of the fuel (kJ kg^{-1}), W_f is the weight of fuel consumed in the flaming front (kg m^{-2}) R is the forward rate of spread of the fire (m min^{-1}), and 60 is a conversion factor so that the units for I are in kW m^{-1}. Byram uses the term "available fuel" to describe W_f, but it is evident that he means the weight of fuel available to the flaming fire front. Alexander (1982) provides a detailed discussion of measures of fire intensity. In the remainder of this thesis, intensity can be taken to mean Byram's fireline intensity.

Heat (release) per unit area is the product of the heat yield of fuels, *H*, and the weight of fuel consumed in the flaming front, W_f. Therefore, *HPA* is identical to the quantity HW_f in equation (1). Heat per unit area can alternatively be expressed (Andrews and Rothermel 1982) as

$$HPA = I_R t_R \tag{2}$$

where I_R is reaction intensity (kW m^{-2}) and t_R is residence time in seconds (Anderson 1969)

$$t_R = \frac{12.595}{\sigma} \tag{3}$$

where σ (cm^{-1}) is the characteristic surface-area-to-volume ratio (cm^{-1}) of the fuel bed.

Neither Rothermel's (1972) model nor BEHAVE (Andrews 1986) explicitly computes W_f, but because HW_f in equation (1) is equivalent to *HPA*, W_f can be computed as

$$W_f = \frac{HPA}{H} \tag{4}$$

There has been some confusion in determining W_f for use in equation (1) and its variants. Total fuel load, W_t, is the maximum amount of fuel, including duff and large woody fuels (> 76 mm diameter), that can possibly be consumed in a hypothetical fire of the highest intensity in the driest fuels (Byram 1959). Available fuel, W_a, is that portion of the total fuel load that is consumed in a given fire. It includes the consumption of duff and large woody fuels, most of which takes place after passage of the fire front. Equation (1) requires W_f, the usually much smaller quantity of fuel that is consumed in the fire front. By contrast, the Forestry Canada Fire Danger Group (1992) uses equation (1) to define fire intensity (as opposed to Byram's fireline intensity) in the Canadian Forest Fire Behavior Prediction (FBP) System, by using W_a (total fuel consumption) in place of W_f. In forest fuels W_a can be many times larger than W_f, so "fire intensity" defined in the Canadian FBP System may also be many times larger than fireline intensity. Values of fire intensity from the Canadian FBP System may not be directly comparable to values of fireline intensity reported here.

Variable names from the Rothermel spread model (1972) cause further confusion. In his model, W_o ,which he called total fuel load, is actually a subset of the total fuel load defined by Byram. Unlike W_t, W_o includes only those fuel components that can contribute significantly to fire behavior at the flaming front. By convention, only the dead fuels less than 76 mm diameter and live fuels less than 6 mm diameter are included in W_o (Rothermel 1972). In the Rothermel (1972) model, W_n is the net weight of W_o after the mineral fraction has been subtracted. Mineral fraction is usually held constant at

0.055, so $W_n = W_o$ (1 - 0.055). Some authors (Bessie and Johnson 1995) have apparently used W_n in place of W_f. This error can result in a many-fold over-calculation of intensity using equation (1), because the Rothermel model predicts that W_f is only a small fraction of W_n in forest fuels.

It will later be necessary to estimate the spread rate that leads to a given fireline intensity by rearranging equation (1). The difficulty of determining W_f for use in equation (1) and its derivatives can be avoided by replacing HW_f with HPA in equation (1)

$$I = \frac{HPA * R}{60} \tag{5}$$

Surface Fire Behavior

Surface fire spread rate can be predicted using Rothermel's (1972) model as adjusted by Albini (1976) and implemented in BEHAVE (Andrews 1986). Headfire rate of spread can be expressed using Rothermel's (1972) formulation for upslope winds:

$$R_{surface} = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}} \tag{6}$$

where the variables are defined in the appendix. The Rothermel model has many input factors. For ease of use, fuel characteristics have been combined into standard fuel models (Anderson 1982) that represent generic fuelbeds. Custom fuel models can be created from a fuel inventory or by adjusting one of the standard fuel models (Burgan 1987, Burgan and Rothermel 1984). As employed in this analysis, the Rothermel model can be used with either standard or custom fuel models.

Crown Fire Behavior

Crown fires burn in the crown layer above the surface fuels. Available crown fuels are characterized by high moisture content and low bulk density compared to surface fuels. It is possible for a fire to burn in conifer tree crowns without a coincident surface fire, such as occurred on the 1987 South Mowich fire on the slopes of Mount Rainier, USA (Huff 1988). However, most crown fires depend upon a supporting surface fire to provide the required heat flux (Van Wagner 1977). Van Wagner (1977) identifies three types of crown fire: passive, active and independent. A passive crown fire is one in which individual trees (or small groups) torch out, and the overall forward rate of spread can be higher than the surface fire alone. Passive crowning is also called intermittent crowning (Forestry Canada Fire Danger Group 1992), candling, and torching.

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). Active crown fires are also called continuous (Forestry Canada Fire Danger Group 1992) and running crown fires. 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. Independent crown fires are infrequent, short-lived (Van Wagner 1993) and require a combination of steep slope, high windspeed, and low foliar moisture content.

Currently we have only the Rothermel (1991) statistical model for predicting crown fire rate of spread in the United States. His correlation was intended for the Northern Rocky Mountains and other areas with similar fuels, climate, and topography. He used linear regression to relate observed crown fire spread rates to predictions made with his surface fire model using fuel parameters from Fire Behavior Fuel Model (FM) 10 (Anderson 1982) with midflame windspeed at 40% of the 6.1-m (20-ft) windspeed, the standard height for measuring windspeed in the U.S. In simple form, the Rothermel (1991) correlation for crown fire spread rate is

$$R_{crown} = 3.34\left(R_{10}\right)_{40\%} \tag{7}$$

where $(R_{10})_{40\%}$ is the spread rate predicted with Rothermel's (1972) surface fire model using the fuel characteristics for FM 10 and midflame windspeed set at 40% of the 6.1-m windspeed.

Note that the input factors from FM 10 must be used in this correlation, not the actual surface fuel characteristics. Bessie and Johnson (1995) used actual surface fuel characteristics, which can result in errors of nearly an order of magnitude. However, the mandatory use of FM 10 applies only to predicting crown fire spread rate — surface fire spread rate can still be predicted with any appropriate standard or custom fuel model. Also, the midflame wind for use in the correlation must be set at 40% of the open windspeed, not at the midflame wind estimated for the surface fire. For surface fires, midflame winds are estimated by multiplying the open wind (6.1-m in the United States) by a wind reduction factor, *WRF*, the ratio of midflame to open windspeeds. In forest stands on level ground, Albini and Baughman (1979) estimate *WRF* from stand height and crown filling fraction (the fraction of the canopy volume that is occupied by tree crowns). The *WRF* for forest stands is most often in the range 0.10 to 0.25. A *WRF* of 0.4 characterizes fully-exposed fuels with no tree cover, such as grasslands and chaparral shrub fields.

Rothermel's correlation is limited to wind-driven fires — plume-dominated fires such as the 1985 Butte fire (Rothermel and Mutch 1986) are not predicted by this correlation (Rothermel 1991). In addition to these limitations, there are additional assumptions we must make in the coupled model. First, we assume the Rothermel crown model estimates the spread rate of fully-active crown fires, though some of his fires were likely not fully-active — for example, the 1989 Black Tiger fire (National Fire Protection Association 1990). In that respect the Rothermel correlation might underestimate the spread rate of a true fully-active crown fire. Second, we assume that the model predicts the flame front spread rate alone, without the effect of spotting. However, the observed spread rates used in the correlation included the effect of short- and medium-range spotting on overall fire spread rate. In that respect the correlation should over-predict spread rate of the flame front itself. The combined effects of fires with spotting and less-than-fully-active crowning in the Rothermel correlation on predicted active crown fire spread rate is uncertain. However, the overestimation due to spotting probably exceeds the underestimation due to less-than-fully-active crowning. Until a model capable of estimating flame front spread rate for crown fires is available we must use the Rothermel correlation with the knowledge that it probably overestimates flame front spread rate by some unknown amount.

Despite these limitations, the lack of an alternative model requires that we use Rothermel's (1991) method to predict spread rate of a fully-active crown fire flame front. To account for the overprediction of flame front spread rate, we can use an adjustment factor. New models of active crown fire spread rate can be substituted in the following analysis as they become available. Equation (7) can be written

$$R_{active} = 3.34\left(\frac{I_R\xi(1+\phi_w+\phi_s)}{\rho_b\varepsilon Q_{ig}}\right)_{FM10} \tag{8}$$

where all terms are evaluated for the characteristics of FM 10. As predicted by Rothermel's correlation, crown fire rate of spread depends on surface fuel moisture contents, open windspeed, and slope steepness, but not on actual surface or crown fuel characteristics. Crown fire spread rate probably also varies with other crown characteristics like moisture content and bulk density of canopy fuels, but this model does not incorporate those inputs.

The Rothermel correlation can be extended to include the effect of foliar moisture content, *FMC*, on crown fire spread rate using the foliar moisture effect, *FME*, defined by Van Wagner (1974, 1989, 1993)

$$FME = \left(\frac{(1.5 - .00275FMC)^4}{460 + (25.9FMC)} \right) \tag{9}$$

The *FME* is always applied as a ratio of *FME* to a normal value, FME_O, where FME_O is based on the *FMC* in the data used to construct the crown spread rate model. The *FMC* of the fires used in the Rothermel correlation was not documented and surely varied among the fires. Therefore, using the *FME* concept with Rothermel's model will require a derivation of FME_O based on some alternative *FMC*, such as an overall average *FMC* among all species during the fire season in the Northern Rocky Mountains. Taking the range of *FMC* to be 85 - 120 percent and assuming the average of 100 percent, the ratio FME/FME_O ranges from 0.714 - 1.31. Although the *FME* concept can be easily incorporated into this hazard assessment system, for simplicity it will not be included in this presentation.

For crown fires, W_f is the combined weight of surface and crown fuels consumed in the flaming front. An active crown fire consumes nearly all of the fine crown fuels, while a passive crown fire consumes only a portion (Van Wagner 1993). Active crown fires have higher intensities than surface fires because both W_f and R are higher than a surface fire. Intensity of a crown fire can be computed using equation (1), using crown fire rate of spread and including W_{crown} in W_f.

Criterion for Crown Fire Initiation

Van Wagner (1977) theorized that crown fuels ignite when heat supplied by a surface fire drives off fuel moisture and raises crown fuels to ignition temperature. He identified the critical (minimum) fireline intensity of a surface fire, $I'_{initiation}$, that will initiate a crown fire. Van Wagner's (1977) separate equations can be combined as follows to compute $I'_{initiation}$ in kW m^{-1}:

$$I'_{initiation} = \left(\frac{CBH(460 + 25.9FMC)}{100} \right)^{3/2} \qquad (10)$$

where CBH is the crown base height (m). The coefficient 100 in the denominator is an empirical constant based on a single observation.

For further analysis, $I'_{initiation}$ is converted to its equivalent rate of spread, $R'_{initiation}$, by rearranging equation (5) and substituting $I'_{initiation}$ for I, following the concepts in the Canadian FBP System (Forestry Canada Fire Danger Group 1992) and Van Wagner (1993)

$$R'_{initiation} = \frac{60 I'_{initiation}}{HPA} \qquad (11)$$

Because *HPA* is a function of fuel characteristics and fuel moisture, equation (11) must be evaluated for each combination of fuel model and fuel moisture condition.

Crown base height for use in equation (10) can be difficult to measure in multi-story stands and stands with ladder fuels. Van Wagner (1993) reduced *CBH* to account for ladder fuels in a two-story stand. In terms of its consequences to crown fire initiation, *CBH* can be defined as the lowest height above the ground at which there is sufficient crown fuel to propagate fire vertically through the canopy. Using this definition, ladder fuels such as lichen, moss and dead branches can be incorporated. Sando and Wick (1972) provide a method of estimating crown base height of non-uniform stands based on the height at which a minimum bulk density is found. Other ladder fuels that increase the intensity of the surface fire (such as understory trees, shrubs and needle drape) are best accounted through custom surface fuel modeling or by simple adjustment of predicted surface fire intensity to include their effect.

Van Wagner's crown fire initiation criterion has not been well tested, but there is general agreement among researchers that it includes the major variables important to initiating a crown fire. We see from equation (10) that $I'_{initiation}$ depends on foliar moisture content and crown base height. Alexander (1988) provides graphs showing the relationships among these factors. Of course, in the Rothermel model surface fire intensity depends on surface fuels (load, surface-area-to-volume ratio, heat content, packing ratio, moisture contents), midflame windspeed, and slope steepness. Different stands can have the same value of $I'_{initiation}$ (*e.g.*, similar *CBH* and *FMC*) but different predicted intensities (*e.g.*, different surface fuel characteristics, wind reduction factor or moisture contents). Therefore, critical fireline intensity is itself insufficient to compare the relative potential for crown fire initiation.

Criterion for Active 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 (active crowning) if a critical horizontal mass flow rate of fuel into the flaming zone, *S*, is exceeded

$$S = R_{active} CBD \qquad (12)$$

where R_{active} is the after-crowning forward rate of spread and *CBD* is the crown bulk density (kg m^{-3}). Keyes (1996) mis-interpreted R_{active} in equation (12) to mean the surface fire spread rate. Van Wagner (1977) found a critical mass flow rate of 0.05 kg m^{-2} sec^{-1} for one fire in a red pine plantation, slightly lower than the values given for experimental fuel beds by Thomas (1963). Until more data on the critical mass flow rate for crown fires in a wide range of forest types are available we must rely on Van Wagner's critical mass-flow rate of 0.05 kg m^{-2} sec^{-1}. Rearranging equation (12), substituting 0.05 for *S*, and multiplying by 60 to compute R'_{active} in m min^{-1} (Alexander 1988), the critical (minimum) rate of spread for active crowning, R'_{active}, is

$$R'_{active} = \frac{3.0}{CBD} \tag{13}$$

Crown bulk density is the weight of crown fuel per unit volume of canopy space (Alexander 1988). It is a bulk property of the stand, not an individual tree, and therefore would be more accurately termed canopy bulk density. With Rothermel's surface fire model we specify the fuels that may potentially be consumed in the flaming fire front (W_O) — the model then estimates what portion of that fuel actually contributes to frontal fire behavior. However, with crown bulk density we specify, before the fact, the crown fuels that are available in a fully-active crown fire. It is reasonable to assume that the foliage, lichen, and moss is consumed in the flaming front of a fully-active crown fire.

Some portion of the live and dead branchwood less than 6 mm diameter should also be consumed in the flaming front (Brown and Bradshaw 1994, Brown and Reinhardt 1991, Reinhardt and others 1997). A model by Call and Albini (1997) suggests that 65% of canopy fuel 0-6 mm diameter at 100 percent moisture content would be consumed in a crown fire. However, Call and Albini (1997) acknowledge that their model overpredicts consumption in small size classes.

For uniform stands, *CBD* can be computed as the available crown fuel load divided by crown length. Following Sando and Wick (1972), Reinhardt and others (in preparation) developed a technique to estimate "effective" *CBD* in non-uniform stands from a stand inventory. They do not assume a uniform vertical distribution of crown fuel, so *CBD* does not necessarily equal crown load divided by crown length — load and bulk density must be determined independently. Alexander (1988) provides additional suggestions on the determination of *CBD*.

Following Van Wagner (1977) and Alexander (1988), we use the criteria for initiation and sustained spread of crown fires to classify a fire as surface, passive crown, or active crown fire (Table 1).

Table 1 Classification of fire types using Van Wagner's (1977) threshold criteria. In the U.S., Isurface is predicted from BEHAVE (Andrews 1986), and Ractive from Rothermel (1991). I'initiation and R'active are from Van Wagner (1977).

	$R_{active} < R'_{active}$	$R_{active} > R'_{active}$
$I_{surface} < I'_{initiation}$	surface fire	surface fire
$I_{surface} > I'_{initiation}$	passive crown fire	active crown fire

Derivation of the Torching and Crowning Indices

In this section I will provide a quantitative method of assessing the relative crown fire hazard of different stands by coupling the existing fire behavior models presented above. For a hazard assessment of a given site, fuels and topography can be considered constant, while weather varies significantly throughout the day, from day to day, and throughout the season.

In the fire behavior models presented above, weather is manifested in two basic inputs — windspeed and dead fuel moisture contents. One measure of crown fire potential is the fraction of time that a hypothetical fire in a stand would be classed as a crown fire. From a description of the surface fuels, crown fuels and site characteristics needed for the above models, we can define critical combinations of dead fuel moisture and windspeed that result in surface, passive crown, and active crown fires. Consider a simulation for a hypothetical fuel complex with the following characteristics: FM 10, slope = 0, *CBH* = 1.5 m, *CBD* = 0.17 kg m^{-3}, *FMC* = 100 percent, *WRF* = 0.15, live surface fuel moisture = 100 percent (Figure 1). In this example, the passive crown fire region is fairly narrow, and active crowning can occur under moderate burning conditions.

The fire weather record could then be examined to determine how often the different types of crown fire would be expected. Depending on the temporal resolution of the weather record, we could express crown fire potential as the number of hours or days per season that conditions existed for certain types of crown fire. Such an index is not only an ordinal comparison (ranking) of different fuel complexes, but should be an interval comparison as well. That is, if one stand is expected to support crown fire twice as often as another, we can easily consider that it has twice the crown fire potential. However, such an analysis would require a long history of windspeed and fine dead fuel moisture at a finer temporal resolution than is commonly available.

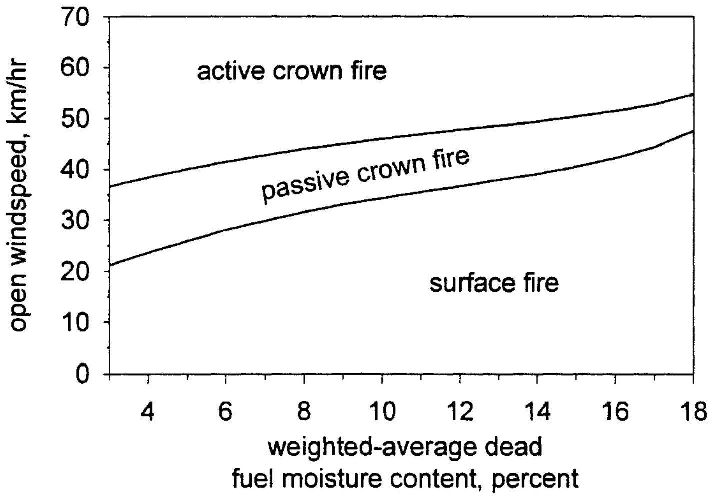

Figure 1 Simulation of Torching and Crowning Indices showning regions of crown fire behavior.

Because such data will not be available for many stands, we will derive alternative indices of crown fire potential that do not rely on climatology. Crown fire hazard can be assessed simply in terms of the environmental conditions that produce the critical fire behavior necessary to initiate or sustain crown fire in a particular surface/crown fuel complex. Such an assessment will properly ordinate different stands, but will not produce an interval index of crown fire hazard. The more detailed analysis is a simple extension of the ordinal method we will describe.

While it is possible to compute all combinations of dead fuel moisture and windspeed that lead to crown fire activity for a given fuel complex (Figure 1), for a relative hazard assessment it is sufficient to hold fuel moistures constant at values that represent typical conditions, extreme conditions, or any other moisture condition of interest. Windspeed is highly variable and probably the most important environmental factor affecting crown fire initiation, sustained active spread, and final rate of spread. We can determine the critical open windspeeds (O, 6.1-m above the canopy) that lead to crown fire activity for a set of site characteristics, surface and crown fuel characteristics, and fuel moisture conditions. Sites that can initiate or sustain a crown fire at lower windspeeds are more "at risk" of crown fire. Therefore, we will use the critical open windspeeds for crown fire initiation and active spread as stand-specific indicators of crown fire hazard.

The Torching Index (TI) is defined as the 6.1-m windspeed at which crown fire is expected to initiate, based on Rothermel's (1972) surface fire model and Van Wagner's (1977) crown fire initiation criteria. It is a function of surface fuel characteristics (fuel model), surface fuel moisture contents, foliar moisture content, crown base height, slope steepness, and wind reduction by the canopy. Similarly, The Crowning Index (CI) is the 6.1-m windspeed at which active crowning is possible, based on Rothermel's (1991) crown fire spread rate model and Van Wagner's (1977) criterion for active crown fire spread. It is a function of crown bulk density, slope steepness and surface fuel moisture content.

The Torching and Crowning Indices can be found graphically by plotting $R_{surface}$, R_{active}, $R'_{initiation}$ and R'_{active} over a range of open windspeeds, holding moisture content at some specified level (Figure 2).

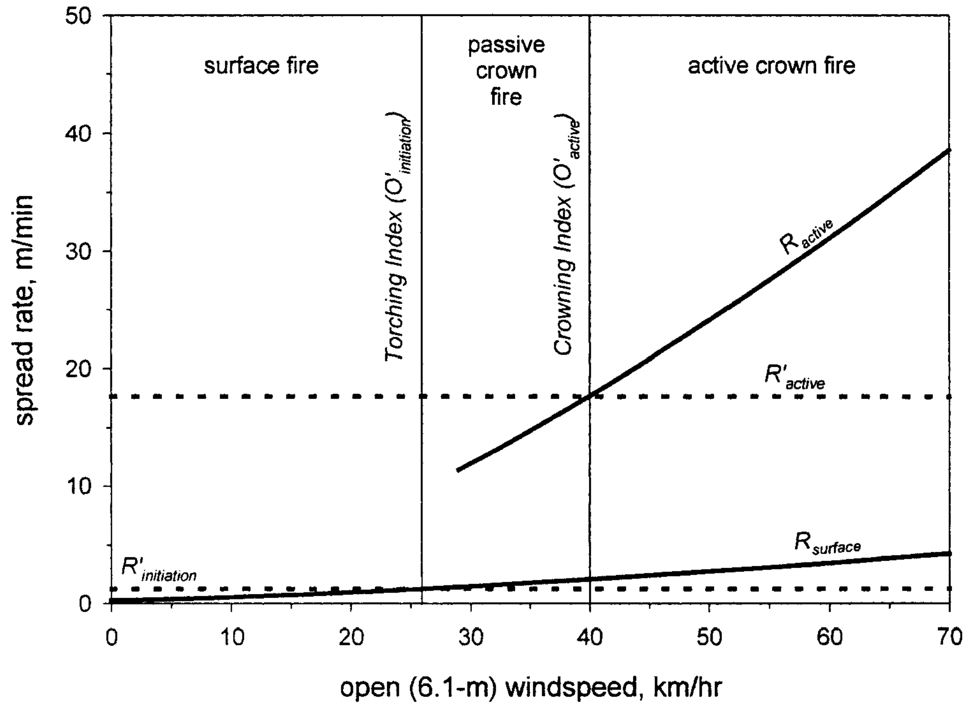

Figure 2 Graphical derivation of the Torching and Crowning Indices.

In Figure 2, we use the same inputs as for the example in Figure 1, with (weighted-average) fine dead fuel moisture held at 5 percent. Van Wagner's fire classification is also shown on the graph. The Torching Index (TI) is the open windspeed (x-axis) at which the predicted surface fire spread rate, $R_{surface}$, equals the critical spread rate for crown fire initiation, $R'_{initiation}$. Similarly, the Crowning Index (CI) is the open windspeed at which the predicted active crown fire spread rate, R_{active}, equals the critical spread rate for active crowning, R'_{active}.

The effects of slope are difficult to generalize because slope can either increase or decrease fire spread rate depending on wind direction. In his analysis of crown fire spread, Rothermel (1991) suggests assuming level ground for modeling average crown fire behavior over large areas, and assuming upslope winds for worst-case analysis. Because our purpose is hazard assessment, we limit our analysis to the worst-case scenario — upslope winds. Using the coupled model one can evaluate the effects of wind direction with respect to slope on crown fire potential. However, in the Rothermel models, the effects of slope are usually quite small compared to the effects of wind, so wind direction will in most cases have a small effect on the critical windspeeds.

It is possible to derive analytical solutions for the Torching and Crowning Indices. Critical windspeed for crown fire initiation is the windspeed at which $R'_{initiation} = R_{surface}$, for the given set of surface fuel moistures. Combining equations (6) and (11) allows us to express $R'_{initiation} = R_{surface}$ as

$$\frac{60I'_{initiation}}{HPA} = \frac{I_R\xi(1+\phi'_{w(initiation)}+\phi_s)}{\rho_b\varepsilon Q_{ig}} \tag{14}$$

where $\phi'_{W\ (initiation)}$ is the critical wind coefficient for crown fire initiation. Solving equation (14) for $\phi'_{W\ (initiation)}$ gives

$$\phi'_{w(initiation)} = \frac{60I'_{initiation}\rho_b\varepsilon Q_{ig}}{HPA\xi I_R} - \phi_s - 1 \tag{15}$$

Rothermel (1972), expressed in SI units by Wilson (1980) with midflame windspeed (*U*) in km hr^{-1}, defines ϕ_W

$$\phi_w = C(54.683U)^B\left(\frac{\beta}{\beta_{op}}\right)^{-E} \tag{16}$$

where *C*,*B*, and *E* are constants for any given surface fuel complex that depend only on σ, and β/β_{op} is the ratio of actual to optimum packing ratio of the fuelbed (Rothermel 1972). Combining equations (15) and (16) and converting to the open windspeed gives us $O'_{initiation}$

$$TI = O'_{initiation} = \left(\frac{1}{54.683WRF}\right)\left(\frac{\frac{60I'_{initiation}\rho_b \varepsilon Q_{ig}}{HPA\xi I_R} - \phi_s - 1}{C\left(\frac{\beta}{\beta_{op}}\right)^{-E}}\right)^{\frac{1}{B}} \tag{17}$$

The Torching Index can be computed for any combination of surface fuels, fuel moistures, crown base height, wind reduction factor, and foliar moisture content.

Similarly, to derive the Crowning Index, O'_{active}, we solve for O'_{active} such that R_{active} equals R'_{active}, which in turn is expressed in terms of crown bulk density (equation 13). Solving first for the critical mid-flame windspeed,

$$U'_{active} = \left(\frac{1}{54.683}\right)\left(\frac{\frac{\left(\frac{3.0}{CBD}\right)\rho_b \varepsilon Q_{ig}}{3.34 I_R \xi} - \phi_s - 1}{C\left(\frac{\beta}{\beta_{op}}\right)^{-E}}\right)^{\frac{1}{B}} \tag{18}$$

As in equation (8), the terms from Rothermel's crown fire rate of spread equation are evaluated only for FM 10, so all terms are constant except I_R and εQ_{ig}, which vary with fuel moisture, and CBD and ϕ_S. Simplifying equation (18), substituting fuel characteristics for FM 10 and converting to open wind, we have

$$CI = O'_{active} = 0.0457\left(\frac{\dfrac{164.8\varepsilon Q_{ig}}{I_R CBD} - \phi_s - 1}{.001612}\right)^{0.7} \qquad (19)$$

where the terms are evaluated for the fuel characteristics of FM 10.

In summary, equation (17) can be used to compute the Torching Index, an ordinal index of the susceptibility of a stand to some kind of crown fire. Equation (19) is used to compute the Crowning Index, an ordinal index of the susceptibility of a stand to active crown fires. The indices incorporate the effects of surface fuel model (load, characteristic surface-area-to-volume ratio, packing ratio), surface fuel moisture content, crown base height, foliar moisture content, crown bulk density, and slope steepness.

PART II. APPLICATION OF THE INDICES

In the first part of the thesis I derived two indices of crown fire potential from the links among existing fire behavior models. In this part I use the indices to compare alternative hazard reduction treatments in a second-growth ponderosa pine stand. In addition to crown fire hazard, I will also compare changes in surface and crown fuel load, and potential surface fire behavior resulting from the treatments. Also, the costs and revenue associated with each treatment will be described.

STUDY AREA

The study area is located in the Sixmile Creek drainage on the Lolo National Forest, about 20 miles northwest of Missoula, Montana. 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 95-100 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 which historically received heavy Indian use. Prior to 1900, fires occurred at an average interval of about eight 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 indicate that there have been no fires in this stand since its initiation.

Slopes within the study area are generally south-facing and incline 5-20 percent. The area is located at about 4000 feet in elevation. Habitat type (Pfister and others 1977) over most of the study area is *Pseudotsuga menzesii/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 (Figure 3). 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 established Douglas-fir seedlings per acre (1 to 4.5 feet tall), but only 15 of ponderosa pine.

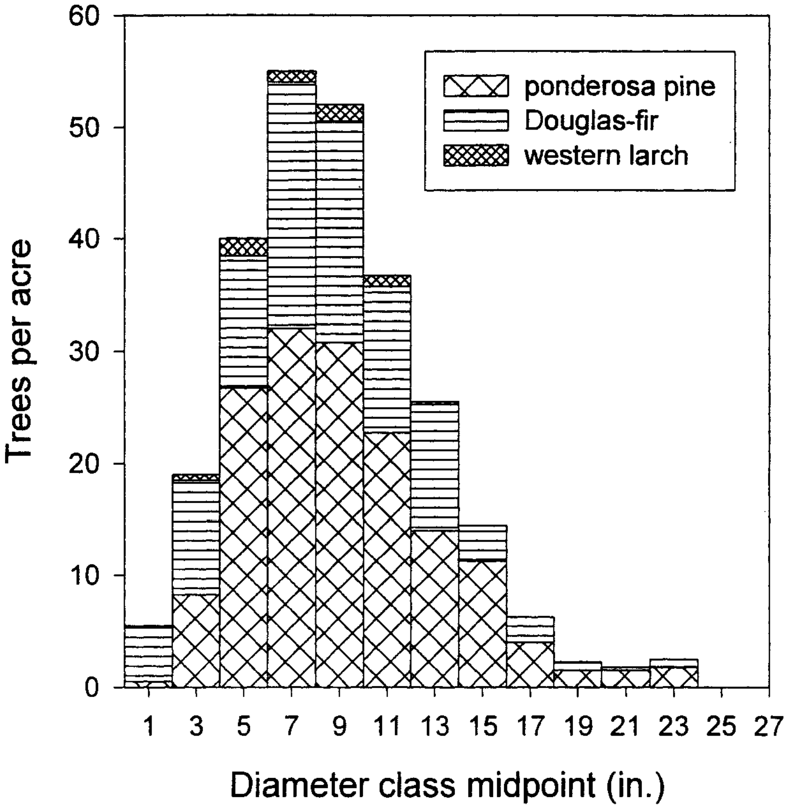

Figure 3 **Trees per acre (>4.5 ft. tall) by 2-inch diameter class, before treatment. There are an additional 427 Douglas-fir and 15 ponderosa pine seedlings per acre.**

METHODS

The methods section is divided into sub-sections dealing with treatment description, fuel and vegetation sampling, potential surface and crown fire behavior, and financial feasibility.

Treatments

The treatments were designed around three contrasting "themes", each with the overall goal of reducing fire hazard and improving forest health. The three alternatives emphasize: (1) minimum impact, (2) revenue production, and (3) forest restoration (Table 2).

Four rectangular 6-acre treatment units were established, one for each treatment plus an untreated control. A principle 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 (*i.e.* from below or from above).

Table 2 Summary of treatment specifications.

Unit	1	2	3
Treatment emphasis	minimum impact	revenue production	forest restoration
Residual basal area	100 ft^2/ac	75 ft^2/ac	75 ft^2/ac
Thinning type	from below (light)	from above (crown)	from below (mod.)
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.

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 the 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 were not considered because of the importance of reducing crown fuels to minimize the crown fire risk.

Harvesting took place in the spring of 1993. Pile burning and firewood removal in unit 1 occurred through that fall. Unit 3 was broadcast burned 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 degrees F, and the high was near 70 degrees F. Minimum relative humidity was 35 percent. Ignition began at 1:00 pm and was completed by 5:00 pm. 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 quite green with pinegrass. Flame lengths averaged 2-3 feet, with occasional flareups of 5-6 feet. The fire covered approximately 85-90 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 1/10-ac circular plot for inventory of trees taller than 4.5 feet, a 1/300-acre circular plot for tallying the number of trees between 1 and 4.5 feet tall by species, a planarintercept transect for estimating dead, down fuel loading by size class, three point samples of duff depth, and four 1-foot square quadrats for estimation of needle litter, herbaceous and shrub fuels (Brown and others 1982).

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, 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, mid-summer 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 described above 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 (*e.g.* 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 these small treatment units, a method of predicting fire behavior which combines a fuel inventory with a standard fire behavior fuel model (Anderson 1982) will 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, however, was "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 Byram's definition of intensity (equation 1). 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 should result in fire behavior predictions which 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 using the Torching and Crowning Indices.

Crown Fire

The relative susceptibility of each treatment to crown fire initiation and sustained crown fire spread will be assessed using the Torching and Crowning Indices described in Part I. Rothermel's (1991) drought summer fuel moistures will be used. Wind direction will be assumed to be uphill.

The Torching Index is the 20-ft windspeed at which a surface fire can ignite crown foliage. It is a function of surface fuel loading, slope steepness, crown base height, foliar moisture content, wind reduction factor (canopy cover), and surface fuel moisture content. A high value of the Torching Index indicates low susceptibility to crown fire initiation, because high windspeeds occur infrequently. The TI scale is open-ended, so it is possible for TI values to greatly exceed the range of windspeeds commonly encountered. Such a condition indicates a combination of factors, mainly fuel load and crown base height, that make crown fire initiation nearly impossible.

The Crowning Index is the 20-ft windspeed at which active crowning is possible. It is a function mainly of crown bulk density, but also dead fuel moisture content and slope. Like the TI, low values of CI indicate high susceptibility to active crown fire, because low windspeeds occur quite frequently.

The accuracy of the TI and CI is limited by the accuracy of the many models used to derive them. However, the internal consistency of the underlying models allows us to use the TI and CI as ordinal indices.

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 that each treatment produced. Before computing the net cost or revenue, the various costs and revenues must be converted to a common basis. 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. The reader should note that 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, reduced fire suppression cost) or non-monetary benefits (improved wildlife habitat, reduced suppression cost, 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 effect 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 financial feasibility of the treatments.

Revenue was estimated by multiplying the unit volume of harvest (MBF/ac) in each unit (determined from the pre-sale timber cruise) by the average log price for the species/product mix harvested ($/MBF) to arrive at the revenue per acre ($/ac). 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 financial 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, and
timber stand improvement.

Not all of these costs will apply when estimating the financial 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 much 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 in the west side of Region 1, but only $13/MBF for private industry lands (Keegan and others 1996). Non-industrial private land management costs (often through a consulting forester) are not reported, but probably are more similar to those of private industry than the Forest Service. Because of this difference in sale design and administration costs between ownerships, cost-feasibility is reported for both national forest and private land.

Other sigificant 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

While the untreated control was a little more dense than the other units, it is similar enough to provide a good demonstration of initial stand conditions. The average stand diameter was increased after treatment in all units (Table 3), 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 (from 10.4 to 13.3 inches) because it was thinned from below with moderate intensity.

Table 3 Measures of stand density and tree size before and after treatment.

		basal area (ft^2/ac)		density (trees/ac)		Average DBH (in.)	
	Treatment	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	

Potential Surface Fire Behavior

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 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.

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

Class/component	Unit (treatment)									
	1 (Minimum Impact)			2 (Revenue Production)			3 (Forest Restoration)			4 (Untreated)
	pre	post	% change	pre	post	% change	pre	post	% change	
litter	1.25	1.11	-11%	1.18	0.95	-19%	1.18	0.69 *	-42%	1.16
herbaceous	0.19	0.17	-11%	0.22	0.26	18%	0.31	0.37	19%	0.10
1-hr	0.23	0.17	-26%	0.42	0.19 *	-55%	0.41	0.06 *	-85%	0.27
10-hr	0.89	1.19	34%	1.13	2.23 *	97%	1.53	0.98	-36%	0.92
100-hr	1.02	1.31	28%	1.46	1.02	-30%	1.03	1.46	42%	0.58
Total fine fuels	3.6	4.0	10%	4.4	4.7	5%	4.5	3.6	-20%	3.0
1000-hr sound	5.3	1.6	-69%	4.0	0.8 *	-80%	6.2	4.7	-24%	3.8
1000-hr rotten	1.7	0.7	-59%	1.5	0.9	-40%	2.8	0.3	-88%	3.5
duff	17.1	18.2	6%	15.9	21.3	34%	17.7	15.0	-15%	17.7
small trees	0.11	0.02 *	-82%	0.11	0.05	-55%	0.07	0.0 *	-100%	0.1
Total load	27.8	24.5	-12%	25.9	27.7	7%	31.2	23.6	-24%	28.1

* denotes a statistically significant difference from pre-treatment at the 10 percent level of confidence.

Table 5 Surface fuel characteristics and wind reduction factor.

Unit		1	2	3	4
Treatment		minimum impact	revenue production	forest restoration	untreated
load (t/ac)	1-hr	1.45	1.40	1.12	1.63
	10-hr	1.19	2.23	0.98	1.12
	100-hr	1.31	1.02	1.46	1.02
	herb	0.08	0.13	0.18	0.10
SAV[1] (1/ft)	1-hr	2500			
	live	3000			
depth (ft)		.23	.27	.21	.22
bulk density (lb/ft^3)		0.803			
Heat yield (BTU/lb)		8000			
wind reduction factor		0.20	0.25	0.20	0.15

[1] SAV is the surface-area-to-volume ratio of the specified fuel particle size class.

Table 6 Crown fuel characteristics.

Unit	1	2	3	4
Treatment	minimum impact	revenue production	forest restoration	untreated
crown base height (ft)	34	32	36	20
stand height (ft)	70			
crown bulk density (kg/m^3)	0.064	0.045	0.051	0.082
foliar moisture content (%)	100			
canopy closure (%)	70	50	60	80

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-hr	4
dead 10-hr	5
dead 100-hr	7
live	78

Predicted fireline intensity and flame length for the units can be shown as a function of 20-ft windspeed (Figure 4). The 20-ft wind is used because there are different wind reduction factors for the treated and untreated stands (see Table 5) as a result of a change in canopy closure. Also, weather forecasts usually 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 mid-flame windspeed by combining the wind and slope coefficients of the model (as in BEHAVE [Andrews 1986]) and dividing by the wind reduction factor to get the effective 20-ft 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% slope with no wind and a wind reduction factor of .2 and the above fuel moisture conditions. The slope is equivalent to adding a 15 mph 20-ft wind. However, if there were already a

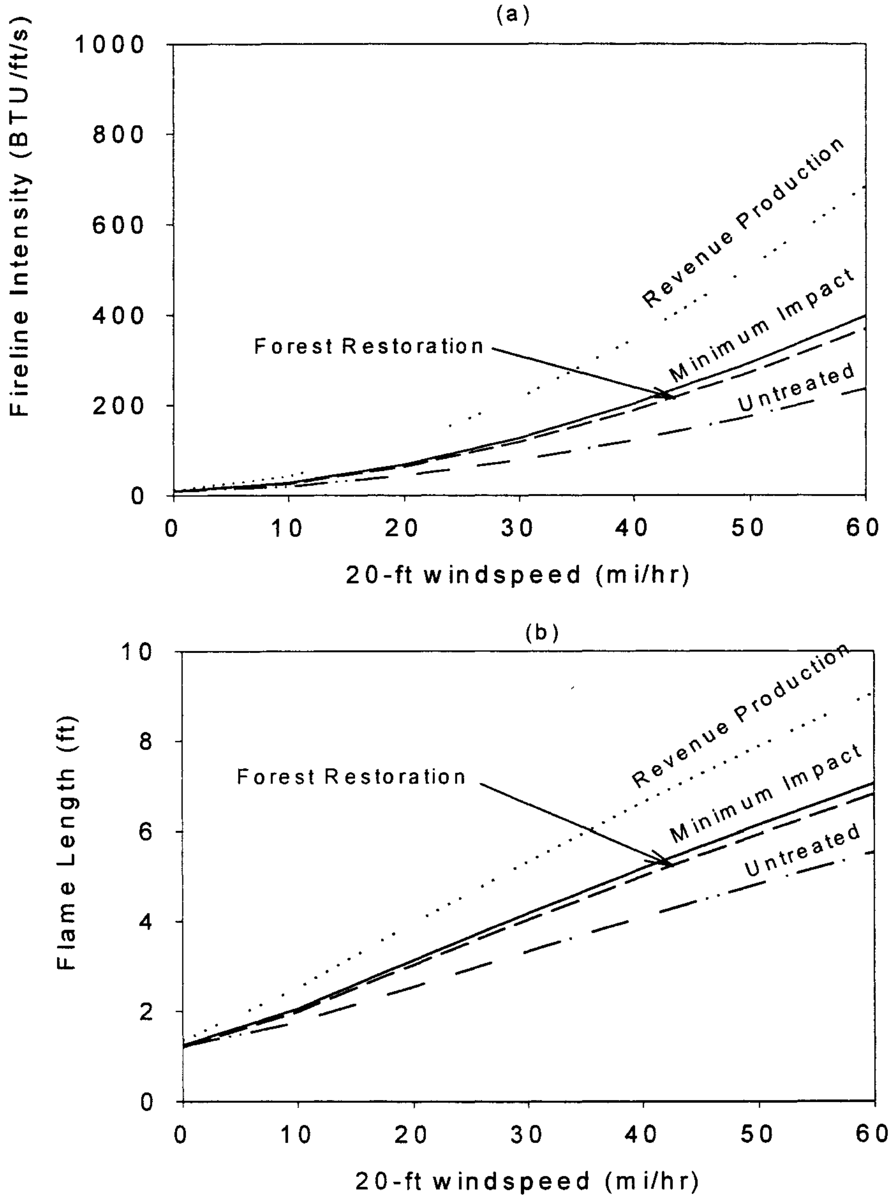

Figure 4 Predicted surface fireline intensity (a) and flame length (b) of the treatments.

20 mi/hr 20-ft wind blowing directly up slope, the slope would represent only 6 mph additional wind. Wind and slope effects are further complicated by cross-slope winds. Because slope is identical in all the treatment units, the relative fire hazard assessment can be conducted without considering slope. Therefore, to simplify the discussion, slope is assumed to be zero.

Surface fire intensity and flame length is predicted to be higher in the treated stands (Figure 4) because the more open stand conditions lead to higher mid-flame 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 Initiation Potential

The Torching and Crowning Indices were computed as described above. The critical 20-ft windspeed to initiate crowning (TI) for each of the treatments during Rothermel's (1991) drought summer fuel moisture conditions is shown below:

Unit	Treatment	Critical 20-ft windspeed for crown fire initiation ("drought summer" fuel moistures) Torching Index
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 TI increased in Treatments 1 and 3 because the crown base was raised by the low thinning (Treatment 1) and broadcast burn (Treatment 3). 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 it was the most exposed to wind after treatment. The TI refers to the initiation of a crown fire. Whether the crown fire is simple torching of individual trees or an active crown fire is determined by a second criterion for sustained crown fire spread (see below).

Note the very high windspeeds theoretically necessary to initiate crown fire in these stands, indicating there is little risk of crown fire initiation even in the untreated stand. This is due to the relatively high crown bases and light surface fuel loads of the study area. 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-ft windspeeds as low as 22 mi/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 feet 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 potential for crown fire initiation.

Moreover, the critical windspeeds for crown fire initiation are based on average surface fire intensity and average crown base height within the treatment 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 may initiate crowning in these portions of the stand. Although the TI may not accurately predict the exact windspeed at which crowning will begin, it does permit us to rank the treatments by the critical 20-ft 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.

Potential for Sustained Crown Fire Spread

The critical windspeed for sustained crown fire spread (CI) is a function of crown bulk density and the after-crowning rate of spread, should a crown fire be possible. 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 windspeeds among treatments results solely from differences in crown bulk density (see Table 6). Critical 20-ft windspeeds for sustained crown fire spread are shown below:

Unit	Treatment	Critical 20-ft windspeed for sustained crown fire spread ("drought summer" fuel moistures) Crowning Index
1	Minimum impact	33
2	Revenue production	43
3	Forest restoration	39
4	Untreated	28

Other factors equal, 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 values (most susceptible) come from the untreated stand.

It is desirable that a treatment not only prevent crown fires from initiating within the treated area, but also be able to bring an active crown fire back to the surface. The importance of TI 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.

Interpretation of the meaning behind differences in critical windspeeds (for either initiation of 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/hr occur much less than half as frequently as winds in excess of 20 mi/hr.

Economic Feasibility

One objective of this study was to determine the financial 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 vs. 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 nine-foot multiples) rather than random lengths for sawlogs (two-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 (Bureau of Business and Economic Reserach 1996) indicates the following prices ($/MBF) for logs delivered to western Montana mills:

	Product	
Species	Sawlogs	Peelers
PP	$ 359	$ 350
DF	$ 390	$ 493

Source: Bureau of Business and Economic Research (1996), 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/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
1	16%	16%	34%	35%	100%
2	8%	14%	39%	39%	100%
3	16%	30%	36%	18%	100%

Source: USFS pre-harvest timber cruise
Note: numbers may not sum to 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 costs , 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/administration costs for Idaho and western Montana National Forests (Keegan and others 1996) is shown. (Sale costs for private land are only $13/MBF [compare with $52/MBF for National Forests]).

Sale design/administration costs used here include: surveying, prescriptions, environmental analysis, appeals, timber cruising, marking, and harvest administration.

Logging costs include 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 logging costs include the cost of machine-piling slash at the landing or back-hauling. Logging costs 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 costs in Unit 1 were higher because a more labor-intensive method was used. The contractor provided the information on logging costs 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 USFS 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/ac, 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/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 USFS Ninemile Ranger District (in cooperation with the University of Montana and the Intermountain Fire Sciences Laboratory) at a cost of $1600, or $75/MBF ($267/acre).

Net Revenue

As indicated in Table 7, all treatments are financially feasible because 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, fuel, *etc.* increases. The price of logs, however, fluctuates widely with shifting supply and demand for lumber and logs. Figure 5 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 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 re-stated that the net revenue reported in Table 7 and Figure 5 represents only immediate-term monetary benefits. Treatments 1 and 3 removed less volume in this

Table 7 Treatment costs and revenue.

Unit	1	2	3
treatment	minimum impact	revenue production	forest restoration
harvest volume[1] (MBF/ac) (A)	1.71	5.23	3.56
logging cost[2] ($/MBF) (B)	215	200	
slash disposal[3] ($/MBF) (C)	45	1	75
planning cost[4] ($/MBF) (D)	52		
total cost (B+C+D) ($/MBF) (E)	312	253	327
total revenue[5] ($/MBF) (F)	403	412	389
net revenue (F-E) ($/MBF) (G)	91	159	62
net revenue (GxA) ($/ac) (H)	156	832	222

[1] Source: pre-sale timber cruise
[2] Source: Keegan and others (1995) and contractor estimates
[3] Source: Contractor estimates and timber sale report
[4] Source: Keegan and others (1996)
[5] Source: Fourth Quarter 1996 Log Price Report, Bureau of Business and Economic Research (1996), University of Montana.

entry and therefore have less residual growing stock than treatment 2. Therefore, the value of the residual timber stand following treatment 2 will be less than that following the other treatments. Moreover, the lighter treatments, especially treatment 1, can be re-treated sooner and more frequently than treatment 2. Comparing the present value of these periodically re-treated 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. 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

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 them, 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/ac 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 which 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 United States Forest Service and other land management agencies may find such a treatment useful in areas with high recreational values in which 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, re-treatment should be considered on a 10-20 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/ac) 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/ac) and was effective at reducing crown fire potential by reducing crown fuel. 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 well 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 little mortality is expected in the vigorous overstory. Re-treatment of this stand should not be necessary for 20-30 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 certainly the most effective in reducing fire hazard. Indeed, any treatment which 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. Although the prescribed residual basal area was the same in units 2 and 3, less growing space was made available in this unit because the thinning was from below. Surface and crown fuel dynamics should be similar to unit 2. Re-treatment of this stand should be considered at 15-20 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 several advantages. A heavier harvest would generate more income, and perhaps create more "natural" conditions. The lower residual basal area would also favor ponderosa pine regeneration, though that was not an objective of these treatments. However, this treatment already removed half of the basal area of the original stand. Further reductions in basal area could potenatially result in increased wind and snow damage.

CONCLUDING REMARKS

This thesis shows the derivation of two indices of crown fire potential the forest managers can use to assess the relative crown fire potential of different stands or alternative treatments. The Torching Index indicates the potential for some kind of crown fire activity (passive or active) by comparing predicted fireline intensity with the critical fireline intensity for crown fire initiation. Similarly, the Crowning Index indicates the potential for active crown fire by comparing the potential spread rate of an active crown fire with the critical spread rate computed using Van Wagner's (1977) criterion. Future improvements to these indices will include making the indices interval, rather than ordinal as they are now.

Fire hazard 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 which 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/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, these commercial thinning treatments will become more difficult on steeper slopes, where logging and road-building costs are higher. On sites where steep slopes or lack of marketable wood products makes these treatments difficult, 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.

APPENDIX — List of Symbols

Symbol	Definition
B, C, E	Terms in Rothermel's (1972) model, all functions of σ
CBD	Crown bulk density, kg m^{-3}
CBH	Crown base height, m
FMC	Crown foliar moisture content, percent
FME	Foliar moisture effect
HPA	Heat (release) per unit area, kJ m^{-2}
H	Heat yield of fuel, kJ kg^{-1}
I	Byram's fireline intensity, kW m^{-1}
$I'_{initiation}$	Critical I for initiating a crown fire, kW m^{-1}
I_R	Reaction intensity, kW m^{-2}
O	Open (6.1-m) windspeed, km hr^{-1}
Q_{ig}	Heat of preignition, kJ kg^{-1}
R	Forward rate of spread, m min^{-1}
R_{final}	R for any type of fire, m min^{-1}
R_{active}	R for a fully-active crown fire, m min^{-1}
$R_{surface}$	R for a surface fire, m min^{-1}
$R'_{initiation}$	Critical R for initiating a crown fire, m min^{-1}
R'_{active}	Critical R for sustaining an active crown fire, m min^{-1}
S	Mass-flow rate of crown fuel, kg m^{-2} s^{-1}
t_R	Flame residence time, min
U	Mid-flame windspeed, km hr^{-1}
W_f	Weight of fuel consumed in the flaming front, kg m^{-2}
W_t	Total fuel load, kg m^{-2}
W_a	Available fuel, or total fuel consumption, kg m^{-2}
W_o	Fine fuel that can potentially contribute to flaming front, kg m^{-2}
W_n	W_o with the mineral conent removed, kg m^{-2}
W_{crown}	Weight of available canopy fuel, kg m^{-2}
WRF	Wind reduction factor
β/β_{op}	Packing ratio/optimum packing ratio
ε	Effective heating number
ξ	Propagating flux ratio
ρ_b	Oven-dry fuelbed bulk density, kg m^{-3}
σ	Surface-area-to-volume ratio of fuel particles, cm^{-1}
ϕ_s	Slope factor
ϕ_w	Wind coefficient
$\phi'_{w\ (initiation)}$	Critical wind coefficient for crown fire initiation

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