# Potential Fire Behavior Is Reduced Following Forest Restoration Treatments

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**Abstract**—Potential fire behavior was compared under dry, windy weather conditions in 12 ponderosa pine stands treated with alternative thinning prescriptions in the wildland/urban interface of Flagstaff, Arizona. Prior to thinning, stands averaged 474 trees/acre, 158 $ft^2$/acre basal area, crown bulk density 0.0045 lb/$ft^3$, and crown base height 19.2 ft. Three thinning treatments differing in residual tree density were applied to each of three stands (total of nine treated, three control). Treatments were based on historic forest structure prior to Euro-American settlement and disruption of the frequent fire regime (*circa* 1876). Thinning reduced stand densities 77–88 percent, basal areas 35–66 percent, crown bulk densities 24–48 percent, and raised crown base height an average of 11 ft. Before thinning, simulated fire behavior under the $97^{th}$ percentile of June fire weather conditions was predicted to be intense but controllable (5.4 ft flame lengths). However, active or passive crownfires were simulated using crown base heights in the lowest quintile (20 percent) or winds gusting to 30 mph, representing the fuel ladders and wind gusts that are important for initiating crown burning. Under the identical conditions after thinning, all three treatments resisted crown burning. The degree of resistance was related to thinning intensity. It is crucial to remove thinning slash fuels through prescribed burning or other means. If not removed, slash fuels can cause crownfire behavior in the thinned stands under severe wildfire conditions. Finally, the crownfire resistance achieved through thinning will deteriorate over time unless maintenance burning and/or thinning is continued.

## Introduction

Flagstaff, Arizona, is located at the northwestern end of the largest contiguous ponderosa pine forest in the world. Increased fire intensity and severity are major concerns around Flagstaff and generally in southwestern ponderosa pine forests (Swetnam and Betancourt 1998), due to the regional increase in surface and canopy fuels following a century or more of fire exclusion and other human-caused disruptions of ecological processes (Cooper 1960; Covington and others 1994). In 1996, the two largest wildfires in the history of the Coconino National Forest burned a few miles north of Flagstaff. Seeking to prevent such fires from burning into developed areas, a collaborative group called the Grand Canyon Forests Partnership was formed to restore ecosystem health, reduce catastrophic fires, and improve economic benefits and management on public lands (GCFP 1998).

Tree thinning, prescribed burning, and/or other fuel reduction methods can reduce the hazard of intense fires (for example, Van Wagtendonk 1996; Graham and others 1999; Agee and others 2000). Using these techniques to restore a regime of frequent, low-intensity fires and tree structures approximating the relatively open presettlement forest stands should, in theory, simultaneously address the Partnership's goals. These treatments have potential for improving ecosystem health (Kolb and others 1994), reducing fire hazard (Covington and others 1997), and offering some economic benefits through forest product removal (Larson and Mirth 1998). Actually achieving this array of outcomes in complex ecosystems and social systems is difficult, requiring choices among competing interests. For example, Scott (1998a) compared the economic, aesthetic, ecological, and fire behavior tradeoffs of a set of alternative fuel treatments in a western Montana ponderosa pine forest. Kalabokidis and Omi (1998) carried out a similar analysis in a Colorado lodgepole pine forest.

The Grand Canyon Forests Partnership's initial wildland/urban interface experimental treatments were started in 1998 in cooperation with the Coconino National Forest and Rocky Mountain Research Station. The experiments had multiple objectives, but our focus in this paper is only on the treatment effects on potential fire behavior. The greatest concern in the wildland/urban interface is crownfire, both "passive" crownfire (tree torching) and "active" crownfire (fire spreading through the canopy). Crownfires spread rapidly (Rothermel 1991), resist control by hand crews and often mechanical or aerial equipment (Pyne and others 1996), and threaten structures with intense heat and firebrand showers (Cohen 2000).

Several complementary actions can improve the ability of communities to resist fire hazards to lives and property, including enhanced firefighting resources, improved access routes and rural address systems, heightened public awareness, reduction of structure flammability (Cohen 2000), and reduction of forest susceptibility to crownfire. The forest treatments discussed here address this latter factor. Local

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initiatives are under way to enhance other fire-resistance factors in the Flagstaff wildland/urban interface.

Until recently, fire behavior modeling tools such as BEHAVE (Andrews 1986) simulated only surface fire behavior. New tools such as FARSITE (Finney 1998) and Nexus (Scott 1999) have greatly increased the ease with which many aspects of crownfire behavior can be modeled and compared. It is important not to attach too much specificity to crownfire behavior predictions: the fundamental reason that crownfire modeling has advanced slowly is that crownfires are rare and occur in extraordinarily complex weather and fuel environments (Rothermel 1991). With caveats, however, simulations provide useful insights into the relative differences between treatments and the relative sensitivity of crownfire behavior to different variables.

From previous simulations with FARSITE and Nexus, as well as from literature results (Van Wagtendonk 1996; Scott 1998a,b), we recognized that simulations often resulted in outputs that appeared contrary to actual wildfire experience. In particular, simulated fires using our fuel and weather conditions proved nearly impossible to crown using realistic data, even though real fires had crowned under similar or even less severe conditions. One possible solution was to manipulate model output with adjustment factors. However, this method is unsatisfactory for modelers and their audiences, who would prefer to use well-supported numbers.

We tried a different approach. Both with weather and fuel data, we reasoned that "average" conditions were a misrepresentation of the real forest situation. For instance, to cross the threshold into tree torching, surface flame lengths must preheat the branches and leaves close to the bottom of the crown. Achieving this transition in simulations has been difficult because the average crown base height is often a relatively high value (15–30 ft). The fuel ladders, surface fuel jackpots, and wind gusts that facilitate the transition to the crown in real fires are not accounted for when uniform averages are used.

Taking the variability of the data into account could help simulate more realistic fire behavior, but which fraction of the variability is important? A single low crown is probably insufficient to initiate a crownfire, but crownfires can start and be sustained in strong winds even with much less than 50 percent of the stand in a crownfire-susceptible condition. We chose to rank the data by quintiles—20 percent groups—and compare fire behavior and treatment effects on both the stand averages and the susceptible quintiles, suggesting that the fire behavior in the vulnerable quintiles may be important in triggering intense fires.

# Methods

## Treatments

The Grand Canyon Forests Partnership chose to compare three treatments differing in residual tree density. All treatments were based on the presettlement pattern of tree structure as inferred from: (1) living trees of presettlement origin, characterized by larger size and yellowed bark (White 1985; Covington and Moore 1994), and (2) remnant material from snags, logs, and stumps of presettlement origin, which were well-conserved in the dry environment in the absence of fire (Dieterich 1980; Fulé and others 1997; Covington and others 1997; Mast and others 1999). All living presettlement trees were retained. In addition, wherever evidence of remnant presettlement material was encountered, several of the largest postsettlement trees within 30 ft were retained as replacements. If suitable trees were not found within 30 ft, the search radius was extended to 60 ft. The three thinning treatments each had a different replacement tree density:

- 1.5-3 replacements: replace each remnant with 1.5 trees (in other words, 3 replacements per every 2 remnants) if the replacements were 16 inches d.b.h. or larger, otherwise replace each remnant with 3 trees. Because relatively few greater than 16 inches postsettlement trees were encountered in any of the sites, all the thinning treatments tended to retain the higher number of replacement. The 1.5-3 treatment, called "full restoration," reduced tree density most closely to presettlement levels.
- 2-4 replacements: replace remnants with 2 trees greater than 16 inches d.b.h., otherwise 4 trees.
- 3-6 replacements: replace remnants with 3 trees greater than 16 inches d.b.h., otherwise 6 trees.
- Control treatment: no thinning, no burning.

## Study Sites

The treatments were tested on three experimental blocks in or adjacent to the Fort Valley Experimental Forest, approximately 15 km NW of Flagstaff, Arizona (fig. 1). Each block contained a 35-acre replicate of each of the three thinning levels and a control. The study area is at 7,400 ft elevation with gentle topography and a cool, subhumid climate (Avery and others 1976). Mean annual precipitation is 57 cm, with approximately half occurring as snow. The remainder occurs as summer monsoonal rains following the spring/early summer drought. Soils are of volcanic origin, a fine montmorillonitic complex of frigid Typic Argiboroll and Mollic Eutroboralf (Mast and others 1999). Experimental

**Figure 1**—Prescribed burning in Fort Valley treatment area, May 12, 2000.

blocks were laid out in cooperation with Forest Service staff, subject to constraints of other experimental studies and wildlife habitat. As a result, the treatment units in experimental blocks 1 and 2 could not be contiguous. All treatments were randomly assigned.

The timing and method of treatment differed in the experimental blocks due to economic constraints, primarily the very low value of the material removed, and to the Partnership's intention to make the site available to different operators. Thinning of the blocks began in November 1998 and was completed in September 1999. Blocks 1 and 2 were thinned with a mechanical feller and limbed at the tree, resulting in broadcast slash fuels. Block 3 was thinned in a whole-tree harvesting operation, resulting in slash piles. Piles in block 3 were burned in February 2000. All blocks were scheduled for broadcast burning in the spring or fall 2000.

## Measurements

Twenty experimental block (EB) plots were established on a 60-m grid in each of the 12 units. Plot centers were permanently marked with iron stakes at ground level and slope and aspect were recorded. Overstory trees over breast height (bh, 4.5 ft) were measured on a 0.1 acre (37 ft radius) circular fixed-area plot. Species, condition (1-living, 2-declining, 3-recent snag, 4-loose bark snag, 5-clean snag, 6-snag broken above bh, 7-snag broken below bh, 8-downed, 9-cut stump), and d.b.h., were recorded for all live and dead trees over breast height, as well as for stumps and downed trees that surpassed breast height while alive. Tree heights and average crown base height per plot were measured. Trees below breast height and shrubs were tallied by condition class and by three height classes (0–15.7, 15.8–31.5, and 31.6–54 inches) on a nested 0.025 acre (18.5 ft radius) subplot. Shrubs over breast height were also measured. Herbaceous plants and canopy cover (vertical projection) were measured along a 164-ft line transect oriented up- and down-slope. Point intercept measurements were recorded every 11.8 inches along each transect. Dead woody biomass and forest floor material were measured on a 50 ft planar transect in a random direction from each plot center. Fuels were measured by diameter/moisture timelag classes (1H timelag = 0–0.25 inch diameter, 10H = 0.25–1 inch, 100 H = 1–3 inches, 1000H = over 3 inches, sound (S) and rotten (R) categories). Woody debris biomass was calculated using procedures in Brown (1974) and Sackett (1980). Forest floor depth measurements were converted to loading (Mg/ha) using equations from Ffolliott and others (1976). Plots were originally measured from August through November 1998. After thinning, preburn fuels were measured on the same transects in October 1999.

## Modeling

Fire behavior was modeled with the Nexus Fire Behavior and Hazard Assessment System (Scott and Reinhardt 1999). As described by Scott (1998a, 1999), Nexus integrates models of surface fire behavior (Rothermel 1972) with crown fire transition (Van Wagner 1977) and crown fire spread (Rothermel 1991). Nexus is similar to the landscape fire behavior modeling program FARSITE (Finney 1998) in that both link the same set of surface and crownfire models. However, Nexus is better suited for comparing fire hazards under alternative conditions because environmental and fuel factors are kept constant for each simulation, rather than changing continuously with time and location, as in FARSITE.

Custom fire behavior fuel models were developed and tested with the NEWMDL and TSTMDL modules of BEHAVE (Andrews 1986). Pretreatment fuel models were modified from the standard fire behavior fuel model 9, "hardwood litter" (Anderson 1982). Postthinning fuel models were modified from standard model 11, "light slash." Future fuels, after thinning and burning, are likely to have reduced woody fuel loads and increased herbaceous fuels. A hypothetical future fuel model was developed by modifying standard model 2, "timber (grass and understory)." The predicted future herbaceous fuel load was 200 lbs/acre, based on a basal area/herbaceous production relationship developed in northern Arizona (Brown and others 1974).

Crown fuels were estimated with locally developed allometric equations for ponderosa pine shown in table 1. Crown volume was estimated using averages of maximum tree height (top of the canopy) and crown base height (bottom of the canopy). Crown bulk density was calculated as crown biomass divided by crown volume. This procedure is straightforward and appears to adequately represent the canopy fuels actually available in a ponderosa pine crown fire. Alternative methods of crown fuel estimation can lead to substantially different numerical values, so density values in different studies may not be directly comparable. The situation is further complicated by the relatively high sensitivity of crownfire behavior modeling to canopy bulk density.

Fire weather extremes representing the 90$^{th}$ and 97$^{th}$ percentiles of low fuel moisture, high winds, and high temperature were calculated from 30 years of data on the Coconino National Forest using the FireFamily Plus program (Bradshaw and Brittain 1999). Weather values were calculated for the entire fire season (April 23 to October 16) as well as for June, historically the month with the most severe fire weather (table 2). Fire behavior information from the two largest wildfires on the Coconino, the 1996 Horseshoe (May) and Hochderffer (June) fires, was used to estimate wind gusts during periods of extreme fire behavior

**Table 1—**Allometric equations for ponderosa pine foliage and fine branches.

| Variable | Equation | $R^2$ |
|---|---|---|
| Total foliage | ln(biomass, kg) = –3.9274 + 1.9654 ln(d.b.h., cm) | 0.96 |
| Needle-bearing twigs | ln(biomass, kg) = –4.5478 + 1.7352 ln(d.b.h., cm) | 0.85 |
| 0-0.63 cm branches | ln(biomass, kg) = –4.3268 + 1.4172 ln(d.b.h., cm) | 0.57 |

**Table 2**—Fuel moisture, wind, and temperature for the Coconino National Forest, 1970–1999. The 90th and 97th percentiles are shown for the entire fire season (April 23 to October 16) and for the month of June.

| Variable | Fire season | | June | |
|---|---|---|---|---|
| | 90th percentile | 97th percentile | 90th percentile | 97th percentile |
| 1 H moisture (percent) | 3.2 | 3.0 | 2.3 | 2.2 |
| 10 H moisture (percent) | 4.4 | 4.0 | 3.0 | 3.0 |
| 100 H moisture (percent) | 7.2 | 6.5 | 5.0 | 4.7 |
| Wind speed (mph) | 17.7 | 22.4 | 20.0 | 25 |
| Temperature (°F) | 82 | 82 | 89 | 89 |

(McCoy 1996). Wind gusts to 40 mph and sustained winds of 30 mph were observed on these fires. The 30-year fire weather record also shows that winds of 30 mph or more were recorded in the 1,300 hours observation on approximately 1 percent of June days.

## Results

Prior to treatment, forest structural conditions were similar across the study sites (table 3). Basal area ranged from 148.5 to 167.7 ft$^2$/acre, while tree density was more variable (386.7 to 603.9 trees/acre). Average stand heights were within 7 ft of each other across the sites (67.2 to 73.9 ft) and average crown base heights were within approximately 4 ft (17.4 to 21.5 ft). Crown bulk density values averaged 0.064 to 0.083 kg/m$^3$, similar to values reported by Scott (1998a) in a Montana ponderosa forest. Thinning reduced tree density and biomass most strongly in the full restoration (1.5-3) treatment and least in the 3-6 treatment, as expected. Postthinning densities ranged from 56.8 to 98.3 trees/acre, an average reduction of over 396 trees/acre (77 percent to 88 percent of trees removed). Because the largest trees were retained, however, basal area and crown biomass decreased by much smaller proportions. Postthinning basal area ranged from 44 percent to 65 percent of pretreatment values. Thinning reduced crown bulk density to 52 percent to 76 percent of pretreatment values. Crown base height was raised an average of 11 ft and the lowest quintile (20 percent) of crown base height was raised an average of 10.6 ft from 8.5 ft before thinning to 19.1 ft after thinning. Pretreatment surface fuels averaged 25.4 tons/acre, but the quintile (20 percent) of plots with the heaviest loading of less than 1000H fuels averaged 38.2 tons/acre (table 4). Postthinning fuels were surprisingly similar between the broadcast slash blocks (11 tons/acre of less than 1000H fuels) and the whole-tree harvested block (7.2 tons/acre of less than 1000H fuels). However, the primary difference was an extra 3.9 tons/acre of 1H fuels in the broadcast blocks, the fuel component most strongly influencing fire behavior. The broadcast blocks did have 80 percent more heavy fuel (more than 1000H and duff) loading, 18 versus 10 tons/acre. Burnout of these heavy fuels would be expected to lead to increased canopy and soil heating in the broadcast blocks after the passage of the flaming front.

Fires modeled in pretreatment conditions using the average stand values for crown bulk density and crown base height remained surface fires (table 5) even under the severe

**Table 3**—Forest stand structure and crown fuels at the Fort Valley study sites. See text for description of treatments. Prior to thinning, the lowest quintile of crown base heights averaged 8.5 feet. After thinning, the lowest quintile of crown base heights in the treated units averaged 19.1 feet.

| | Control | Full restoration (1.5-3) | Intermediate (2-4) | Intermediate (3-6) |
|---|---|---|---|---|
| | | **Pretreatment** | | |
| Basal area (ft$^2$/acre) | 164.3 | 151.5 | 167.7 | 148.5 |
| Trees/acre | 480.6 | 386.7 | 603.9 | 422.3 |
| Crown bulk density (lb/ft$^3$) | 0.0052 | 0.0040 | 0.0044 | 0.0042 |
| Average crown base height (ft) | 21.5 | 19.1 | 17.4 | 18.9 |
| Minimum crown base height (ft) | 11.5 | 8.2 | 6.6 | 8.4 |
| Crown fuel load (ton/acre) | 5.2 | 4.8 | 5.3 | 4.6 |
| Stand height (ft) | 67.2 | 73.9 | 73.2 | 69.7 |
| | | **Postthinning** | | |
| Basal area (ft$^2$/acre) | 164.3 | 67.8 | 77.7 | 97.2 |
| Trees/acre | 480.6 | 56.8 | 68.8 | 98.3 |
| Crown bulk density (lb/ft$^3$) | 0.0052 | 0.0021 | 0.0026 | 0.0032 |
| Average crown base height (ft) | 21.5 | 29.1 | 31.9 | 27.4 |
| Minimum crown base height (ft) | 11.5 | 12.6 | 17.0 | 18.0 |
| Crown fuel load (ton/acre) | 5.2 | 2.0 | 2.3 | 2.9 |
| Stand height (ft) | 67.2 | 73.9 | 73.2 | 69.7 |

**Table 4**—Surface fuel characteristics. Fuels were measured on the study sites except for the "hypothetical posttreatment fuels" (see text).

| Description | 1 H | 10 H | 100 H | Live | SAV | SAVLive | Depth | Moist. Ext. | Heat | 1000 HS* | 1000 HR* | Duff* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *- - - - - - - - ton/ac* | | | *- - - - - - - - -* | *- - - - - -1/ft* | *- - - - -* | *ft* | *percent* | *BTU/lb* | *- - - - - - - - ton/ac* | | *- - - - - - - -* |
| Pretreat average | 2.9 | 0.8 | 2.3 | 0 | 2500 | 500 | 0.4 | 25 | 8000 | 5.9 | 4.8 | 8.7 |
| Pretreat top 20 percent | 4.3 | 1.7 | 5.9 | 0 | 2500 | 500 | 0.5 | 25 | 8000 | 11.3 | 4.8 | 10.2 |
| Postthinning (broadcast slash) | 7.2 | 1.2 | 2.6 | 0 | 1500 | 500 | 1.0 | 15 | 8000 | 7.1 | 3.9 | 7.0 |
| Postthinning (whole-tree harvest, piled slash) | 3.3 | 1.2 | 2.7 | 0 | 1500 | 500 | 1.0 | 15 | 8000 | 2.2 | 0.8 | 7.0 |
| Hypothetical posttreatment fuels: grass and understory, modified FBFM 2) | 2.0 | 1.0 | 0.5 | 0.1 | 3000 | 1500 | 0.5 | 15 | 8000 | N/A | N/A | N/A |

*These variables are not included in fire behavior fuel models.

**Table 5**—Fire behavior outputs using the average pretreatment fuel loads under the June 97th percentile weather conditions with 97th percentile winds (top), 30-mph winds and lowest quintile crown base height (center), and posttreatment crown fuels with 30-mph winds and lowest posttreatment quintile crown base height (bottom). Foliar moisture content was held constant at 100 percent, wind reduction factor was 0.3, and slope was 7 percent (study site average) for all simulations.

| | Control | Full restoration (1.5-3) | Intermediate (2-4) | Intermediate (3-6) |
|---|---|---|---|---|
| | **Pretreatment (June 97th percentile weather)** | | | |
| Fire type | Surface | Surface | Surface | Surface |
| Crown percent burned | 0 | 0 | 0 | 0 |
| Rate of spread (ft/min) | 28 | 28 | 28 | 28 |
| Heat/area (BTU/ft$^2$) | 491 | 491 | 491 | 491 |
| Flame length (ft) | 5.4 | 5.4 | 5.4 | 5.4 |
| **Crown fire outputs** | | | | |
| Torching index (mph) | 54 | 49 | 45 | 48 |
| Crowning index (mph) | 28 | 34 | 32 | 33 |
| | **Pretreatment (June 97th percentile weather, 30-mph winds, lowest quintile crown base height)** | | | |
| Fire type | Active | Passive | Passive | Passive |
| Crown percent burned | 100 | 58 | 74 | 65 |
| Rate of spread (ft/min) | 128 | 90 | 105 | 97 |
| Heat/area (BTU/ft$^2$) | 2331 | 1473 | 1876 | 1569 |
| Flame length (ft) | 31.3 | 20.2 | 25.2 | 21.6 |
| **Crown fire outputs** | | | | |
| Torching index (mph) | 23 | 23 | 23 | 23 |
| Crowning index (mph) | 28 | 34 | 32 | 33 |
| | **Posttreatment (June 97th percentile weather, 30-mph winds, lowest quintile crown base height)** | | | |
| Fire type | Active | Surface | Surface | Surface |
| Crown fraction burned | 100 | 0 | 0 | 0 |
| Rate of spread (ft/min) | 128 | 37 | 37 | 37 |
| Heat/area (BTU/ft$^2$) | 2331 | 491 | 491 | 491 |
| Flame length (ft) | 31.3 | 6.2 | 6.2 | 6.2 |
| **Crown fire outputs** | | | | |
| Torching index (mph) | 23 | 49 | 49 | 49 |
| Crowning index (mph) | 28 | 55 | 47 | 40 |

fire weather conditions represented by the June 97$^{th}$ percentile (table 2). Fire behavior outputs were virtually identical across treatments prior to treatment, with only slight differences in the torching index (an estimate of the windspeed required to initiate tree torching or "passive" crown fire behavior) and the crowning index (an estimate of the windspeed required to support "active" fire spreading through the crown). The minor fluctuations in these two indices reflected the small differences in crown base height (important for the transition from surface fire to torching) and canopy bulk density (important for sustaining active crownfire). The torching index showed that a wind of at least 45 mph would have been needed to cause passive crownfire. If fire were already in the crown or entered from outside the stand, a windspeed of 28–34 mph would have sufficed to sustain active canopy burning. However, both indices were above the modeled 25 mph windspeed.

The simulated flame lengths, 5.4 ft, would have precluded direct attack by firefighters but mechanized equipment or indirect attack would have a high likelihood of successful suppression (Pyne and others 1996). The fact that modeled fires were amenable to suppression even under severe wildfire conditions is an accurate reflection of reality: the overwhelming majority of wildfires on the Coconino are contained below 10 acres (99.6 percent, fire records 1970–1999).

With 30 mph winds and/or the lowest quintile of crown base height, however, crownfire was simulated in the pretreatment sites. Keeping the crown base height at the average values but increasing wind to 30 mph led to conditional crownfire behavior (crownfire won't start, but could be sustained if it entered from outside the stand) in the stand with the highest crown bulk density. Lowering the crown base height to 8.5 ft, the average of the lowest pretreatment quintile, caused active or passive crownfire in all the sites at both the 25 and 30 mph windspeeds (table 5). Because 30 mph or higher wind gusts occur, and because at least one-fifth of the modeled forest is vulnerable to crownfire, these results may bridge the apparent contradiction between observed crownfire behavior and the unrealistically high windspeeds required for simulated crownfires using average stand characteristics.

Thinning treatments substantially reduced fire behavior under the same environmental circumstances. As shown in table 5, with the identical 30 mph wind and the lowest quintile of posttreatment crown base height, the simulated fire did not achieve any category of crown burning. All three treatments had the same torching index (49 mph) but the crowning index differed with canopy bulk density. The modeled 3-6 treatment could support conditional crownfire at windspeeds as low as 40 mph, while the modeled 1.5-3 treatment required 58 mph, 45 percent higher.

Although the comparison in table 4 shows a clear change in fire behavior due to the restoration treatments, the postthinning fuels are different than the pretreatment fuels. As the treatments progress, the slash fuels created by thinning are scheduled to be removed by prescribed burning. Mechanical means could also be used. But as long as these fuels remain in the stand, they present a threat of intense fire behavior. Active or passive fires crowned in all the simulated stands, including the treated sites, using either the broadcast or the whole-tree harvest slash fuel models in table 4. With standard fuel model 11, however, the control had active crownfire but the treated stands had only surface fires.

Fire behavior in future fuels, after removal of the slash, will probably be influenced by a higher herbaceous component. Under the hypothetical model presented in table 4, with 30 mph winds and the lowest quintile of crown base height, conditional crown fire was predicted for the control stands and surface fire for all the treated stands.

## Discussion

Model results should always be applied cautiously. Current models that link surface and crownfire behavior are highly sensitive to crown base height, windspeed (or wind reduction factor), fuel moisture, and surface fuel model variables (1H fuel loading, herbaceous fuels, surface-area-to-volume ratio, fuel bed depth). We held slope constant at 7 percent (the average slope of the experimental blocks) but similar fuels on steeper slopes would exhibit higher fire intensity. There are a number of uncertainties in the models integrated in Nexus, reflecting the complexity of fire behavior (Scott 1998b). The actual numerical values used for model inputs produced realistic predictions but in some instances the differences between crown and surface fire behavior were separated by only a few miles/hr of windspeed (table 5). If wind gusts of higher speeds or higher surface fuel loadings were encountered, portions of the stands would be more likely to exhibit crownfire behavior. The behavior of real fires in these stands would be affected by roads, meadows, surrounding forest fuels, landscape topography, and suppression activities.

The purpose of the modeling analysis was not to accurately estimate the behavior of a real fire but rather to compare the treatment alternatives. All three thinning treatments tested by the Grand Canyon Forests Partnership substantially reduced the potential for passive and active crownfire. All the treatments increased crown base height to nearly 30 ft, making passive crownfire initiation difficult. However, the different thinning levels in the three treatments created differences in crown bulk density that were reflected in the potential for active crownfire. Prior to treatment, the crowning indices of all the stands were separated by only 6 mph (top section of table 5). After treatment (bottom of table 5), the crowning index ranged from 28 mph (control stands), 40 mph (3-6 treatment), 47 mph (2-4 treatment), to 55 mph (1.5-3 treatment). In relative terms, taking the control crowning index as unity, the 3-6 treatment required 43 percent more windspeed, the 2-4 treatment required 68 percent more windspeed, and the 1.5-3 treatment required nearly double (96 percent) more windspeed, for active crownfire.

The restoration treatment is not complete when the thinning is finished. Slash fuels increase the fire hazard as long as they remain on the ground, so prompt treatment with prescribed fire or mechanical means is important. Over time, vegetation in the treated units will change as both herbaceous plants and trees respond to the thinning. The potential intensity of grass-fueled fires should not be underestimated. Stand basal area even in the full restoration stands remained high enough to limit predicted herbaceous production to approximately 200 lbs/acre. If herbaceous production in the treated stands reached the 1,000 lbs/acre in the standard fire behavior fuel model 2, passive crownfire was predicted in the lowest crown base quintile for all treatments under severe weather conditions. However, grass fuels would be unlikely to have reached full productivity or to be fully cured in June. Even with a high fireline intensity, grass fires are of short duration with few heavy fuels and are more amenable to control than timber fires.

Strictly from a fire control perspective, therefore, a balance of relatively more trees and relatively less grass, such as the 2-4 or 3-6 treatments, might be useful in areas close to homes. On the other hand, future fire behavior will also be influenced by the growth of residual trees and new regeneration. Treatments with relatively high residual density might more rapidly grow back into a hazardous condition. Maintenance burning and/or further thinning can be used to regulate growth and keep the stands relatively crownfire-resistant. The failure to carry out these management activities would eventually eliminate the original treatment effects on fire behavior.

Potential fire behavior is an important consideration in the design of wildland/urban interface forest treatments, but it is not the only consideration. Fire hazard tradeoffs should be recognized and evaluated against many other forest values. In the present analysis, we have incorporated some of the variability in fuels and weather. A more complete analysis, however, could include spatial variability within stands and across landscapes, temporal variability (diurnal to seasonal change), successional change (years to centuries), and predicted changes in land use. In addition to modeling intensity and behavior of the flaming front, the effects of fuel burnout and smoke production should be considered. Many of the tools and components of such a comprehensive analysis are being rapidly improved.

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