The Effects of Brush Cutting and Burning on Fuel Beds and Fire Behavior in Pine-Oak Forests of Cape Cod National Seashore

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Abstract

Pine-oak forests comprise 46% of the vegetation of Cape Cod National Seashore. Flammable ericaceous shrubs, especially *Gaylussachia baccata*, dominate the understories and combined with heavy litter fuel loads increase the probability of intense surface fires. Past research has evaluated the use of brush cutting and prescribed burning to reduce fire hazard and to construct custom fuel models to predict fire behavior. Results suggest that the two treatments combined will better accomplish this goal than when they are applied separately. The goal of this project is to evaluate the effectiveness of combined treatments.

Six, 0.5-acre plots were established in 2003 at the Lombard-Paradise Hollows Fire Management Research Area on Cape Cod National Seashore, Truro, MA. The plots were treated in 2003, and treatment effects were evaluated by fuel sampling and the application of prescribed fire in 2004. The effects of combined brush cutting and prescribed fire on fuel bed characteristics and fire behavior were documented. Fuel load and fuel depth were examined before and after treatments to explain differences in fire behavior observed on the 2004 prescribed burns.

Combining brush cutting and burning treatments significantly reduced litter depth, litter load, shrub depth, and shrub load compared to controls ($p < 0.05$). This was reflected in lower mean flame lengths (cut/burn=1.2 ft; control=3.6 ft) and lower mean rates of spread (cut/burn=4.5 ft/min; control= 7 ft/min) on treated plots. Brush cutting followed by burning redistributes fuels over a shallower fuel depth, which increases the packing ratio of the fuel bed. Custom fuel models derived from the fuels data better predict observed fire behavior than standard fuel models available from BehavePlus fire prediction software (citation: year?).

Introduction

Since 1985,one of the longest-running prescribed fire experiments in the National Park Service has been conducted at Cape Cod National Seashore. Over the past 20 years 48, 0.1-acre

plots have received either brush cutting or prescribed fire treatments at one-to four-year intervals during either the dormant or growing season. Five plots were left as controls. The goal of this work was to identify effective methods for reducing fuel load and depth of ericaceous shrub understories in pitch pine-oak forests. As an outgrowth of the ongoing, long-term research, William A. Patterson III of University of Massachusetts at Amherst and David W. Crary, Jr. of Cape Cod National Seashore have established a Joint Fire Science Program funded Fuels Demonstration Project to document the effects of combined prescribed fire and brush cutting treatments on fuel loading and fire behavior (Patterson and Crary 2004). Six, 0.5-acre plots were established and fuels were treated mechanically and with prescribed fire in 2003. The project will benefit fire managers through the development of 1) a set of methods to efficiently sample fuels to gather input data for the surface fire behavior prediction system BehavePlus, and 2) custom fuel models for the pine-oak forest fuel type that reflect the effects of treatments on fire behavior.

Preliminary results from the experiment begun in 1986 indicated that combinations of brush cutting and prescribed fire might be more effective in reducing potential hazardous surface fuels than each treatment implemented separately (Patterson, personal communication). Due to high fuel loads (fine fuel loads can exceed 10-13 tons/acre) prescribed burning in the dormant season without prior mechanical treatment can produce intense fire behavior that can damage oak canopies (Patterson and Crary 2004). Brush cutting treatments alone are inefficient and impractical given the large area needing treatments. For initial fuel reductions at Cape Cod National Seashore, combined treatments applied during the growing season may more effectively reduce hazardous fuels than either of the treatments applied separately (Patterson and Crary 2004). The specific objective of this project is to compare fire behavior (flame length, rate

of spread) on three, 0.5-acre plots that have been treated with brush cutting and prescribed

burning to fire behavior on three untreated plots.

Literature Review

Pitch pine-oak forests are found on the Atlantic coastal plain and on interior glacial

outwash plains of the mid-Atlantic and northeastern U.S. Often referred to as "pine barrens"

(Dell'Orfano 1999), the largest of these are found in central New Jersey, and on Long Island and

Cape Cod. The term barrens dates to a New England colloquial phrase that describes areas of

land that have extremely infertile and droughty soils (Rawinski 1987). They are often poor

agricultural land and many have remained unplowed although most were exploited for wood

products such as firewood, pine tar, and building materials. Barrens were frequently burned by

Native Americans who used fire to increase the abundance of food sources such as blueberries

and deer browse (Patterson and Sassaman 1988). The long history of fire use by Native

Americans, has made fire an ecological factor that has influenced vegetation composition and

lead to the evolution of species that live in areas of relatively high fire frequency (Patterson and

Sassaman 1988).

The pine-oak forests of Cape Cod National Seashore consist of vegetation that is well

adapted to xeric growing conditions and periodic fire. The summer climate of Cape Cod is

characterized as having high humidity and warm temperatures modified by maritime influences.

However, sandy soils do not hold water, and xeric conditions are conducive to the development

of flammable ericaceous vegetation, which increases fire risk despite moderate annual rainfall

(Matlack et al. 1993a). These soils are also highly acidic, which retards microbial decomposition

of the timber litter on the forest floor (Rawinski 1987). This allows a thick layer of surface fuels

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to accumulate. Fine fuels (needles and leaves) and downed woody fuels dry rapidly on these well-drained soils (Crary 1988).

The dominant canopy species on Cape Cod are *Pinus rigida* (pitch pine), *Quercus alba* (white oak), and *Q. velutina* (black oak). Patches of *Quercus ilicifollia* (scrub oak) can be found growing sparingly in the sub-canopy. The low shrub layer is dominated by an upland ericaceous shrub group consisting of *Gaylusaccia baccata* (huckleberry)*, Vaccinium* spp. (blueberries), and *Gaultheria procumbens* (wintergreen). The leaves of these shrubs, particularly huckleberry, contain volatile hydrocarbons and can ignite and burn in the summer when leaves are green and contain abundant moisture (Putnam 1989).

The canopy and forest floor vegetation has adapted to periodic low intensity fires through key life history traits. Pitch pines have thick bark that protects the cambium from heat damage. If young stems are top-killed, they re-sprout after a fire. Mature stems can refoliate after crown fire by epicormic sprouting (Rawinski 1987; FEIS; Forman and Boerner 1981). Both white and black oaks can sprout from the stump after surface fires (Rawinski 1987; Forman and Boerner 1981). Huckleberry and blueberry have an underground network of rhizomes that allows rapid re-sprouting following fire (Matlack et al. 1993b).

Fuel bed characteristics describe how much fuel is available to burn (fuel load) and how that load is distributed above the ground (fuel bed depth). Fuel load is the weight of fuel per unit area (e.g. tons/acre) (Andrews et al. 2005). Fuels can be further subdivided into time-lag size classes of 1-, 10-, and 100 hour - based upon the amount of time needed for the fuel particle to dry out relative to the fuel particle's size (Table 1). The 1-hr timelag dead fuel category has the largest influence on surface fire behavior and includes leaves, needles, and small twigs.

Table 1. Timelag classification for dead fuel.

Timelag Class	Roundwood Diameter (inches)
1-hour	0-0.25
10-hour	0.25-1.0
100-hour	1.0-3.0
1000-hour	3.0+

Fuel bed depth is the average height (above the top of the duff layer) of surface fuels that is contained in the combustion zone of a spreading fire front (Andrews et al. 2005). It is measured in feet (or meters) and consists of litter, shrub, slash, and grass components. Using fuel load and depth values, a packing ratio can be calculated to better estimate the arrangement of available fuels. The packing ratio is the fraction of a fuel bed occupied by fuels, or the fuel volume divided by the bed volume (Andrews et al. 2005). Packing ratio increases as fuel load increases or fuel beds become shallower (i.e. fuel depth decreases).

Fire behavior is defined as the dynamics of a fire event (Pyne et al. 1996). Fire behavior is characterized in this project by rate of spread (ROS) and flame length (FL). Rate of spread is the relative activity of a fire in extending its horizontal dimensions and is expressed in feet per minute (ft/min) or chains per hour (ch/hr) (Andrews et al. 2005). Flame length is the distance measured from the tip of the flame to the middle of the flaming zone at the base of the fire. It is measured at an angle when the flames are tilted due to effects of wind and slope (Andrews et al. 2005). Flame lengths are important to prescribed fire and wildfire personnel, because they are related to fire line intensity and hence directly influence appropriate fire suppression tactics (Table 2).

Fire behavior is directly related to fuel load and fuel bed depth as they affect packing ratio. If the packing ratio of the fuel bed is increased relative to pre-treatment conditions, lower flame lengths and slower rates of spreads are expected.

Table 2. Fire suppression limitations with regards to flame lengths.

Flame Length (ft)

≤4'	fires can generally be attacked at the head or flanks by persons using hand tools. Handline should hold fire.
4'-8'	Fires are too intense for direct attack on the head by persons using hand tools. Handline cannot be relied on to hold fire.
8'-11'	Fires may present serious control problems; torching out, crowning and spotting. Control efforts at the head will probably be ineffective.
>11'	Crowning, spotting and major fire runs are probable. Control efforts at the head of the fire will be ineffective.

Fire spread models were developed by the United States Forest Service (USFS) to predict surface fire behavior relative to a fuel model. A fuel model is a set of numbers (e.g. fuel load and depth) that define fuel inputs (Pyne et al. 1996). BehavePlus is a modeling program that was developed by the USFS to estimate site-specific surface-fire behavior using one of thirteen standard fire behavior prediction system (FBPS) fuel models for common fuel types (Appendix 1). The latest version is BehavePlus3 (Andrews et al. 2005). Outputs including FL and ROS are used by fire suppression and prescribed fire personnel to determine strategy and tactics specific to the objective of the incident. None of BehavePlus' standard fuel models produce fire behavior outputs that adequately represent observed fire behavior in pine-oak forest fuels, however (Patterson et al. 2005).

Fire Hazards on Cape Cod

Cape Cod National Seashore contains a significant wildland fire interface consisting of over 600 houses, businesses, and other structures (Dell' Orfano 1996) amid extensive pitch pine-oak forest fuels. Past fire suppression policies have resulted in large accumulations of surface

fuels and closed canopies of flammable pitch pine (Crary 1988). The combination of high fuel loading and an overcrowded tourist destination results in the potential for wildland fire ignitions.

Cape Cod's pine-oak forests are similar in species composition and fuel loading to those on Long Island and New Jersey (Matlack 1993). In 1995 two separate fires burned 9,500 acres in Long Island in two days (Dell'Orfano 1996). Several houses and other structures were destroyed by a fire front with 40-to-100-foot flame lengths. Drought conditions and high winds contributed to fire severity. Similar fire behavior was observed in the Plymouth County, Massachusetts fire of May 1957. Fifteen thousand acres burned in two days with flame lengths exceeding 100 feet (Winston 1987). Fires in Ossipee, New Hampshire and Montague, Massachusetts burned hundreds of acres during the spring of 1957. These catastrophic fires occurred in areas where past wildfires had been actively suppressed and fuel loading was high.

Fuel Treatments

Unpublished results from the 20-year-long brush cutting and burning project in Truro indicate that brush cutting or burning alone does not fully address hazardous fuel load or fire behavior concerns. Brush cutting reduces fuel bed depths but does not reduce fine fuel loads. In fact, cutting brush increases surface 1- and 10-hr woody fuel loads. Burning reduces fine fuel loads, but is inherently dangerous due to high flame lengths. Burning also leaves a large standing dead shrub component that results in re-burns within a year or two being almost as intense as the first (Patterson, personal communication). Brush cutting followed by prescribed surface fires at 3-5 year return intervals should result in fires moving though compacted, fuel-reduced beds with lower rates of spread and intensity.

Objective

The objective of this project is to evaluate the feasibility of applying low-intensity prescribed burning and brush cutting treatments to safely reduce fuel loads at Cape Cod National Seashore. Fuel loading, fuel bed depth, and percent cover were characterized before and after treatments in three, 0.5-acre plots that were first brushcut in June 2003 and then burned in July (C/B plots). Three untreated, 0.5-acre control plots were established and sampled in the same manner as the treated plots. Prescribed burns in May 2004 were used to evaluate fire behavior on all six plots. Fire behavior and fuel bed characteristics were measured and compared on all plots.

To achieve the objective, the following null and alternative hypotheses were developed:

H_{01}: There is no difference in fuel bed characteristics between treated and untreated plots.

H_{A1}: Brush cutting followed by burning reduces fuel load and fuel bed depth.

H_{02}: There is no difference in fire behavior between the treated and untreated plots.

H_{A2}: Brush cutting followed by burning reduces flame length (fire intensity) and rate of spread.

Study Area

The study area is located on federal land in South Truro, Massachusetts, between Lombard and Paradise Hollows, west of U.S. Route 6, and just north of the Wellfleet – Truro town line (Figure 1). The climate of the area is characterized as having cool moist winters and warm summers (Leatherman 1979). The study area rests on a high-lying outwash plain (elevation 33 meters) formed by the Channel Ice Lobe at the end of the Wisconsin Stage of the Pleistocene Epoch (Strahler 1966). The soils are Hinckley coarse sands, light brown and loose textured, and are underlain to a depth of 40 to 60 feet by yellow coarse sand (Latimer et al. 1924). The sandy soil and underlying coarse material predisposes the vegetation to drought.
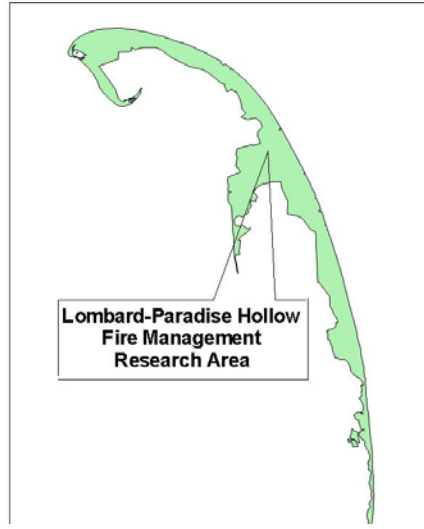
Figure 1. Location of the study area within Cape Cod National Seashore, Truro, MA.

Pine-oak forests comprise 46% of the vegetation of Cape Cod National Seashore (Patterson and Crary 2004). The Lombard-Paradise Hollow Fire Research Area has basal areas that range from 90-120 ft^2/acre; depending upon the amount of pitch pine present, with areas of denser pitch pine having higher basal areas (Patterson, unpublished data). Stand dynamics consist of early successional pines being replaced by white and black oak due to a lack of disturbance to regenerate pitch pine seedlings (Patterson et al. 1983). Scrub oak occurs in the understory along with black huckleberry, and late low sweet and early low blueberry (*Vaccinium vacillans* and *V. angustifolium*). Wintergreen and Pennsylvania sedge (*Carex pennsylvanica*) are the most common non-woody species.

The Lombard-Paradise Hollow Fire Management Research Area originally consisted of 60, 0.1-acre plots and four larger plots of 1-to-2 acres each (Figure 2). The Joint Fire Science Program (JFSP) plots are located in the eastern section of the research area (Figure 2).
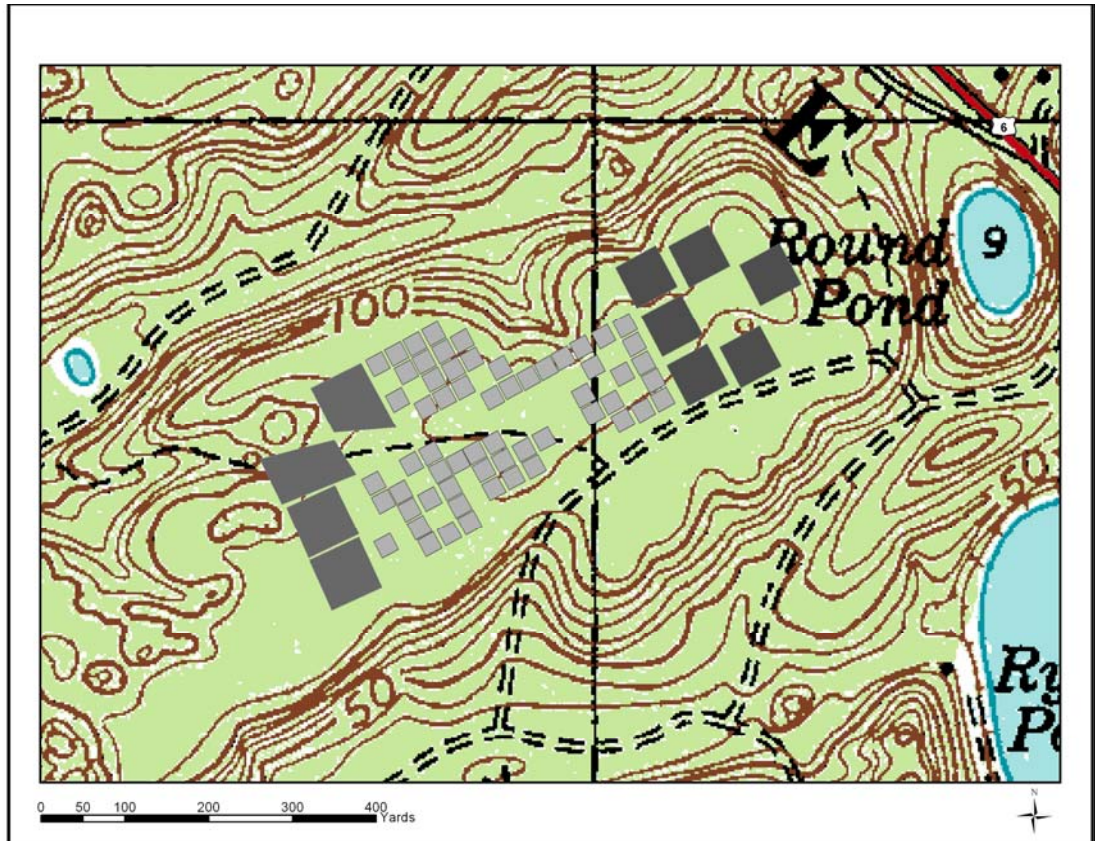
Figure 2. Lombard-Paradise Hollow Fire Management Research Area. The 60 original 0.1 acre plots are light grey; the four larger (1-2 acre) plots (to the west) are medium grey, and the six, 0.5 acre JFSP plots (to the east) are dark grey.

This project involved the six, 0.5-acre JFSP plots (Figure 3). JFSP plots 1, 3, and 5 received combined brush cutting and burning treatments (C/B). Plots 2, 4, and 6 were initially left untreated to serve as controls for the fire behavior tests.
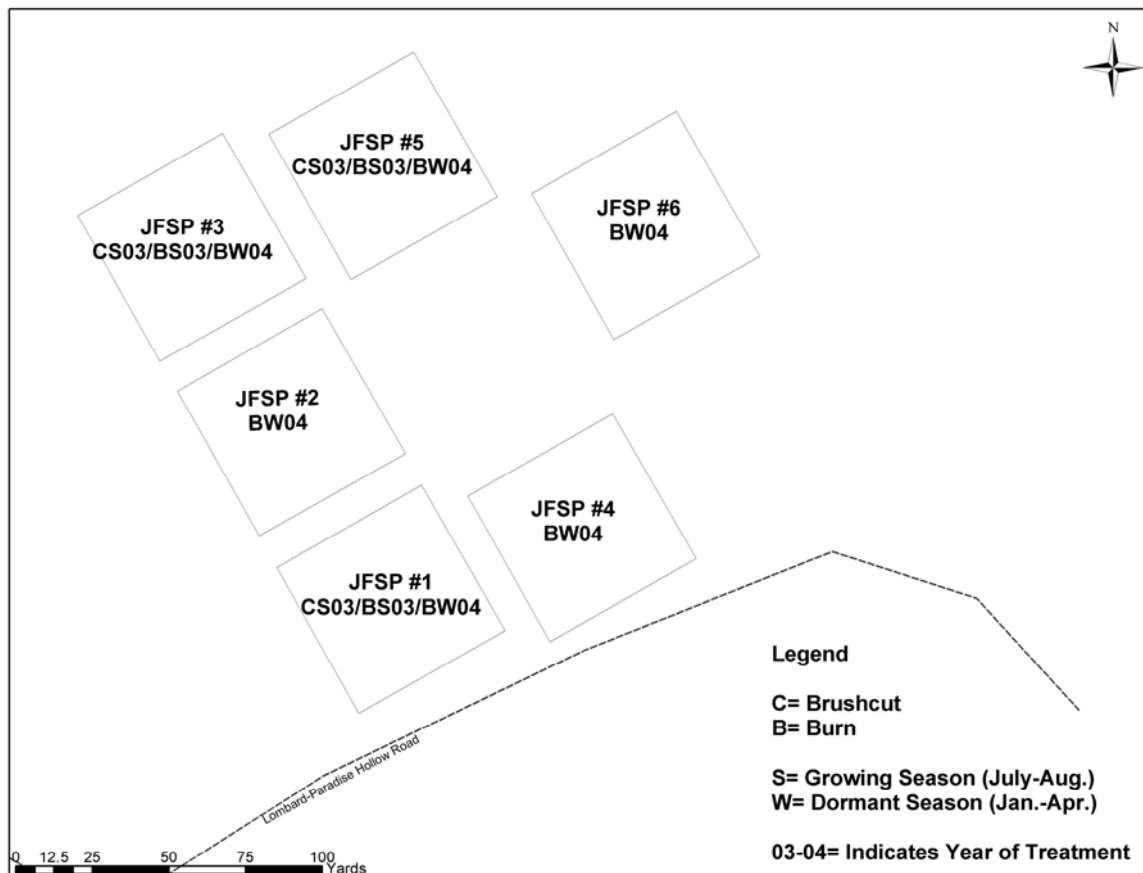
Figure 3. JFSP treatment plots, Lombard-Paradise Hollow Fire Management Research Area, Cape Cod National Seashore.

Methods

Study Design

The six 0.5-acre JFSP plots were delineated and marked in an area of homogeneous vegetation and topography in June 2003. Three replicate plots of each treatment (C/B and control) were established (Patterson and Crary 2004). Three-meter-wide fuel breaks were cut around each plot to confine treatments to assigned plots and to provide access to the area.

Treatment Implementation

Shrubs on plots 1, 3, and 5 were cut using hand-held *Stehl* brushcutters in June 2003, shortly after leaf-out when root carbohydrate reserves in huckleberry are low (Droge and

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Patterson 1995). The three plots were burned in late July (Figure 3). By implementing two treatments in the same growing season we hoped to reduce fuel loads, which had been augmented by the brush cutting, and to reduce the vigor of resprouting huckleberry plants by forcing them to produce new sprouts when root reserves were low. All six plots were burned in the May 2004 so fire behavior comparisons could be made.

Field Measurements

Fuel bed characteristics were measured to quantify changes in fuel load and fuel bed depth. For each 0.5-acre plot, surface fuels were harvested from 9, 40 cm by 40 cm subplots (Brown et al. 1982) to quantify fuel loads as live and dead rooted shrubs, litter, and 1-, 10-, and 100-hr dead down woody fuels. Point intercept (PI) sampling (Mueller-Dombois and Ellenberg 1974) was used to determine cover and depth of litter and vegetation. For each plot, a grid was used to systematically sample 225 pre-determined points. Depths of litter, down wood, and standing shrubs were measured for each sampling point. Downed woody fuels were inventoried along transects (five/plot) (Brown 1974). An in-depth description of fuel harvest sampling, point-intercept sampling, and Brown's planar intercept method can be found in Appendix 2.

In 2004, all standing trees on plots 1, 2 and 3 were tallied recording diameter at breast height (dbh), status (live or dead), and crown class to determine basal area, stem density, and first-order fire effects by species.

Fire behavior observations were obtained from three or four head fires from each plot. Not all fire behavior observations were included in the mean ROS and FL for the plot due to wind shifts and/or varying fuel conditions. A subset of fire behavior observations was selected to calculate a mean ROS and FL that best represented a head fire on the plot.

Sampling Timeline

Fuel bed characteristics were quantified before and after treatments so that changes in observed fire behavior could be explained. For the cut/burn plots (1, 3, 5) fuel harvesting and point intercept sampling were conducted in June 2003 (before brush cutting), July 2003 (after brush cutting but before burning), and before burning in May 2004. Point intercept sampling was conducted in August 2003 (after the July burn) and before the burn of May 2004. Fuels were sampled in the control plots before burning in April of 2004. Post-fire fuel loads were measured in May and June of 2004. Post-fire fuel bed depths were measured on both the brushcut and control plots in August 2004.

Data Analysis

Sampling was designed to efficiently collect input data for the development of a custom fuel model using BehavePlus3. Differences in treatment effects on fuel bed characteristics were tested with difference of means tests (Sokal and Rohlf 1995).

To build custom fuel models in BehavePlus3, the fuel load, fuel bed depth, surface area to volume ratios, moisture of extinction, and heat content for the fuel bed in question must be known (Andrews et al. 2005). Surface area to volume ratios and heat content values were determined using the BehavePlus3 user's guide (Andrews et al. 2005). The moisture of extinction used for pine-oak litter is 25% (Patterson, unpublished data). Fuels harvested from 40cm x 40cm plots provided fuel loads. Fuel bed depth was measured using systematic point intercept sampling that allowed litter depth and shrub depth to be measured. For this project, litter/slash depth and shrub depth values were combined to calculate a total fuel bed depth using a weighted average formula using NEXUS, a fire behavior-modeling program (www.fire.org). This weighted average uses load and depth for litter, slash, shrubs, and grass to derive a depth

that is proportional to the fuel load. A packing ratio relative to each treatment was calculated

using fuel load and fuel depth values. The packing ratio was calculated by NEXUS.

Results

Stand Data

The JFSP plots have canopies dominated by pitch pine and white oak, which

together comprise 75% of stand basal area (Table 3). Smaller black oaks have the highest

stem densities (Table 3). Pre-treatment fuel loads ranged from 5-6 tons/acre, with 74% of

the load being non-woody litter and standing shrubs (Table 4). Downed wood in the 10-

and 100-hour timelag classes comprise the balance (1-2 tons/acre) of the fuel. Litter

depths are less than shrub depths, which average 0.46 ft and 1.29 ft respectively. Shrub

cover was approximately 70% (Table 4).

Table 3. JFSP plots stand data.

Stand Report	Basal Area	% Basal Area	Density	% Density	Mean DBH
	ft2/acre		(stems/acre)	(%)	(inches at breast height)
Pitch Pine	43.3	37.6	68.5	27.3	10.8
White Oak	43.2	37.5	150.0	40.6	7.3
Black Oak	28.5	24.8	215.3	30.2	4.9
Eastern White Pine	0	0.0	1.6	0.1	1.0
Total	**115.0**	**99.9**	**435.4**	**98.2**	**6.0**

Table 4. Pre-treatment fuel bed parameters for JFSP plots 1, 3, and 5 (sampled 7/03).

A. Fuel Loads					
Total Load (tons/acre)	Litter Load (tons/acre)	1-hr woody (tons/acre)	10-hr (tons/acre)	100-hr (tons/acre)	Shrub Load (tons/acre)
5.74	3.30	0.73	0.68	0.06	0.96

B. Fuel Depths		
Litter Depth (ft)	Shrub Depth (ft)	Shrub Cover (%)
0.46	1.29	70.67

Fuel Load

Data describing fuel loads are summarized in Table 5. The initial cutting treatments in June 2003 increased 1-hr non-woody loading in plots 1, 3, and 5, from 3.94 to 4.87 tons/acre (Figure 4). The mean 1-hr woody loading was increased from 0.62 to 1.49 tons/acre (Figure 5). None of these increases were significant ($p > 0.10$).
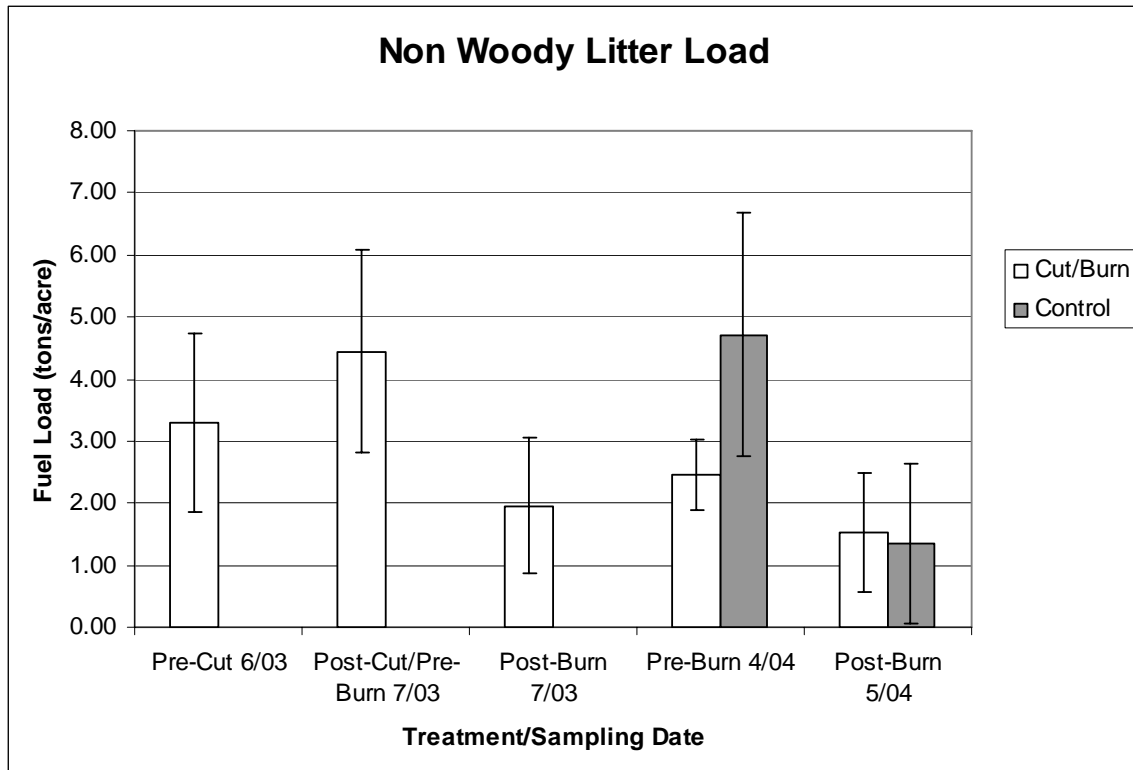
Figure 4. Effects of treatments on non-woody litter loads estimated by harvest sampling (error bars indicate 95% confidence limits).

After the first prescribed burn in July 2003, mean 1-hr woody fuel loads for the C/B plots were reduced but not significantly ($p > 0.10$). Woody one-hr fuels were significantly reduced ($p < 0.05$) by 68% after the initial burn treatment (Figure 5). Before the burn of May 2004, the control plots (2, 4, and 6) had a significantly ($p < 0.10$) higher 1-hr nonwoody (litter) fuel load than the already-treated C/B plots (4.71 tons/acre vs. 2.72 tons/acre; Figure 4). The burn of May

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2004 significantly reduced ($p < 0.05$) 1-hr non-woody fuel loads in the control plots by 71%

(4.71 to 1.36 tons/acre; Figure 4).

1-hr Woody Litter Load

Figure 5. Effects of treatments on 1-hr woody litter load established by harvest sampling (error

bars indicate 95% confidence limits).

Ten-hr fuel loads were reduced, but not significantly ($p > 0.10$), from 0.65 ton/acre before

treatments to 0.39 ton/acre after one cut and two burns (Appendix 3). Mean 10-hr fuel load

increased (but not significantly, $p>0.10$) from 0.42 to 0.68 ton/acre in the control plots after one

burn (Appendix 3).

After the initial cut, mean shrub fuel load (live plus dead) was reduced, but not

significantly, from 0.96 to 0.47 ton/acre ($p >0.10$; Figure 6). Mean shrub loads on the C/B plots

were significantly lower ($p < 0.05$) than on the control plots (0.19 vs. 1.03 tons/acre) before the

burn of May 2004 (Figure 6). Mean shrub loads were significantly reduced ($p < 0.05$) by 68% in

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both C/B and control plots after the burn of May 2004 (Figure 6). Mean shrub loads were 81%

less ($p < 0.10$) in the C/B than in the control plots after the burn of May 2004 (0.06 and 0.33

ton/acre; Figure 6).
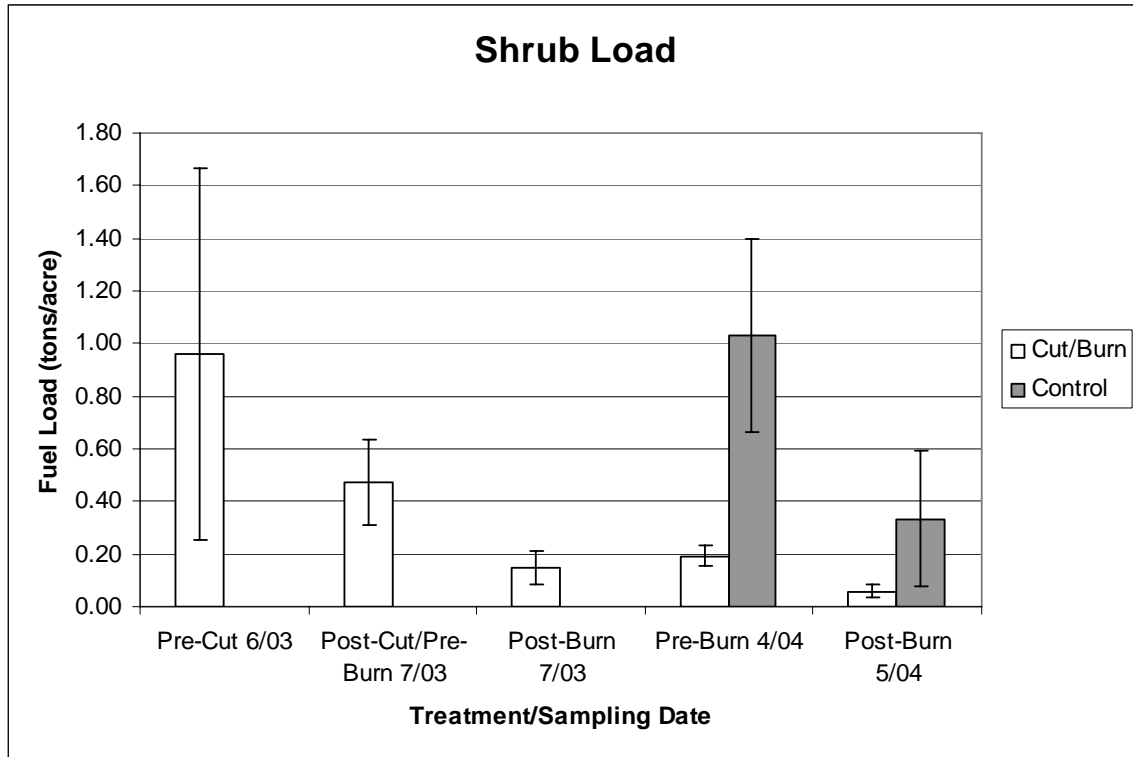
Figure 6. Effects of treatments on shrub loads estimated by harvest sampling (error bars

indicating 95% confidence limits).

Mean total fuel load for the C/B plots was increased (but not significantly, $p > 0.10$) from

5.74 to 6.84 tons/acre after the initial brush cutting treatment of June 2003. After the first burn in

the C/B plots, mean total fuel loads decreased ($p > 0.10$) from 6.84 to 3.87 tons/acre (Figure 7).

Before the burn of May 2004, mean total fuel loads were significantly different between the C/B

and control plots (3.87 tons/acre vs. 6.83 tons/acre; $p < 0.05$) (Figure 7). After the May 2004

burn, mean total fuel loads were reduced ($p > 0.10$) for the C/B plots. Mean total fuel loads were

significantly reduced ($p < 0.10$) after the May 2004 burn for the control plots. Mean total fuel

loads were not significantly different between the C/B and control plots after the burn (2.41

tons/acre vs. 2.92 tons/acre; $p < 0.05$). Detailed summary statistics can be found in Appendix 4
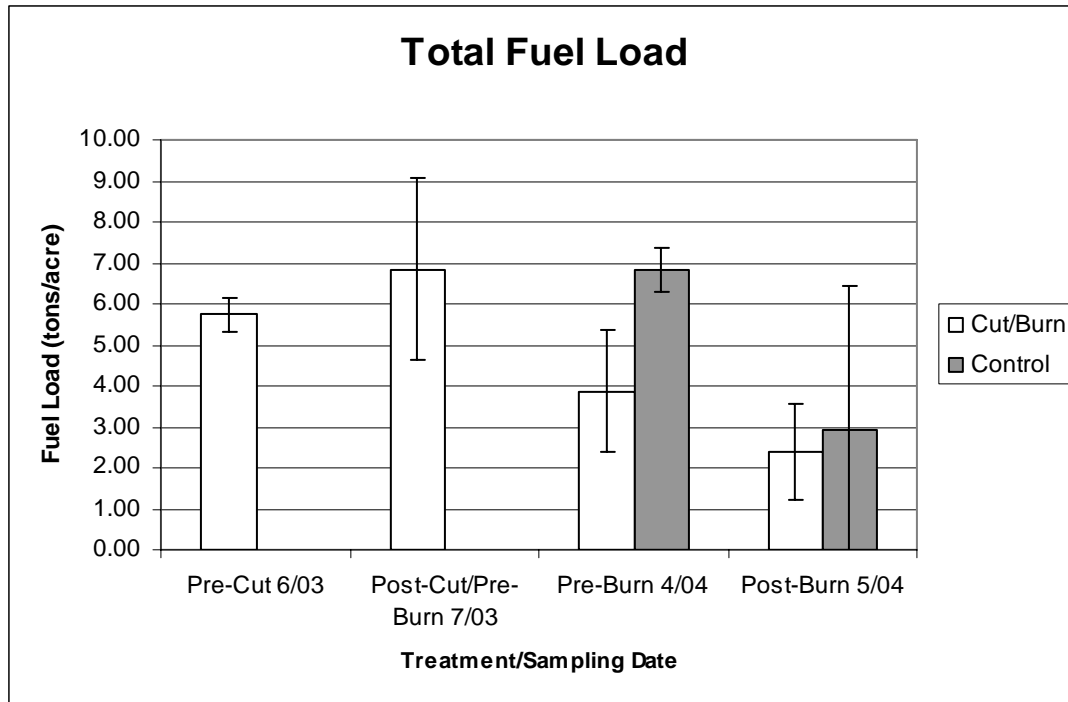
Figure 7. Effects of treatments on total fuel loads estimated by harvest sampling (error bars

indicate 95% confidence limits).

Small sample sizes (n=3) may have contributed to my failure to detect significant changes in

woody 1-hr and 10-hr average fuel loads as a result of the C/B treatment. To better estimate

larger fuel load change over time, each of the three C/B plots were examined individually, by

comparing with-in plot fuel loading before and after treatments with n=9 harvest plots. Non-

woody litter, 1-hr litter, and shrub loads did not change significantly as a result of treatments

(Figures 7-9). To limit variability and decrease confidence intervals, the number of subplots

sampled would have to be increased from nine. Stienz's two-stage sampling algorithm (Steele

and Torrey 1960) was used
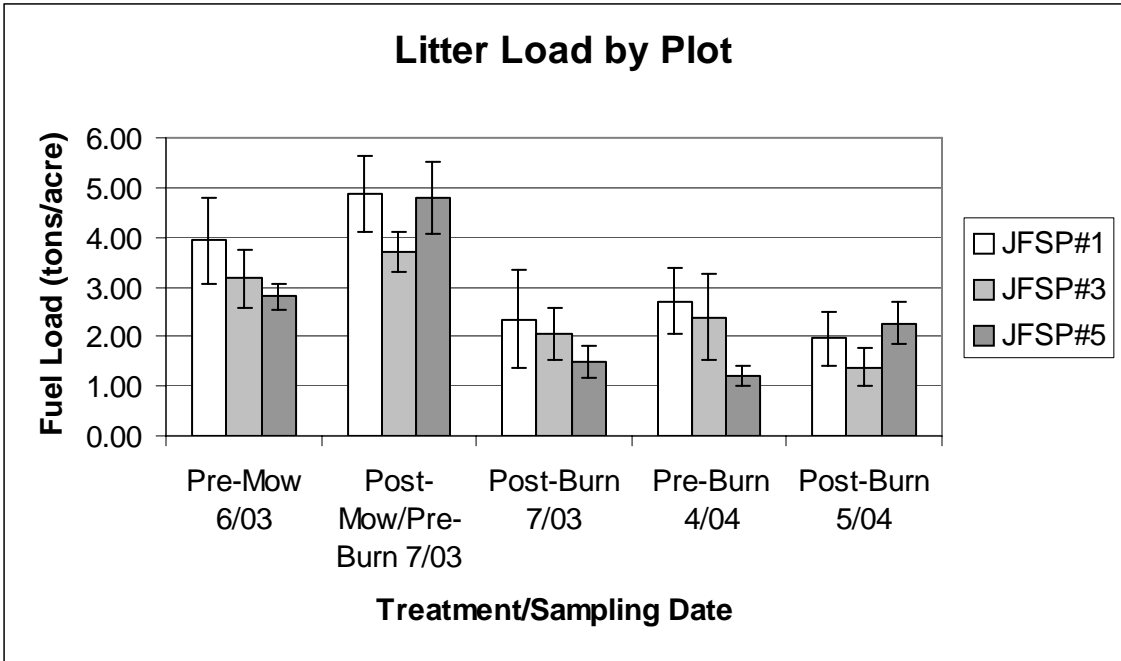
Figure 8. Effects of treatments by plot on litter loads estimated by harvest sampling (error bars indicate 95% confidence limits).
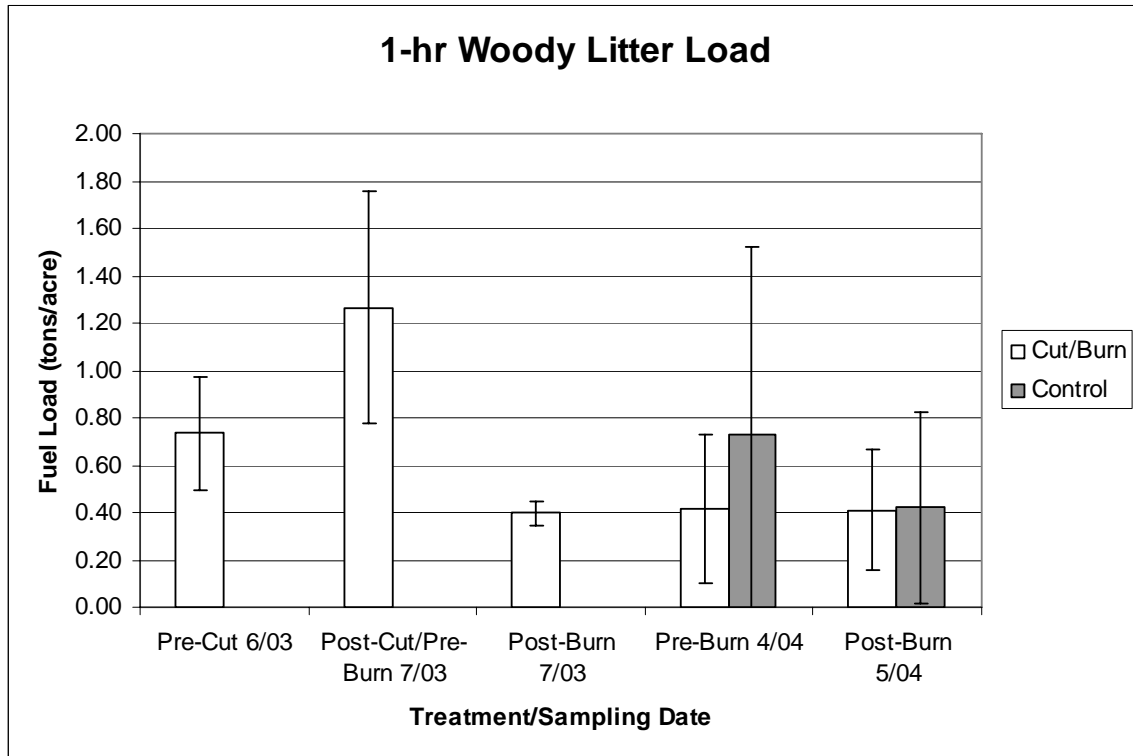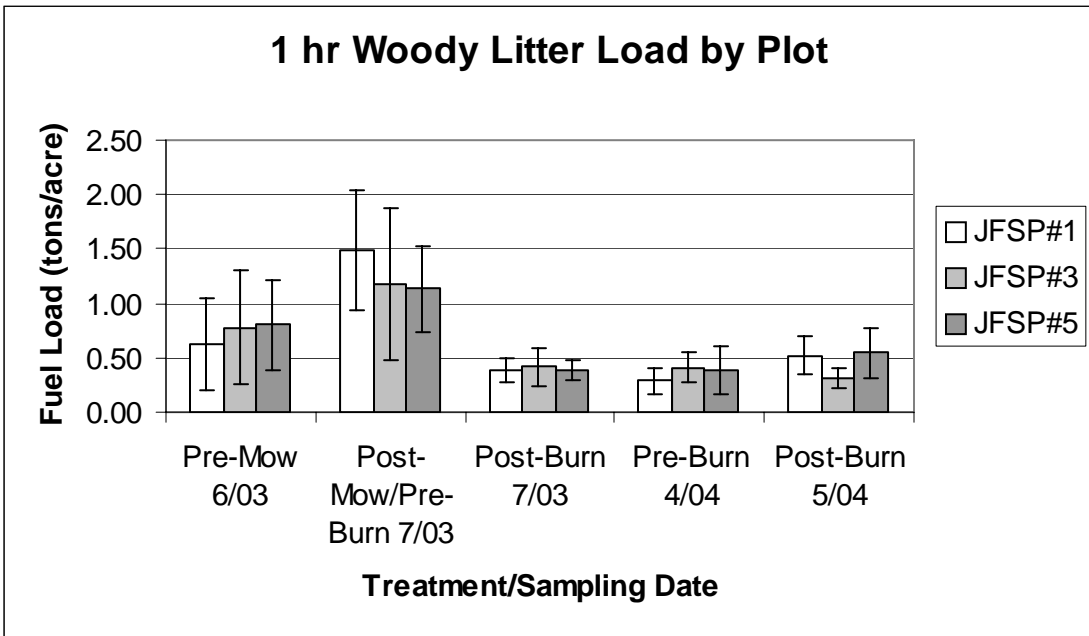

Figure 9. Effects of treatments by plot on 1-hr woody litter loads estimated by harvest sampling (error bars indicate 95% confidence limits).

Shrub Load by Plot

Fuel Load (tons/acre) vs **Treatment/Sampling Date**

Legend: JFSP#1, JFSP#3, JFSP#5

Categories: Pre-Mow 6/03, Post-Mow/Pre-Burn 7/03, Post-Burn 7/03, Pre-Burn 4/04, Post-Burn 5/04
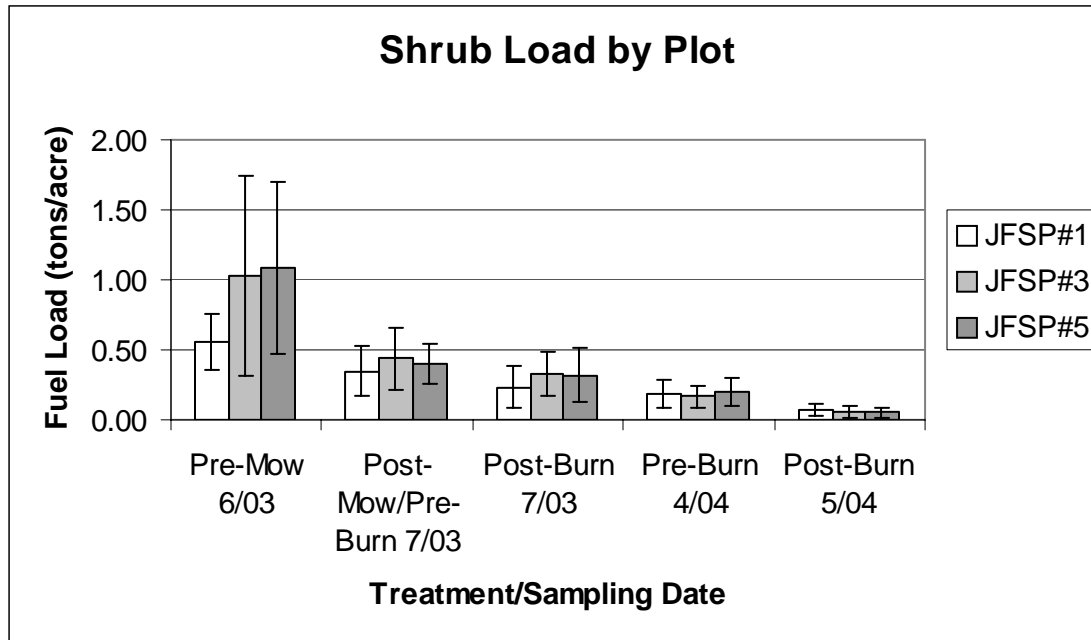
Figure 10. Effects of treatments by plot on 1-hr woody litter loads estimated by harvest sampling (error bars indicate 95% confidence limits).

to estimate the total number of subplots needed to detect significant differences in fuel loads on each plot between the pre-treatment (6/03) and post-burn (7/03). To detect a significant decrease ($p < 0.05$) in 1-hr woody loads, 72 subplots would have to be sampled per 0.5-acre plot before 2003 treatments. Only six subplots would have to be sampled after treatments. To detect a significant decrease ($p < 0.05$) in shrub loads, 21 subplots would have to be sampled per 0.5-acre plot before treatments and 4 subplots after 2003 treatment.

Fuel Depth

Summary statistics for fuel depths and shrub cover are in Table 5. Mean litter depth increased significantly (from 0.46 to 0.61 ft; $p < 0.05$) after the initial brush cutting treatments for the C/B plots (Figure 11). Mean litter depths were reduced by 54% (0.61 ft to 0.28 ft; $p < 0.05$)

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Table 5. Means with 95% confidence intervals for fuel bed parameters.

A. Fuel Load

Plots	Treatment	Total Load (tons/acre)		Litter Load (tons/acre)		1-hr woody (tons/acre)		10-hr (tons/acre)		Shrub Load (tons/acre)	
		mean	95% C.I.	mean	95% C.I.	mean	95% C.I.	mean	95% C.I.	mean	95% C.I.
Mow/Burn	Pre-Cut 6/03	5.74	5.32-6.16	3.30	1.87-4.73	0.73	0.49-0.97	0.68	0.21-1.15	0.96	0.25-1.67
	Post-Cut/Pre-Burn 7/03	6.84	4.62-9.06	4.45	2.82-6.08	1.27	0.78-1.76	0.65	0.2-1.1	0.47	0.31-0.63
	Post-Burn 7/03	2.92	1.43-4.41	1.96	0.87-3.05	0.40	0.35-0.45	0.41	(-)0.05-0.87	0.15	0.09-0.21
	Pre-Burn 4/04	3.87	2.4-5.34	2.46	1.89-3.03	0.41	0.09-0.73	0.37	0.24-0.5	0.19	0.15-0.23
	Post-Burn 5/04	2.41	1.25-3.57	1.52	0.56-2.48	0.41	0.16-0.66	0.42	0.34-0.5	0.06	0.04-0.08
Control	Pre-Burn 4/04	6.83	6.3-7.36	4.71	2.75-6.67	0.73	(-)0.07-1.53	0.42	0.14-0.7	1.03	0.66-1.4
	Post-Burn 5/04	2.92	(-)0.6-6.44	1.36	0.07-2.65	0.42	0.01-0.83	0.68	(-)1.26-2.62	0.33	0.07-0.59

B. Fuel Depth

Plots	Treatment	Litter Depth (ft)		Shrub Depth (ft)		Shrub Percent Cover	
		mean	95% C.I.	mean	95% C.I.	mean	95% C.I.
Mow/Burn	Pre-Cut 6/03	0.46	0.41-0.52	1.29	0.97-1.61	70.67	54-87.35
	Post-Cut/Pre-Burn 7/03	0.61	0.54-0.68	0.42	0.36-0.48	27.41	22.9-31.87
	Pre-Burn 4/04	0.28	0.17-0.39	0.13	0.03-0.10	9.04	(-)0.98-19.06
	Post-Burn 8/04	0.05	0.03-0.07	0.20	0.01-0.39	20.74	9.04-32.4
Control	Aug-03	0.49	0.44-0.54	1.21	1.02-1.4	69.78	66.63-75.93
	Pre-Burn 4/04	0.54	0.44-0.64	0.96	0.5-1.45	56.44	43.9-68.98
	Post-Burn 8/04	0.11	0.10-0.12	0.40	0.37-0.43	39.26	30.97-47.55

after the initial fire in the C/B plots. After initial treatments and before the burn in May 2004, mean litter depths were significantly lower in the C/B plots than in the control plots (0.28 ft vs. 0.54 ft; $p < 0.05$; Figure 11). Mean litter depths were significantly reduced ($p < 0.05$) for both the C/B (by 82%) and control plots (by 80%) after the burn of May 2004. Mean litter depths were significantly different ($p < 0.05$) in the control vs. the C/B plots after the burn of May 2004 (0.05 vs. 0.11; Figure 11).

Figure 11. Effects of treatments on litter depth estimated by point-intercept sampling (error bars indicate 95% confidence limits).

Mean shrub depths were reduced by 67% in the C/B plots (1.29 ft to 0.42 ft; $p < 0.05$) after the initial brush cutting treatment and by 69% after the first burn (from 0.42 ft to 0.13 ft; $p < 0.05$; Figure 12). Before the May 2004 burn, mean shrub depths were significantly less on the C/B than on the control plots (0.13 ft vs. 0.96 ft; $p < 0.05$; Figure 12). Shrub depths on the C/B

plots were half those of the control plots after the May 2004 burn (0.20 vs. 0.40); p<0.10; Figure 12).

Shrub Depth

Figure 12. Effects of treatments on shrub depths estimated by point-intercept sampling (error bars indicate 95% confidence limits).

In the C/B plots, mean fuel bed depths were reduced (but not significantly, $p > 0.10$) after the initial brush cutting treatment (Figure 13). Mean fuel bed depths were significantly reduced by 57% in the C/B plots after the initial burn (0.59 ft to 0.25 ft; $p < 0.05$; Figure 13). Before the May 2004 burn, mean fuel bed depths were significantly different between the C/B and control plots (0.25 ft vs. 0.60 ft; $p < 0.05$; Figure 13). In the control plots, mean fuel bed depth was significantly reduced by 75% after the burn of May 2004 (0.15 vs. 0.60 ft; $p < 0.05$). Mean fuel bed depths were significantly different between the cut/burn and control plots after the burn (0.06 ft vs. 0.15 ft; $p < 0.05$; Figure 13). Cutting and burning increased the packing ratio relative to the controls.
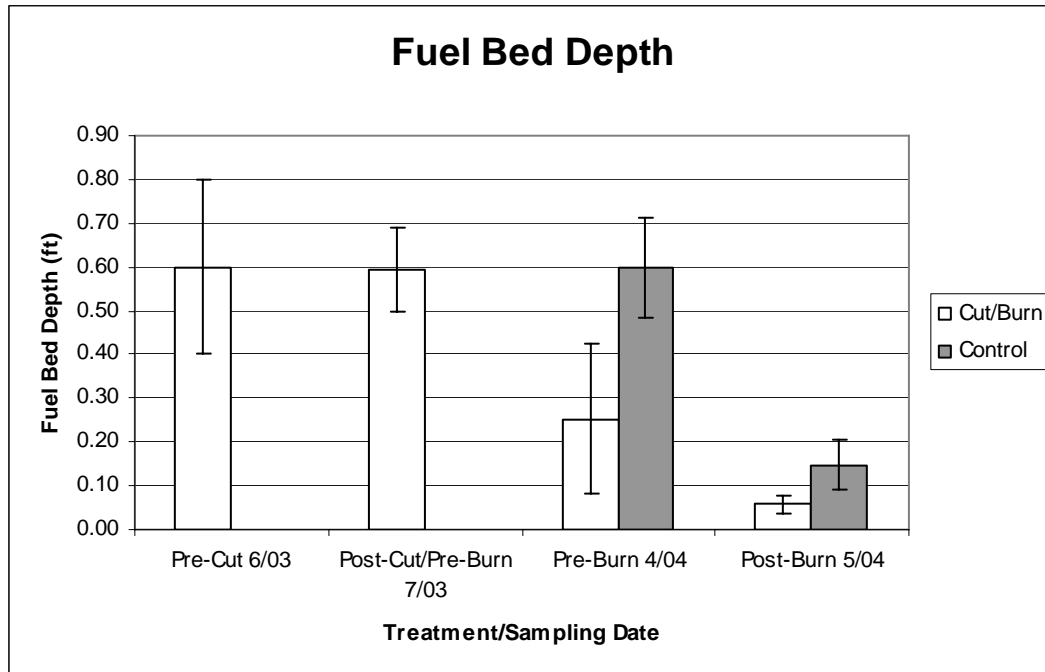
Fuel Bed Depth

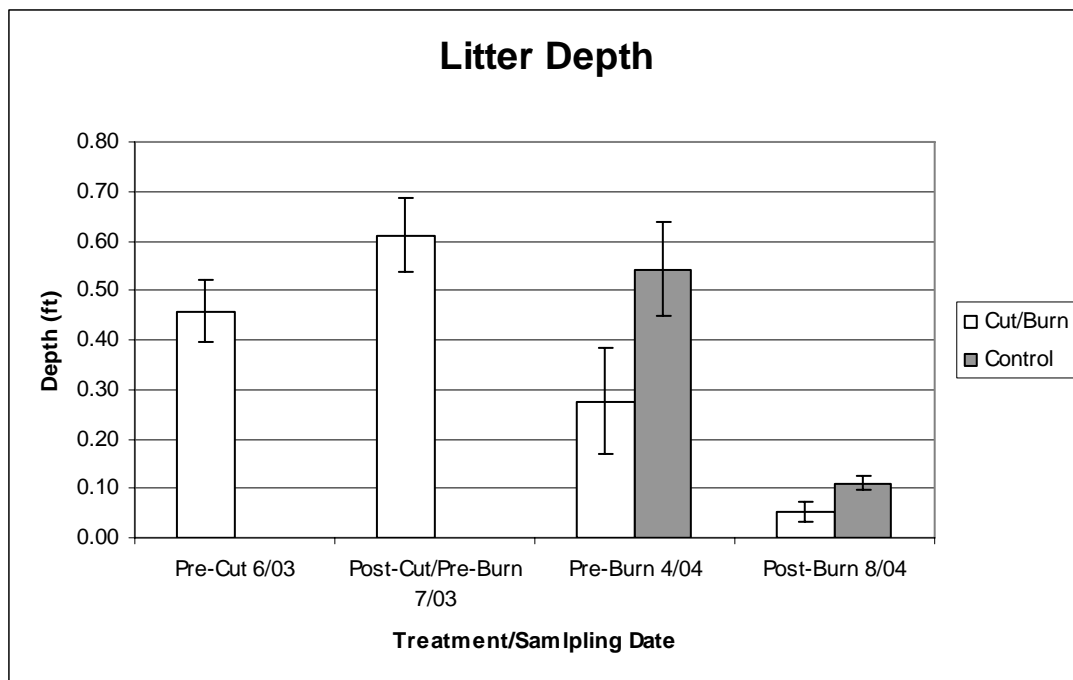Figure 13. Effects of treatments on fuel bed depths estimated by point intercept sampling (error bars indicate 95% confidence limits).

Shrub Cover

Understory woody shrub cover was determined through systematic point-intercept sampling. Mean shrub percent cover after the initial brush cutting treatment in the C/B plots was significantly reduced (from 70.7% to 27.4%; $p < 0.05$; Figure 14). Before the May 2004 burn, mean shrub cover was significantly less on the C/B than on the control plots (9.0% vs. 56.4%; $p < 0.05$; Figure 14). After the May 2004 burn mean shrub cover was significantly reduced (from 56.4% to 39.26 %; $p < 0.05$; Figure 14) on the control plots. Mean shrub cover was also significantly different between the C/B and the control plots after the burn (20.74% vs. 39.3%; $p < 0.10$; Figure 14).
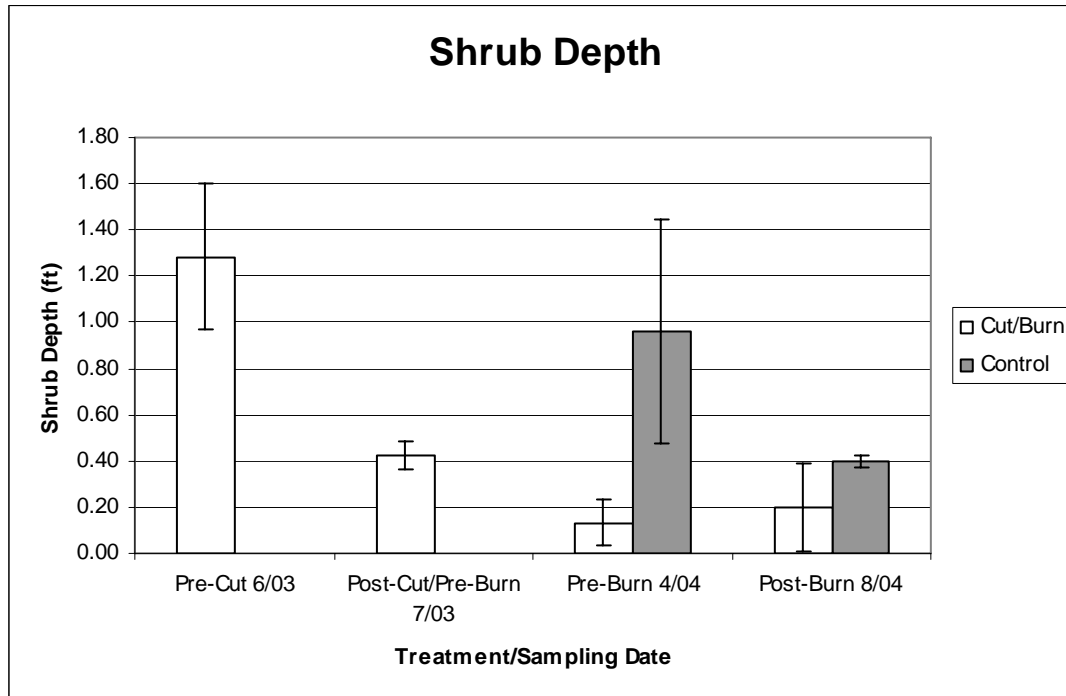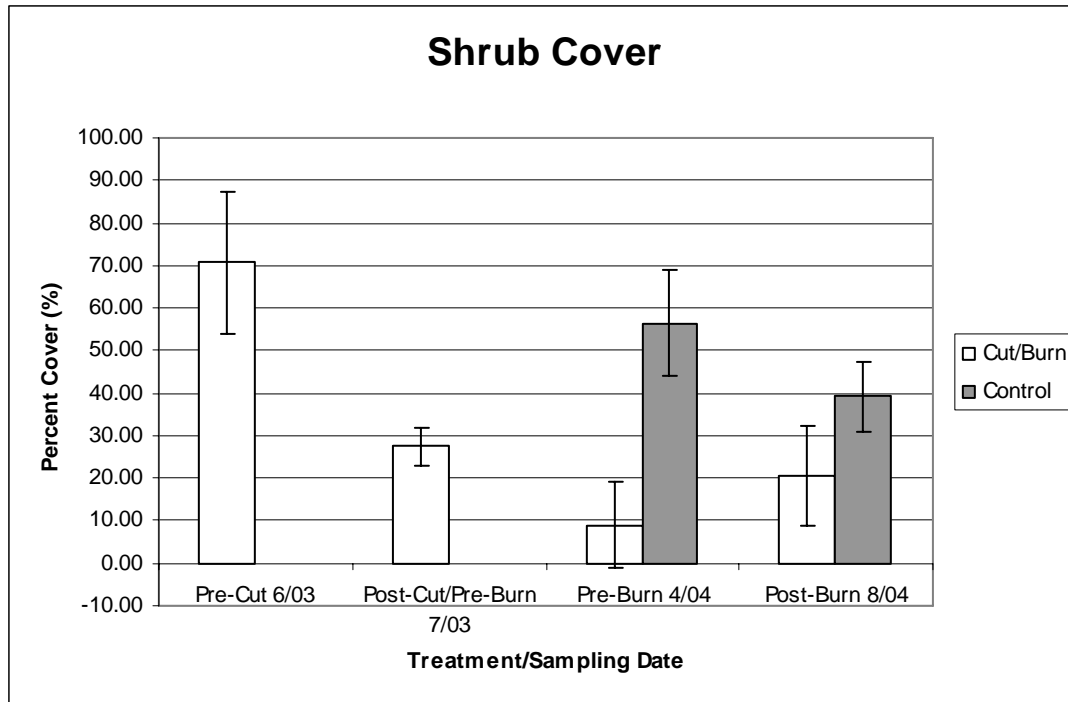
Figure 14: Effects of treatments on shrub cover (%) estimated by point intercept sampling (error bars indicating 95% confidence limits).

Fire Behavior

Observed. The fire behavior for the May 2004 burn was documented with a video camera and rate of spread and flame lengths were estimated using fire behavior poles. The mean observed rate of spread (ROS) for the control plots burned in May 2004 was 6.9 feet/minute. Flame lengths (FL) averaged 3.6 ft. For the C/B plots mean ROS was 4.5 feet/minute with 1.2 feet FL. Fire behavior was significantly reduced ($p < 0.10$) in the C/B plots relative to the untreated plots (Appendix 4). Winds averaged 1.2-2.7 mph for the burns conducted on the six plots. Detailed fire behavior observations for each plot can be found in Appendix 5.

Predicted. Using the fuel bed characteristics sampled before the burns in May 2004 (see Appendix 6), eight custom fuel models were built with BehavePlus3. The fire behavior outputs (rate of spread and flame lengths) based upon eight custom fuel models (six for individual plots plus one each for the average of the treatment and the control) are in Table 6.

Table 6. Observed and predicted fire behavior for the burn of May 2004.

	Rate of Spread (ft/min)		Flame Length (ft)	
	observed	predicted	observed	predicted
JFSP 1 M/B	5.1	1.1	1.35	0.9
JFSP 3 M/B	4.5	1.5	0.85	1
JFSP 5 M/B	4	2.2	1.5	1.4
JFSP M/B Avg	4.5	1.4	1.2	1.2
JFSP 2 C	4.2	4	3	3.1
JFSP 4 C	3.4	4.2	3.4	3.3
JFSP 6 C	13.2	11.8	4.5	5.3
JFSP C Avg	7	5.6	3.6	3.6

In January 2005 the U.S. Forest Service released 27 new fuel models to supplement the

13 standard fuel models which have been available for more than 20 years (Andrews et al. 2005).

I tested all of these fuel models using BehavePlus3.0 to determine if fire behavior could be

accurately predicted for untreated pine-oak fuels. None of the available fuel models yielded ROS

or FL that were as close to the observed values as my custom fuel model (CFM; Table 7).

Table 7. A comparison of observed pine-oak forest fire behavior with standard fuel models.

Fire Behavior	Observed	SFM 4	SFM 7	FM 10	sh4	tu5	t19	CFM
Flame Length (ft)	3.6	12.2	3.6	3.3	1.6	4.8	2.5	3.6
Rate of Spread (ft/min)	7	13.2	11.3	3.8	4.2	4.2	2.8	5.6

SFM 4: Chaparral   Source: BehavePlus3
SFM 7: Southern Rough
SFM 10: Timber with litter and understory
sh4: low load, humid climate, timber-shrub (experimental)
tu5: very high load, dry climate-shrub (experimental)
t19: very high load broadleaf litter (experimental)
CFM: Custom Fuel Model (untreated)

A correlation coefficient was calculated to determine the relationship between observed

and predicted fire behavior values. For rate of spread, an r of 0.90 indicates a strong relationship

between the observed and predicted values. The custom fuel models slightly under predict rate of

spread in this fuel type (see appendix 7). For flame length an r of 0.98 indicates a very strong relationship between the observed and predicted values (Figure 15). The custom fuel models again slightly under predict flame lengths.
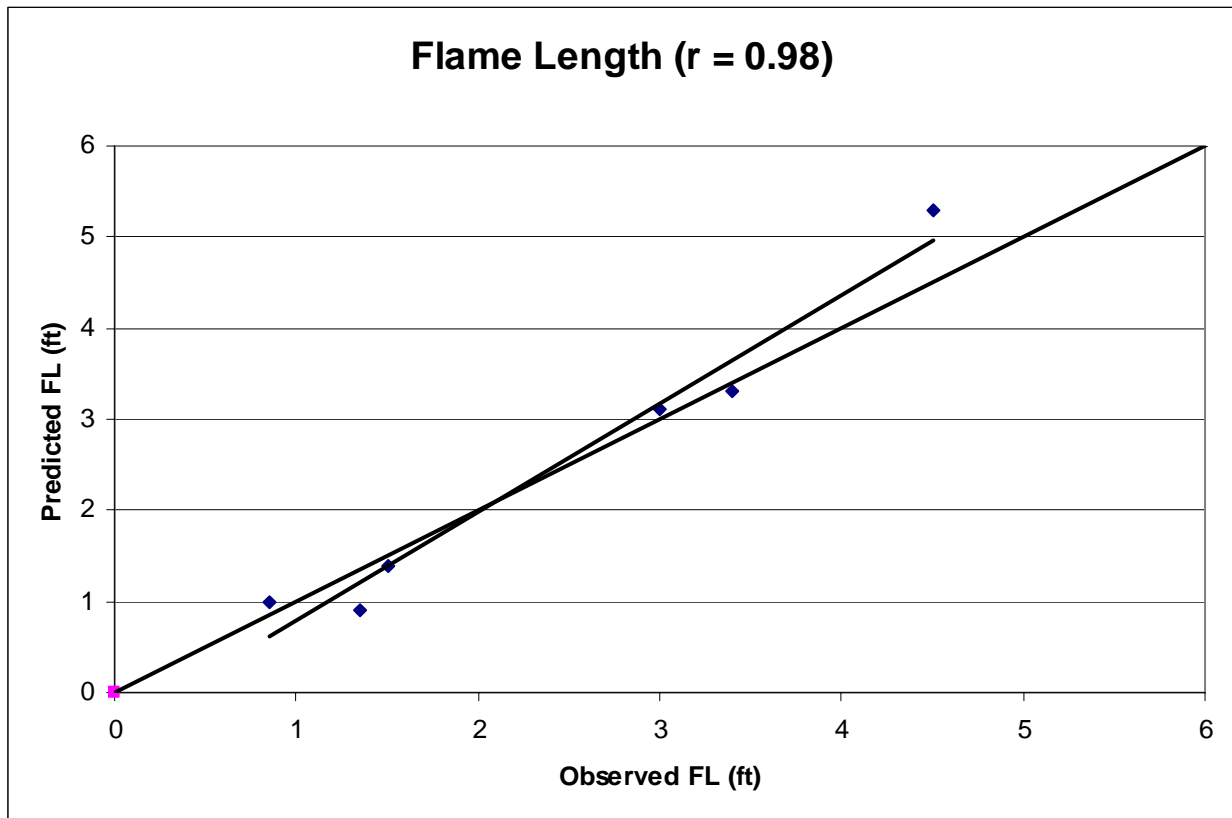
Figure 15. Correlation coefficient for flame length with the unity line showing perfect correlation.

Discussion

The C/B treatment significantly reduced rates of spread and flame lengths relative to control conditions. Cutting shrub understory vegetation followed by prescribed burning significantly reduces future potential surface fire behavior by manipulating fuel bed characteristics. Therefore, the null hypothesis that there is no difference in fire behavior between the treated and untreated plots, was rejected.

Fuel bed characteristics control fire behavior when topography and weather conditions are held constant in all of the JFSP plots. Significant differences in fine fuel loads and depths and shrub loads and depths were quantified; Therefore, the null hypothesis that there is no difference in fuel bed characteristics between treated and untreated plots was rejected.

Fire intensity in pine-oak forests is strongly influenced by abundant non-woody 1-hr litter and live shrub fuels. Litter dries rapidly and ignites readily with a moisture of extinction of approximately 25%. Burning litter preheats shrubs, and fires transition readily from burning in litter to crowing in well-aerated shrub canopies. This results in increased rates of spread and flame lengths compared to fires burning in litter alone. Cutting increases packing ratios beyond the optimum and fire behavior is reduced.

Brush cutting converts shrubs to downed woody fuels which, when cut during the summer, dry sufficiently to allow them to burn within a few weeks. Brush cutting in the summer takes advantage of higher air temperatures and drier forest floors that are conducive to rapid drying. Prescribed fires then consume the litter and woody 1-hr fuels generated by cutting. Following initial cutting and burning in August 2003, shrub cover was 84% less on treated compared to control plots. In August 2004 shrub cover was 47% less on the treated compared to control plots, indicating that understory shrubs in the C/B plots are growing back. Two treatments in a single growing season may have reduced root reserves in shrubs and affected

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their future sprouting potential (Droege and Patterson 1995). Understory fuels cut and burned in the same growing season may reduce shrub cover for several growing seasons following the treatments. Reduced shrub cover results in lower surface fire intensities.

Variability in the data set limited my ability to interpret some of the results. Small sample sizes resulted in high standard errors. Sampling 20-25 subplots instead of 9 would adequately explain variability in leaf litter and standing shrubs, but might be prohibitively time consuming.

The ultimate goal of fuel sampling is to characterize potential fire behavior. Fire is not a static force. As a fire moves through a fuel bed, it encounters different fuel moistures and fuel temperatures based upon the amount of direct sunlight or shading the fuels receive. This causes the fire to gain or loose intensity, which is expressed in varying flame lengths and rates of spread.

Fire behavior is especially sensitive to variations in fuel bed depth (Del'Orfano (1996), but characterizing fuel bed depths is time consuming in pine-oak forests. Sampling 225 points requires approximately 2.5 hours for a 0.5-acre plot. Point-intercept (PI) sampling does effectively generate a large data, however. Large datasets reduce the variability in fuel depth data. Brown's planar intercept method characterized fuel bed depths more quickly than PI sampling but generated only 20 measurements per plot. Fuel depths generated from Brown's DWF lines and point intercept sampling were not significantly different (Appendix 8). Using Stienz's two-stage sampling algorithm, it was determined that 25 measurements per plot would have to be sampled with Brown's DWF lines to detect a significant difference in fuel depths between treatments. To more effectively sample fuel depths, DWF lines could be sampled at five-foot rather than 8.5-foot increments along the 25-ft planar-intercept lines. This would take approximately 1.25 hours per 0.5-acre plot to generate data that would likely have sufficiently low variability to allow statistically meaningful comparisons.

Harvest sampling more effectively characterizes one-hour fuels than DWF lines, whereas DWF lines more effectively characterize the larger 10- and 100-hr woody fuels. DWF lines do not sample fine fuels, however, which I have shown to be extremely important to pine-oak forest fuel models. A combination of modified DWF lines for sampling fuel depth and the load of larger fuel particles and harvest sampling of litter and 1-hr woody fuels would be most effective. The modified DWF lines also effectively characterize litter, slash and shrub depths.

Management Implications and Future Research

Correlation coefficients show strong relationships between observed and predicted flame lengths. None of the 27 standard or experimental fuel models predicts flame lengths with similar accuracy. My results show that the effort to generate fuel data that will allow development of custom fuel models is worthwhile.

Management that combines cutting and prescribed burning treatments re-distributes decreased fuel loads and increases packing ratios to effectively minimize fire behavior in the season following treatments. The rate of recovery of litter loads and fuel bed depths should be the focus of future research.

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Appendix

Appendix 1: Standard fuel models

Fuel model			loading									fuelbed	extinction	Heat
number	DESCRIPTION	units	1	10	100	live	optional1	SAV1	SAVlive	SAVopt1	depth	moisture	content
	0	1	3	4	5	6	7	10	11	12	14	15	16
1	1 Short grass (1 ft.)	English	0.7	0.0	0.0	0.0	0.0	3500	500	0	1.0	0.12	8000
2	2 Timber (grass and understory)	English	2.0	1.0	0.5	0.5	0.0	3000	1500	0	1.0	0.15	8000
3	3 Tall grass (2.5 ft.)	English	3.0	0.0	0.0	0.0	0.0	1500	500	0	2.5	0.25	8000
4	4 Chaparral	English	5.0	4.0	2.0	5.0	0.0	2000	1500	0	6.0	0.20	8000
5	5 Brush	English	1.0	0.5	0.0	2.0	0.0	2000	1500	0	2.0	0.20	8000
6	6 Dormant brush, hardwood slash	English	1.5	2.5	2.0	0.0	0.0	1750	500	0	2.5	0.25	8000
7	7 Southern rough	English	1.1	1.9	1.5	0.4	0.0	1750	1550	0	2.5	0.40	8000
8	8 Closed timber litter	English	1.5	1.0	2.5	0.0	0.0	2000	500	0	0.2	0.30	8000
9	9 Hardwood (long-needle pine) litter	English	2.9	0.4	0.2	0.0	0.0	2500	500	0	0.2	0.25	8000
10	10 Timber (litter and understory)	English	3.0	2.0	5.0	2.0	0.0	2000	1500	0	1.0	0.25	8000
11	11 Light slash	English	1.5	4.5	5.5	0.0	0.0	1500	500	0	1.0	0.15	8000
12	12 Medium slash	English	4.0	14.0	16.5	0.0	0.0	1500	500	0	2.3	0.20	8000
13	13 Heavy slash	English	7.0	23.0	28.1	0.0	0.0	1500	500	0	3.0	0.25	8000
15	15 DBR High Pocosin	English	4.2	2.5	0.0	5.0	3.0	2000	1500	1500	6.7	0.30	9000
16	16 DBR Low Pocosin	English	6.1	2.0	0.0	4.8	2.6	2000	1500	1500	3.1	0.30	9000
17	17 Manzanita	English	3.0	4.5	1.1	1.5	5.0	350	1500	250	3.0	0.15	9211
18	18 Chamise 1	English	2.0	3.0	1.0	0.5	2.0	640	2200	640	3.0	0.13	10000
19	19 Ceanothus	English	2.3	4.8	1.8	3.0	2.8	500	1500	500	6.0	0.15	8000
20	20 Chamise 2	English	1.3	1.0	1.0	2.0	2.0	640	2200	640	4.0	0.20	8000
21	21 Sagebrush/buckwheat	English	5.5	0.8	0.1	0.8	2.5	640	1500	640	3.0	0.25	9200

Appendix 2: Fuel and fire behavior sampling methods

Point Intercept Sampling: For plots 1-6, two 50-meter tapes were strung from west to east along the north and south sides of each plot, with (0,0) starting point being established on the southwest side. A 50-meter tape was strung from the south baseline tape to the north baseline tape every three meters for a total of 15 transects taken for each plot. The southwest corner of each plot was used as a starting point. A 20 decimeter long sampling rod that was marked in increments of ten decimeters was inserted into the leaf litter every three meters along the north/south transect lines. At each of 256 sample points, the highest of the tops of leaf litter and all live and dead vegetation in contact with the sampling rod were tallied to the nearest centimeter and recorded as height above the ground. Any dead vegetation in contact with the sampling rod was recorded as such. Leaf litter that was encountered hung in woody vegetation was counted as the leaf litter maximum height.

Fuel Load: Each 0.5-acre plot was divided into nine 17 x 17 meter square quadrats using a 50-meter tape, flagging, and pacing. Quadrats on the north and east sides of the plots were 16 x 16 and 16 x 17 meter, respectively. Within each quadrat a 40 x 40-cm subplot randomly established the sample area for fuel load by fuel class. Within each subplot all vegetation rooted inside a pre-measured frame was cut at soil level using clippers. All overhanging vegetation was excluded. For each subplot all down wood, dead standing wood, leaf litter, live standing vegetation, grass, and wintergreen were collected and placed by fuel class into individually marked paper bags marked as follows: JFSP; plot number (1-6), treatment code (Burn-B, Mow with Brushcutters and Burn-C/B), subplot number (1-9), and date. Pine cones and acorns were placed inside the down wood bag.

Brown's Planar Intercept for Inventory of Downed Woody Fuels (Brown's Lines)

For all six 0.5-acre plots, starting at the southwest corner, five flags were placed at grid locations 12.5, 12.5; 12.5, 37.5; 25, 25; 37.5, 12.5; and 37.5, 37.5. At each flag, the second hand of a watch was used to select a random compass azimuth. Along this azimuth, a 25-ft line was fixed to the ground using rebar on both ends of a tape. Along each transect line, every piece of downed woody fuel that was intersecting the tape was counted using a meter stick and placed into size classes: 1 hr, 10 hr, 100 hr, 1000 hr. Fuel particles were tallied as being above or within the litter. For each size class, the proportional representation of species (pitch pine, oak, huckleberry/blueberry) was estimated. All pine cones that were intersected by the transect line were counted and recorded. At the intervals 5'-6', 10'-11', and 15'-16 feet along the transect line, fuel depth (cm) was measured by using a meter stick to measure the height of the tallest down woody fuel particle from the litter layer. At 7', 14', and 21 feet, duff depth was measured for the top of the duff to the top of the mineral soil.

Fire Behavior and Pre-Burn Sampling

Prescribed burns on the six, 0.5-acre plots were conducted on May 11-12, 2004. Before all prescribed burns, live fuel moistures were measured on the day of the burn. Three, 0.5-gallon plastic bags were labeled with:

(JFSP, Plot #, Date, and Species)

for GAYBAC (huckleberry), GAUPRO (wintergreen), and VAC (early lowbush plus late lowbush blueberry). Three bags for each of the species were filled with leaves only (no stems). For each burned plot, three ½ gallon bags were also filled with litter prior to the burn. Samples were weighed in their sealed bags first and air dried over night and weighed in bag the next morning. The samples were then emptied into a small paper bag and the plastic bag they were

kept in was weighed. Samples in the paper bag were placed in a drying oven at @70°C for at least two days. Bags and contents were weighed again to calculate the moisture content (percentage oven dry weight). At the site of the burn a protometer was used to measure the moisture content of down woody fuel of by size classes. Twenty to thirty measurements were made in representative locations of each plot.

After a burn was initiated on a plot, the wind speed was recorded every minute with a *Kestrel 3000*-wind meter. Fire weather observations (relative humidity, temperature, wind speed and direction) were taken hourly during both days of prescribed burning. To estimate rates of spread, flame lengths, and flame depth, a set of fire behavior poles were used. Fire behavior poles are five-foot long metal rods that at one-foot intervals have eight-inch rods perpendicular to the main rod. Fire behavior poles were set up at different intervals, different times, and fuel types. Different ignition patterns were used in order to document the behavior of strip head, head, backing, and flanking fires. Fire type, flame length (total length of flames with angle correction), flame depth (total length of advancing flame front), rate of spread (feet per minute), and any general comments about predominant fuels in area (oak litter, pine needles, etc.) were recorded. A *Sony* digital camcorder (*G 426*) was used to record each burn. In addition to one-minute wind observations, average and maximum wind speed were recorded for the entire burn.

Appendix 3: Summary statistics for fuel load

		Plot 1	Plot 3	Plot 5	Avg M/B	stdev M/B	SEM M/B	SE/mean	95% CI M/l	90% CI M/l	Plot 2	Plot 4	Plot 6	Avg C
FUEL LOAD (TONS/ACRE)	Pre-Cut 6/03	5.84	5.54	5.83	5.74	0.17	0.10	0.02	0.42	0.29				
	Post-Cut 7/03	7.59	5.85	7.08	6.84	0.89	0.52	0.08	2.22	1.51				
	Post-Cut/Burn 7/03	3.43	3.08	2.25	2.92	0.60	0.35	0.12	1.49	1.01				
	Pre-Burn 4/04	4.52	3.73	3.36	3.87	0.59	0.34	0.09	1.47	1.00	6.94	6.96	6.58	6.83
	Post-Burn 5/04	2.94	2.22	2.06	2.41	0.47	0.27	0.11	1.16	0.79	1.89	4.54	2.34	2.92
Leaf Litter (tons/acre)	Pre-Cut 6/03	3.94	3.16	2.81	3.30	0.58	0.33	0.10	1.43	0.97				
	Post-Cut 7/03	4.87	3.69	4.78	4.45	0.66	0.38	0.09	1.63	1.11				
	Post-Cut/Burn 7/03	2.35	2.05	1.49	1.96	0.44	0.25	0.13	1.09	0.74				
	Pre-Burn 4/04	2.72	2.39	2.27	2.46	0.23	0.13	0.05	0.57	0.39	5.44	4.81	3.87	4.71
	Post-Burn 5/04	1.96	1.38	1.22	1.52	0.39	0.22	0.15	0.96	0.65	1.11	1.95	1.00	1.36
1 HR (tons/acre)	Pre-Cut 6/03	0.62	0.78	0.80	0.73	0.10	0.06	0.08	0.24	0.16				
	Post-Cut 7/03	1.49	1.17	1.13	1.27	0.20	0.11	0.09	0.49	0.33				
	Post-Cut/Burn 7/03	0.38	0.42	0.39	0.40	0.02	0.01	0.03	0.05	0.03				
	Pre-Burn 4/04	0.29	0.41	0.54	0.41	0.13	0.07	0.18	0.32	0.21	0.38	0.80	1.01	0.73
	Post-Burn 5/04	0.52	0.32	0.39	0.41	0.10	0.06	0.14	0.25	0.17	0.24	0.56	0.46	0.42
10 HR (tons/acre)	Pre-Cut 6/03	0.65	0.50	0.88	0.68	0.19	0.11	0.16	0.47	0.32				
	Post-Cut 7/03	0.83	0.47	0.67	0.65	0.18	0.10	0.16	0.45	0.31				
	Post-Cut/Burn 7/03	0.58	0.45	0.21	0.41	0.18	0.11	0.26	0.46	0.31				
	Pre-Burn 4/04	0.33	0.43	0.35	0.37	0.05	0.03	0.08	0.13	0.09	0.30	0.46	0.51	0.42
	Post-Burn 5/04	0.39	0.45	0.41	0.42	0.03	0.02	0.05	0.08	0.06	0.23	1.58	0.24	0.68
100 HR (tons/acre)	Pre-Cut 6/03	0.00	0.00	0.19	0.06	0.11	0.06	1.00	0.28	0.19				
	Post-Cut 7/03	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00				
	Post-Cut/Burn 7/03	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00				
	Pre-Burn 4/04	0.00	0.33	0.00	0.11	0.19	0.11	1.00	0.47	0.32	0.00	0.06	0.37	0.14
	Post-Burn 5/04	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.20	0.19	0.13
Shrub Load (live and dead) (tons/acre)	Pre-Cut 6/03	0.63	1.10	1.15	0.96	0.29	0.16	0.17	0.71	0.48				
	Post-Cut 7/03	0.40	0.52	0.50	0.47	0.07	0.04	0.08	0.16	0.11				
	Post-Cut/Burn 7/03	0.12	0.17	0.16	0.15	0.03	0.01	0.10	0.06	0.04				
	Pre-Burn 4/04	0.19	0.18	0.21	0.19	0.02	0.01	0.05	0.04	0.03	1.10	0.86	1.13	1.03
	Post-Burn 5/04	0.07	0.06	0.05	0.06	0.01	0.01	0.09	0.02	0.02	0.31	0.24	0.45	0.33

Appendix 4: Summary statistics for fuel depth and fire behavior for burn of May 2004.

		Plot 1	Plot 3	Plot 5	Avg M/B	stdev M/B	SEM M/B	SE/mean	95% CI M/I	90% CI M/I	Plot 2	Plot 4	Plot 6	Avg C	stdev C
Litter COMB (ft)	Pre-Cut 6/03	0.43	0.46	0.49	0.46	0.03	0.01	0.03	0.06	0.04					
	Post-Cut 7/03	0.63	0.63	0.58	0.61	0.03	0.02	0.03	0.07	0.05					
	Aug-03										0.48	0.47	0.51	0.49	0.02
	Pre-Burn 4/04	0.23	0.29	0.31	0.28	0.04	0.02	0.09	0.11	0.07	0.50	0.58	0.55	0.54	0.04
	Post-Burn 5/04	0.06	0.04	0.06	0.05	0.01	0.00	0.08	0.02	0.01	0.11	0.10	0.11	0.11	0.01
Shrub Height (ft)	Pre-Cut 6/03	1.16	1.41	1.29	1.29	0.13	0.07	0.06	0.32	0.21					
	Post-Cut 7/03	0.41	0.45	0.41	0.42	0.03	0.01	0.04	0.06	0.04					
	Aug-03										1.15	1.18	1.29	1.21	0.07
	Pre-Burn 4/04	0.09	0.14	0.17	0.13	0.04	0.02	0.17	0.10	0.07	0.83	0.86	1.18	0.96	0.20
	Post-Burn 5/04	0.14	0.29	0.18	0.20	0.08	0.04	0.22	0.19	0.13	0.41	0.39	0.39	0.40	0.01
% Cover	Pre-Cut 6/03	63.56	76.89	71.56	70.67	6.71	3.87	0.05	16.67	11.31					
	Post-Cut 7/03	25.33	28.44	28.44	27.41	1.80	1.04	0.04	4.46	3.03					
	Aug-03										72.00	70.22	67.11	69.78	2.47
	Pre-Burn 4/04	5.33	8.44	13.33	9.04	4.03	2.33	0.26	10.02	6.80	54.22	52.89	62.22	56.44	5.05
	Post-Burn 5/04	16.44	25.78	20.00	20.74	4.71	2.72	0.13	11.70	7.94	43.11	37.33	37.33	39.26	3.34
student's t, df=2	95%	0.90													
	4.303	2.92													

		Plot 1	Plot 3	Plot 5	Avg M/B	stdev M/B	SEM M/B	SE/mean	95% CI M/I	90% CI M/I	Plot 2	Plot 4	Plot 6	Avg C	stdev C
FUEL BED DEPTH (FT)	Pre-Cut 6/03	0.51	0.65	0.65	0.60	0.08	0.05	0.08	0.20	0.13					
	Post-Cut 7/03	0.62	0.61	0.55	0.59	0.04	0.02	0.04	0.10	0.07					
	Pre-Burn 4/04	0.17	0.28	0.30	0.25	0.07	0.04	0.16	0.17	0.12	0.55	0.61	0.64	0.60	0.05
	Post-Burn 5/04	0.06	0.05	0.06	0.06	0.01	0.01	0.09	0.02	0.02	0.16	0.12	0.16	0.15	0.02
FUEL LOAD (TONS/ACRE)	Pre-Cut 6/03	5.84	5.54	5.83	5.74	0.17	0.10	0.02	0.42	0.29					
	Post-Cut 7/03	7.59	5.85	7.08	6.84	0.89	0.52	0.08	2.22	1.51					
	Pre-Burn 4/04	4.52	3.73	3.36	3.87	0.59	0.34	0.09	1.47	1.00	6.94	6.96	6.58	6.83	0.21
	Post-Burn 5/04	2.94	2.22	2.06	2.41	0.47	0.27	0.11	1.16	0.79	1.89	4.54	2.34	2.92	1.42

Observed Fire Behavior		Plot 1	Plot 3	Plot 5	Avg M/B	stdev M/B	SEM M/B	SE/mean	95% CI M/I	90% CI M/I	Plot 2	Plot 4	Plot 6	Avg C	stdev C
	ROS	5.10	4.50	4.00	4.53	0.55	0.32	0.07	1.37	0.93	4.20	3.40	13.20	6.93	5.44
	FL	1.35	0.85	1.50	1.23	0.34	0.20	0.16	0.85	0.57	3.00	3.40	4.50	3.63	0.78

Appendix 5: Raw and mean fire behavior observations for burn of May 2004

| Pine-Oak Forest (Control)			
JFSP Plot #	**2**	**4**	**6**
rate of spread (ft/min)	4.2	3.4	13.2
flame length (ft)	3	3.4	4.5
Wind (mph)	1.65	1.6	1.9
Time of Fire	13:30	17:00	16:10
Rank	**1**	**3**	**2**
Pine-Oak Forest (Brushcut/Burn/Burn)			
JFSP Plot #	**1**	**3**	**5**
rate of spread (ft/min)	5.1	4.5	4
flame length (ft)	1.35	0.85	1.5
Wind (mph)	1.5	2.2	1.5
Time of Fire	14:25	15:05	17:00
Rank	**2**	**3**	**1**

Average by Treatment

CACO	Average ROS (ft/min)	Average FL (ft)	Average Wind (mph)
Pine-Oak Woodlands (control)	7	3.6	1.7
Pine-Oak Woodlands (brushcutt/burn/burn)	4.5	1.2	1.7

Appendix 6: BehavePlus custom fuel model inputs for burn of May 2004

CACO Treatments	JFSP1-M/B	JFSP3-M/B	JFSP5-M/B	M/B avg	JFSP2-C	JFSP4-C	JFSP6-C	C avg
NEXUS Fuel Model #	22	23	24	28	25	26	27	29
optional (leaves)	6.92	6.28	9.48	7.56	9.65	8.44	9.48	9.19
1-hr	13.70	13.70	13.70	13.70	9.17	14.03	18.56	13.92
10-hr	17.70	17.70	17.70	17.70	21.9	15.4	13.50	16.93
100-hr	34.0	34.0	34.0	34.00	38.6	16.75	29.4	28.25
live (leaves)	0	0	0	0	0	0	0	0
optional1 (1-hr)	**0**	**0**	**0**	0	76.1	71.3	74.0	73.8
optional2 (10-hr)	71	71	71	71	71	71	71	71
Plot #	1	3	5	3	2	4	6	4
slope	0	0	0	0	0	0	0	0
open windspeed	1.5	2.2	1.5	1.7	1.65	1.60	1.90	1.72
wind direction (from uphill)	0	0	0	0	0	0	0	0
wind reduction factor	1	1	1	1	1	1	1	1
Litter-dead optional1(leaves) load	2.72	2.39	2.27	2.46	5.44	4.81	3.87	4.71
Litter-dead optional1(leaves) SAV	2250	2250	2250	2250	2250	2250	2250	2250
Litter-dead 1 hr load	0.29	0.41	0.54	0.41	0.38	0.80	1.01	0.73
Litter-dead 1 hr SAV	1500	1500	1500	1500	1500	1500	1500	1500
Litter-dead 10 hr load	0.33	0.43	0.35	0.37	0.30	0.46	0.51	0.42
Litter-dead 10 hr SAV	109	109	109	109	109	109	109	109
Litter-dead 100 hr load	0.00	0.33	0.00	0.11	0.00	0.06	0.37	0.14
Litter-dead 100 hr SAV	30	30	30	30	30	30	30	30
Slash dead optional1(not used) load	na	na	na	na	na	na	na	na
Slash dead optional1(not used)SAV	na	na	na	na	na	na	na	na
Slash dead 1 hr load	0.14	0.15	0.12	0.14	0.20	0.32	0.17	0.23
Slash dead 1 hr SAV	1500	1500	1500	1500	1500	1500	1500	1500
Slash dead 10 hr load	0.43	0.27	0.46	0.39	1.17	0.69	0.82	0.89
Slash dead 10 hr SAV	109	109	109	109	109	109	109	109
Slash dead 100 hr load	0.21	1.04	0.63	0.62	0.63	0.63	0.21	0.49
Slash dead 100 hr SAV	30	30	30	30	30	30	30	30
Litter-COMB-dead optional 1 (leaves) load	2.72	2.39	2.27	2.46	5.44	4.81	3.87	4.71
Litter-COMB-dead optional 1 (leaves) SAV	2250	2250	2250	2250	2250	2250	2250	2250
Litter-COMB-dead 1 hr load	0.43	0.56	0.66	0.55	0.58	1.12	1.18	0.96
Litter-COMB-dead 1 hr SAV	1500	1500	1500	1500	1500	1500	1500	1500
Litter-COMB-dead 10 hr load	0.76	0.70	0.81	0.76	1.47	1.15	1.33	1.32
Litter-COMB-dead 10 hr SAV	109	109	109	109	109	109	109	109
Litter-COMB-dead 100 hr load	0.21	1.37	0.63	0.73	0.63	0.69	0.58	0.63
Litter-COMB-dead 100 hr SAV	30	30	30	30	30	30	30	30
Shrub dead 1 hr (load)	0.09	0.13	0.09	0.10	0.08	0.08	0.08	0.08
Shrub dead 1 hr SAV	1500	1500	1500	1500	1500	1500	1500	1500
Shrub dead 10 hr load	0.03	0.00	0.03	0.02	0.03	0.03	0.03	0.03
Shrub dead 10 hr SAV	109	109	109	109	109	109	109	109
Shrub dead 100 hr load	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shrub dead 100 hr SAV	30	30	30	30	30	30	30	30
Shrub live foliage load	0.00	0.00	0.01	0.00	0.10	0.10	0.10	0.10
Shrub live foliage SAV	2500	2500	2500	2500	2500	2500	2500	2500
Shrub live Optional1(1 hr) load	0.05	0.04	0.06	0.05	0.57	0.57	0.57	0.57
Shrub live Optional1(1 hr) SAV	1500	1500	1500	1500	1500	1500	1500	1500
Shrub live Optional2(10 hr) load	0.02	0.00	0.00	0.01	0.05	0.05	0.05	0.05
Shrub live Optional2(10 hr) SAV	109	109	109	109	109	109	109	109
Grass live load	0	0	0	0	0	0	0	0
Grass live SAV	0	0	0	0	0	0	0	0
Grass dead load	0	0	0	0	0	0	0	0
Grass dead SAV	0	0	0	0	0	0	0	0
litter-COMB-depth	0.23	0.29	0.31	0.28	0.5	0.58	0.55	0.54
slash depth	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shrub depth	0.09	0.14	0.17	0.13	0.83	0.86	1.18	0.96
grass depth	0	0	0	0	0	0	0	0
heat content	8000.00	8000.00	8000.00	8000	8000.00	8000.00	8000.00	8000
Units(fuel load)	tons/ac	tons/ac	tons/ac	tons/ac	tons/ac	tons/ac	tons/ac	tons/ac
Units(SAV)	1/ft	1/ft	1/ft	1/ft	1/ft	1/ft	1/ft	1/ft
Units(heat content)	BTU/ft2	BTU/ft2	BTU/ft2	BTU/ft2	BTU/ft2	BTU/ft2	BTU/ft2	BTU/ft2
Units(depth)	ft	ft	ft	ft	ft	ft	ft	ft

Appendix 7: Correlation graph

Rate of Spread (r = 0.90)
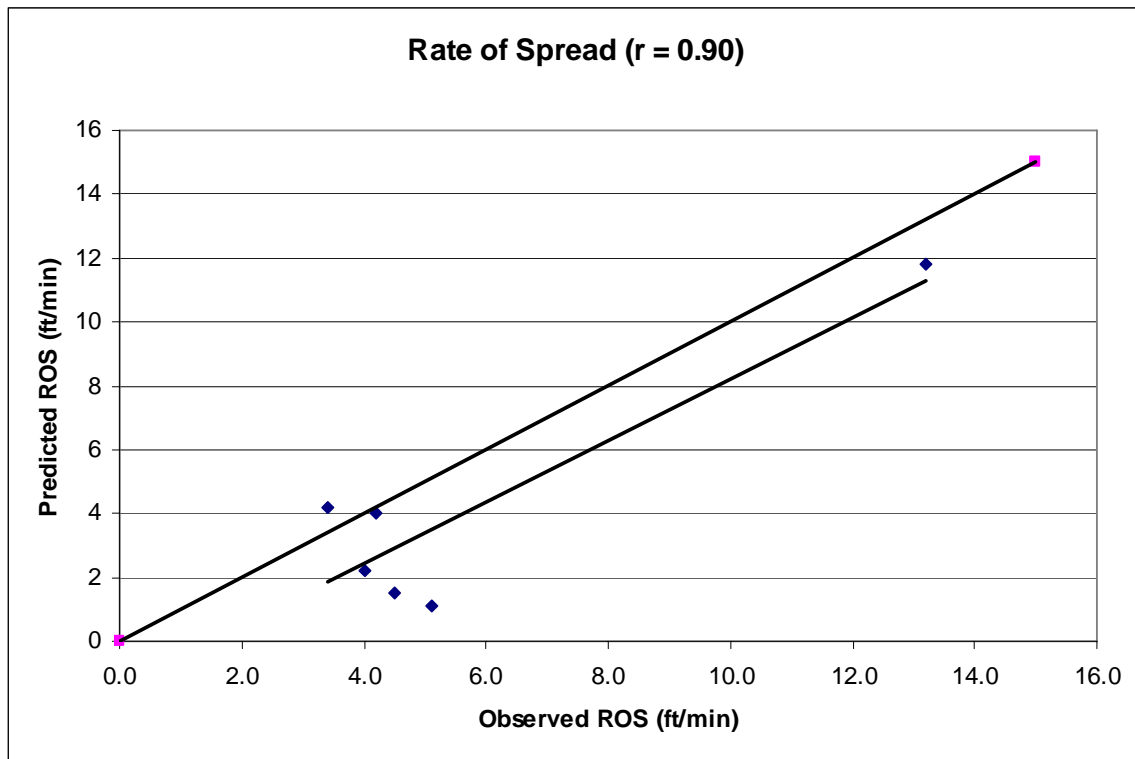
Appendix 8: Brown's DWF Lines vs. point intercept / fuel harvest method

**Comparison of Litter Depths (ft) between Point Intercepth Sampling and Brown's Lines
Pre-Burn April 2004 Data**

plot		Point Intercept (ft)	Brown's Lines (ft)
1		0.23	0.22
2		0.50	0.65
3		0.29	0.25
4		0.58	0.55
5		0.31	0.20
6		0.55	0.55

**Comparison of Woody Fuel Loading (tons/acre) between 40x40 harvest method and Brown's Lines
Pre-Burn April 2004 Data**

	1 hr (tons/acre)		10 hr (tons/acre)		100 hr (tons/acre)	
Plot	40x40	Brown's Lines	40x40	Brown's Lines	40x40	Brown's Lines
1	0.29	0.14	0.33	0.43	0.00	0.21
2	0.38	0.20	0.30	1.17	0.00	0.62
3	0.41	0.15	0.43	0.27	0.33	1.04
4	0.80	0.32	0.46	0.69	0.06	0.62
5	0.39	0.12	0.35	0.46	0.00	0.62
6	1.01	0.17	0.51	0.82	0.37	0.21