2015 Willow Fire
Sierra National Forest

Fire Behavior Assessment Team Summary Report


Pre-fire Plot 4 (transect 1)

Fire entering Plot 4 from down canyon


Post-fire Plot 4 (transect 1)

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Introduction

Wildland fire management relies on quality fire behavior and resource effects predictions. Existing prediction models are based upon limited field data from wildfires, especially quantitative data. The Fire Behavior Assessment Team (FBAT) collects data to improve our ability to predict fire behavior and resource effects in the long-term and provides short-term intelligence to wildland fire managers and incident management teams on fire behavior, fuels, and effects relationships. Increasing our knowledge of fire behavior is also important to firefighter safety; so we can mitigate hazards and prevent accidents. FBAT has seen their data used for a variety of purposes (see Appendix C) and is working to facilitate further applications to safety zone research, fire and fire effects model evaluation, and fuel treatment effectiveness assessments.

This report contains the results of a one week assessment of fire behavior, vegetation and fuel loading, consumption, and fire effects for the Willow Fire. The human-caused Willow Fire and started on July 25, 2015 at 16:34 hours in a rural residential neighborhood 4 miles north of the town of North Fork, California. Over the course of the next 7 days the fire spread rapidly upslope in response to the warm, dry and windy weather. The steep, rugged terrain and lack of roads made access and management of the fire difficult. On July 30th, as a result of fire consuming through several lines of retardant, incident management initiated a large burnout along the primary road system on the southern half of the fire stretching a total perimeter distance of about seven miles. On August 3rd the Willow Fire had grown to a size of 5,737 acres with the majority of the spread effectively contained.

Fuels in the Willow Fire Area consisted primarily of pine and mature mixed shrub below 4500 feet elevation, with mixed conifer and mature shrub above 4500 feet elevation. The southern half of the Willow Fire burned in the footprint of the 2001 North Fork Fire. Live fuel loadings in this area were generally lighter with dead fuel loadings and snag occurrence generally higher.

Fuels and vegetation plots and fire behavior equipment were installed at 6 locations in the vicinity of the Willow Fire, with 4 plots burned by the fire. FBAT installed plots between the dates of July 29 to 31. One plot was burned on July 29 and three plots were burned between July 31 to Aug. 1 during the strategic burnout operations along the southeastern perimeter and interior unburnt vegetation (Figure 2).

Objectives

Our objectives were to:

1. Characterize fire behavior and quantify fuels for a variety of fuel conditions, especially fuel treatment areas. Safety considerations, access, and current fire conditions restrict which areas can be measured.
2. Gather energy transport data during actively burning fires, in conjunction with site characteristics, for the Missoula Fire Lab's safety zone research.
3. Assess and measure representative vegetation to support emission and fire behavior modeling.
4. Assess fire severity and effects based on immediate post-fire measurements.
5. Share the information the FBAT module gathered at the fire.

See this report, and updated versions at: http://www.fs.fed.us/adaptivemanagement/projects_main_fbat.php
See the plot level in-fire videos at: http://www.fs.fed.us/adaptivemanagement/amset_videos.php

Approach/Methods

FBAT selects study sites to represent a variety of fire behavior and vegetation/fuel conditions. Plot selection priorities are also based on safe access and areas that would most likely be burned over within the timeframe that FBAT could be at the incident. Within each plot both fuels and fire behavior data are gathered; a graphic of a plot set up is shown below (Figure 1), though the plot layout changes based on terrain, fuels, and additional objectives (radiant and convective heat for safety zone dataset). The map (Figure 2) displays daily fire progression and approximate plot locations.

Figure 1: Schematic of FBAT fuels and fire behavior study site.

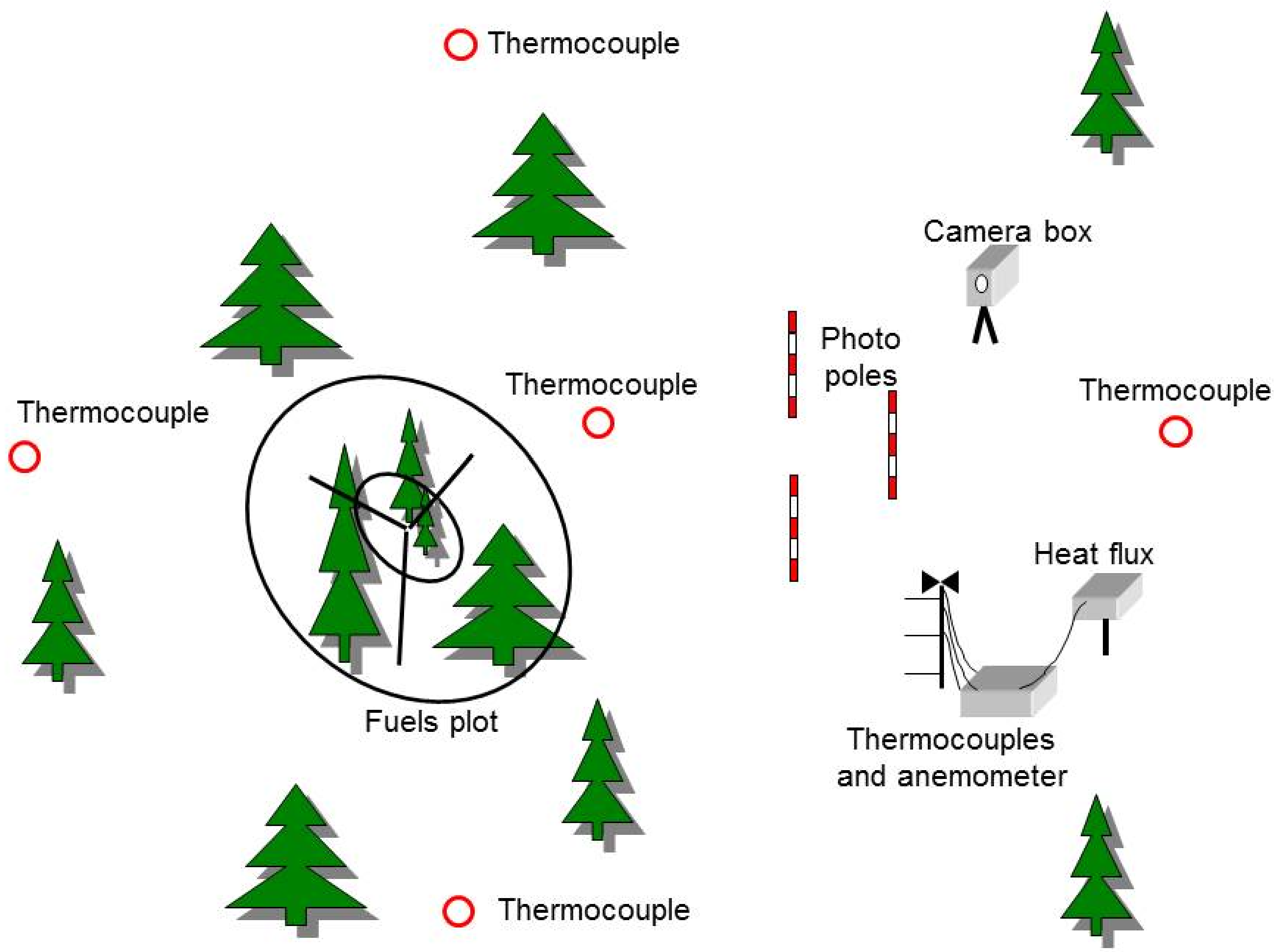
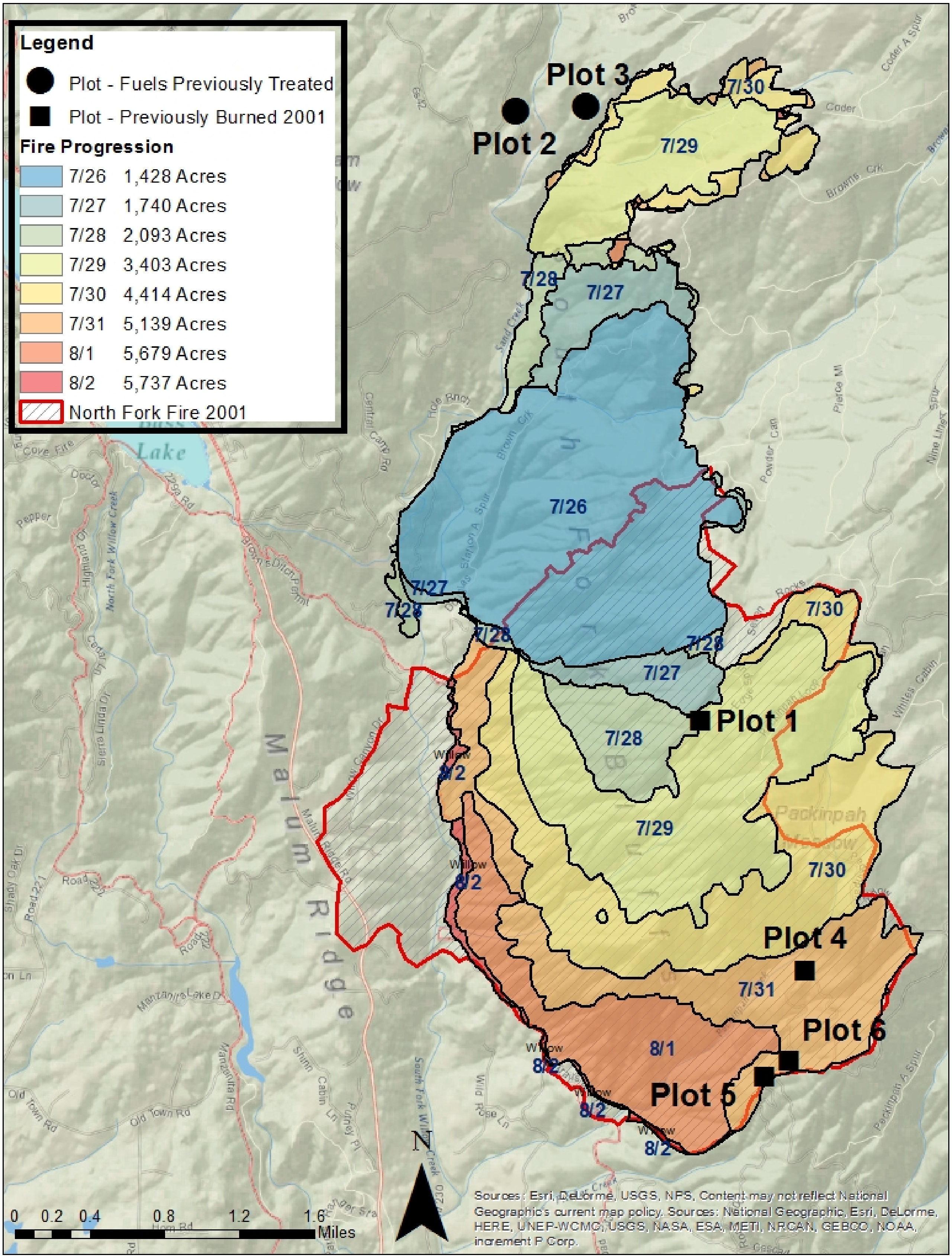


Figure 2: Fire progression and location of FBAT fuels and fire behavior plots in the Willow Fire. Note the progression date does not always match the date fire behavior was captured due to green islands burning and the time of day of infra-red mapping.



Pre- and Post-Vegetation and Fuel Measurements

Vegetation and fuels were inventoried both before the fire reached each plot and then again after the fire at plots. Plots were marked with rebar to provide options for long term monitoring (Figure 3).

Overstory Vegetation Structure and Crown Fuels

Variable radius sub-plots were used to characterize crown fuels and overstory vegetation structure. A relescope (slope-correcting tree prism) was used to create individual plots for both pole (>2.5 to 5.9 in diameter at breast height (DBH) and overstory (>6 in DBH) trees. When possible a basal area prism factor was selected to include between 5 and 10 trees for each classification. Tree species, status (alive or dead), DBH, height, canopy base height, and crown classification (dominant, co-dominant, intermediate or suppressed) was collected for each tree before the fire. Tree height measurements were completed with a laser rangefinder; DBH was measured with a diameter tape.

After the fire, maximum bole char, crown scorch, torch heights and percentages scorch and torch were recorded for each tree. After fire, trees were assumed to be alive if any green needles were present. Changes in canopy base height were estimated from heights of scorch and torch on tree branches, or if necessary from percent of scorch rather than the maximum heights because uneven scorch values occurred sometimes due to trees affected by slope and alignment with heat. Because of smoke and poor lighting, visibility of the full crown is sometimes difficult. If a more accurate assessment of tree survivorship in the plots is desired we recommend another plot visit next year.

The Forest Vegetation Simulator program (FVS, Crookston and Dixon 2005) and its Fire and Fuels Extension (FFE-FVS, Rebain 2010) was used to calculate canopy bulk density, canopy base height, tree density, and basal area both pre- and post-fire for all tree species. FVS/FFE-FVS is stand level growth and yield program used throughout the United States. The Western Sierra variant was used for all calculations.

Understory Vegetation Structure and Loading

Understory vegetation was measured in a one meter wide belt along three 50-foot transects before and after the fire. The fuel and vegetation transects were always in view of the video camera (which will be described below in the “Fire Behavior Measurements and Observations” section). Species, average height and percent cover (based on an ocular estimation) were recorded for all understory shrubs, grasses and herbaceous plants. Biomass of live woody fuels (shrubs and seedlings) and live herbaceous fuels (grasses, herbs, subshrubs) were estimated using coefficients developed for the Behave Fuel Subsystem (Burgan and Rothermel 1984), but calculations were done on a spreadsheet (Scott 2005).

Surface and Ground Fuel Loading

Surface and ground fuels were measured along the same three 50-foot transects as the understory vegetation at each plot. Surface fuel loadings (litter, 1-hr, 10-hr, 100-hr and 1000-hr time lag fuel classes and fuel height) were measured using the line intercept method (Brown 1974, Van Wagner 1968). One and 10-hr fuels were tallied from 0 to 6 ft, 100-hr from 0 to 12 ft and 1000-hr from 0 to 50 ft. Maximum fuel height was recorded from 0 to 6 ft, 6 to 12 ft and 12 to 18 ft. Litter and duff depths were measured at 1 and 6 ft. All measurements were taken both pre- and post-fire. The measurements were used to calculate surface and ground fuel loading with basal area weighted species specific coefficients (van Wagtendonk *et al.* 1996; 1998); and ultimately percent fuel consumption.

Burn Severity

A rapid assessment of burn severity was completed along each transect and for the entire plot area to document the effects of fire on the surface and ground (USDI National Park Service 2003). The National Park Service (NPS) uses fire severity ratings from 1 to 5 when evaluating fire severity. In this rating system 1 represents unburned areas, and 5 represents areas with high fire severity (Appendix B).

Fire Behavior Measurements and Observations

At each plot, multiple sensors (thermocouples, heat flux sensors, and anemometers) and a video camera were set up to gather information on fire behavior (Figure 3). The thermocouples arrayed across the plot have the capability to capture day and time of temperatures from which rate of spread can be calculated. The heat flux sensors capture total, radiant, and convective heat flux from the flame front while the associated anemometers capture wind speed. The video camera is used to determine fire type, flame length, variability and direction of rate of spread, flame duration, wind direction and the direction of fire spread in relation to slope and wind. The sensors are described in more detail below.

Figure 3: Examples of fire behavior equipment set up at the Willow Fire at plot 2. Viewing diagonally from left to right next to the workers are the heat flux sensor, the thermocouple cans (to be buried to measure spread rate), and in the distance is the video camera box.

Rate of Spread and Temperature

Rate of spread was determined both by estimating rate of spread from video analysis and by calculating rate of spread with time stamps from sensors (data loggers with a thermocouple attached). The data loggers are buried underground with the thermocouple at the surface of the fuel bed. The thermocouple is able to record temperature up to six days or until the thermocouple and/or data logger is damaged by heat. The distances and azimuths among thermocouples were measured and these geometrical data and time of fire arrival were used to estimate rate of spread from Simard *et al.* (1984).

Fire Type

Fire type is classified as surface fire (low, moderate or high intensity) or crown fire. Crown fire can be defined as either passive (single or group torching) or active (tree to tree crowning). Fire type was determined from video as well as post-fire effects at each plot. For example, plots where there was complete consumption of tree canopy needles indicate at least torching or passive crown fire.

Flame Length and Flaming Duration

Flame length was primarily determined from video footage. If needed, flame length values could be supplemented by measured tree char height. Flaming duration was based on direct video observation and/or when temperature was measured, from those sensors as well.

Energy Transport

Energy transport data are collected with a heat flux sensor, where flux refers to the rate of energy transfer onto the surface of the sensor measured in units of kW/m^2. As with other recent work (e.g., Frankman *et al.* 2012, Butler *et al.* 2014), we use a Medtherm® Dual Sensor Heat Flux sensor (Model 64-20T), along with calibration relationships derived from laboratory measurements and theory, to provide incident total and radiant energy flux. Radiant flux is detected behind a sapphire window while total flux is detected underneath a blackened surface on the face of the copper plug that houses the detectors. The difference between total and radiant flux is an estimate of convective flux to the sensor (e.g., Frankman *et al.* 2012). Though safety zone guidelines are based on radiant flux alone, Butler (2014) recommends a consideration of total heat flux. The maximum incident heat flux tolerable by firefighters (wearing nomex and protective head and neck equipment) was described as 7 kW/m^2 by Butler and Cohen (1998) in their work on safety zone guidelines. Apart from firefighter safety, heat flux data are useful in developing a fundamental understanding of wildland fire spread and fire effects on trees and soils. Orientation of the sensor relative to the oncoming fire is critical and a successful data collection requires that the flame front approach the sensor within less than approximately +/- 30 degrees of the sensor face (where perpendicular is 0 degrees). The sensor is placed at 1 m above the ground surface and, for small flames, may not be impacted directly by flames, resulting in low heat flux at the sensor. Data summary follows the methods used by the USFS Missoula Fire Sciences Laboratory.

Plot Wind Speed

Wind data collected with cup anemometers placed 5 feet above ground at the locations of the heat flux sensors gives an indication of the wind experienced at each plot as the fire passed through. Wind data on plots with intense fire are only valid only up until the plastic anemometer melts or otherwise is compromised. Wind data were recorded at 1 second intervals and averaged over 10-seconds. Average winds were calculated over the 20 minutes prior to fire detection at the heat flux sensor.

Findings/Results

Pre-fire data were collected at all six plots that we established on the Willow Fire; however post-fire fuels and fire behavior data were only collected at the four plots which burned (plots 1, 4 to 6). The six plots represented different forest/vegetation types and management areas (Table 1). Paired photographs of plots with fuels data are available in Appendix A. Video cameras and rate of spread sensors functioned properly on burned plots. So far (*as of the early Jan. 2016 draft*), wind speed data and heat flux measurements appear to have been obtained on all plots and we're waiting for specialist's time for their summaries.

Table 1: Site description of the 6 plots.

Site	Forest/Vegetation Type	FACTS[1] History	Slope %	Aspect (deg.)	Elevation (ft)
1*	Mixed Conifer	~	30	210	5,640
2	Mixed Conifer	Commercial thin and piling of fuels in 2002	37	88	5,100
3	Mixed Conifer	Thinning 2010, Pile burning 2010/11	14	220	5,250
4*	Mixed Conifer	At edge of 2001 salvage logging treatment.	25	320	4,733
5*	Oak woodland, chaparral	~	42	300	4,331
6*	Mixed Conifer	~	35	270	4,350

* Plot located in the 2001 North Fork Fire burn perimeter.

[1] FACTS is the acronym for **F**orest Service **Ac**tivity **T**racking **S**ystem.

Pre- and Post-Fire Vegetation and Fuel Measurements

Overstory Vegetation Structure and Crown Fuels

Canopy base height, canopy bulk density, and canopy continuity are key characteristics of forest structure that affect the initiation and propagation of crown fire (Albini 1976, Rothermel 1991). Canopy base height (CBH), or the bottom of the tree canopy fuels, is important because it affects crown fire initiation. As stated in Scott and Reinhardt (2001), "Defined in terms of its consequences to crown fire initiation, CBH is the *lowest* height above the ground at which there is sufficient canopy fuel to propagate fire vertically through the canopy." Canopy Bulk Density (CBD), is the mass of canopy fuel available per unit canopy volume (Scott and Reinhardt 2001).

Forest treatments that target canopy base height and canopy bulk density can be implemented to reduce the probability of crown fire (Graham *et al.* 2004). Canopy bulk density varies within the stands measured on the Willow fire, and reaches a maximum value of 0.22 kg/m^3 at the plot 2 (recently untreated) and a minimum value of 0.03 kg/ m^3 at plot 4 (recently burned) prior to the Willow fire. Thinning to reduce canopy bulk density to less than 0.10 kg/m^3 is generally recommended to minimize crown fire hazard (Agee 1996, Graham *et al*. 1999), and for the most part below this point, active crown fire is very unlikely (Scott and Reinhardt 2001). Canopy bulk densities were below this threshold for five of six plots before the Willow fire, and based on post-fire site visits none showed signs of crown fire behavior beyond torching trees. Tree mortality and canopy fuel changes cannot be determined with certainty until one or more years post-fire due to delayed mortality effects and tree recovery rates. Based on immediate post-fire data, the CBD did not change post fire on plot1 or 5, potentially because surface fire did not prune the canopy height or basal area and few differences were found in overstory trees/canopy fuels. Only plot 4 had marked changes in canopy metrics, potentially because the plot only had a few trees to use in calculations. Using FVS-FFE analysis, trees that were estimated as dead post fire are not included in outputs, but we told the program to include hardwood trees.

Table 2: Pre- and post-fire overstory vegetation and crown fuel data by site estimated by FVS-FFE[1]. QMD is the quadratic mean diameter based on tree data collected at the site scale.

Site	Overstory (>6 in DBH) trees/acre		Pole-size (<6 in DBH) trees/acre[2]		QMD (in)		Basal Area (ft²/acre)		Canopy Cover (%)[3]	Canopy Height (ft)		Canopy Base Height (ft)		CBD (kg/m³)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Pre	Post	Pre	Post	Pre	Post
1	18	18	67	67	13	13	106	106	63	52	52	4	4	0.0263	0.0263
2	147		0		25		520		80	110		24		0.2222	
3	175		0		21		435		94	114		2		0.1413	
4	38	25	0	0	22	24	99	79	46	95	109	30	103	0.0256	0.0079
5	5	5	74	74	8	8	36	36	42	17	17	6	6	0.0561	0.0561
6	53	48	0	0	25	25	181	160	69	99	94	30	30	0.0390	0.0320

[1] FVS was programmed to include hardwood species in above estimates.
[2] Note that a zero in post-fire data where pre-fire data was greater than zero indicate all trees were scorched or torched and appeared dead at the time of post-fire sampling. FVS-FFE does not calculate canopy characteristics for dead trees.
[3] Canopy cover was based on field data with densitometer, not FVS outputs.

Fire Effects: Tree Canopy Scorch, Torch, and Bole Char

A few days after the fire burned through each plot (allowing for smoldering combustion to complete and some fire-weakened trees to fall) additional measurements were gathered (char height, maximum heights and percentage of crown scorch and torch) to better assess the fire effects at each plot. Percentage values were determined using ocular estimations, and heights were measured with a laser rangefinder. Severity or fire effects can be accessed from the percentage of scorch and torch for each study plot (Figures 4 and 5). Plot 5 and 1 had minimal scorched (browned or heated) portions of tree canopies, while the majority of tree canopies remained green. In plots 4 and 6 in comparison, the canopies had increased amounts of scorched and torched (foliage consumed) branches. The average bole char height was essentially the same in three of the burnt plots, and plot 5 was the exception partially due the presence of only a few oak trees and being shrub dominated. Plot 4 had the tallest trees, followed by plot 1 then 6. Plot 4 appears to have the greatest amount of trees or canopy that might die due to scorch, but that might change as second order effects occur.

Figure 4. Average percentage of scorch and torch of tree crowns per plot. The portion of tree crown which still appears as live (not scorched or torched) during the immediate post-fire site visit is labeled "green."

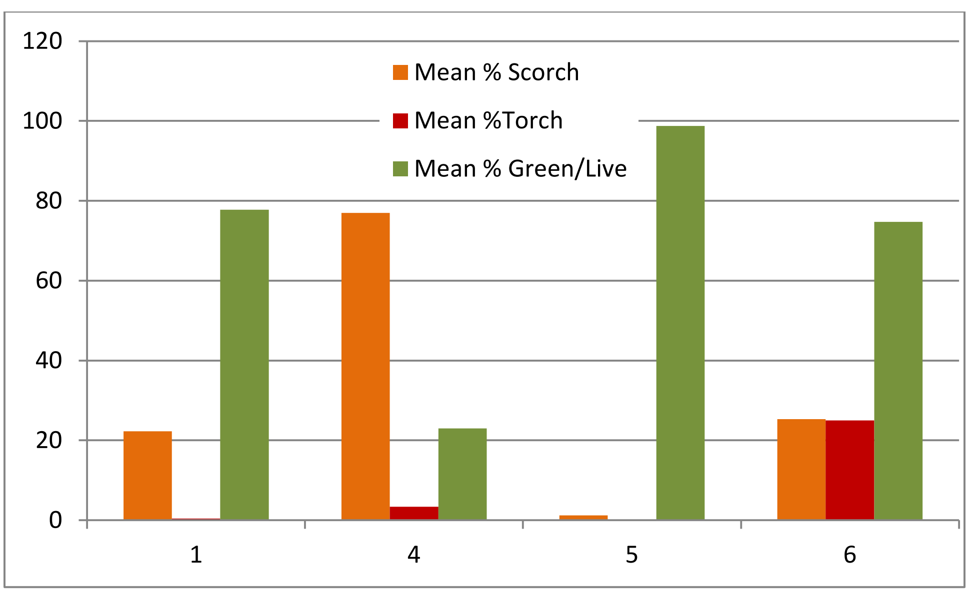
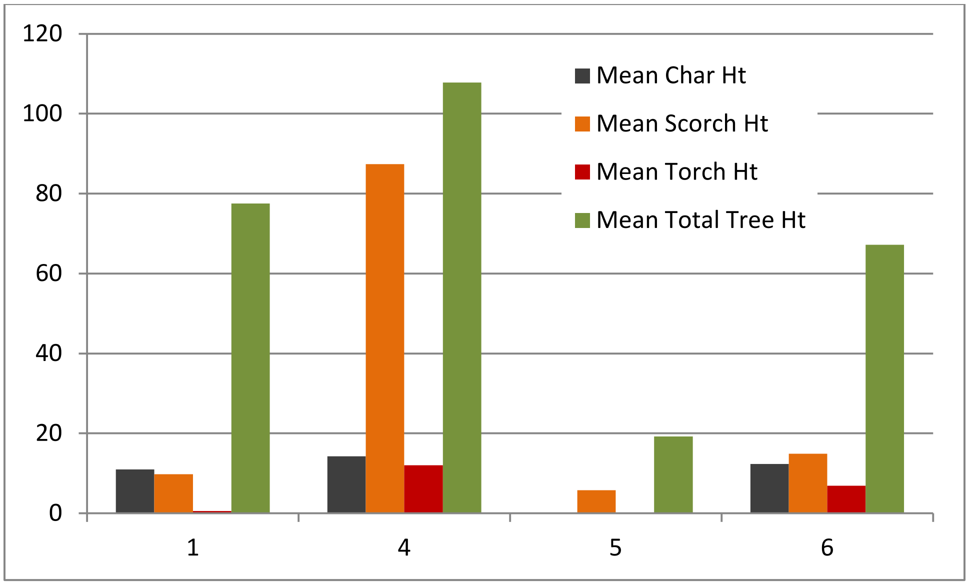


Figure 5. Average height of bole char, scorch and torch height, and total tree height in feet.



Understory Vegetation Loading and Consumption

The understory vegetation varied by forest type and treatment/fire history, but there were very low levels of herbaceous fuels in all plots of 0.008 ton/ac or less, but nearly full consumption of the above ground portion of this layer (Tables 4 and 5). The shrub/seedling fuels had higher loading than herbaceous, but variable amounts between the plots. Plot 5 was shrub, not tree dominated, and data calculated plot five's average loading to 10.6 ton/ac. The areas around Plots 2 and 3 had received fuel or vegetation treatments greater than 10 years ago, and still had less herbaceous and shrub/seedling loading than the other 4 plots that were within the perimeter of the 2001 North Fork fire. Understory vegetation consumption percentage in burned plots was moderate to high percentages (Table 5). Plot 5 had unburnt patches which accounts for the lower consumption percentage. The paired photographs in Appendix A show a sample of the distribution and density of understory flora for each plot, as well as illustrate the change post-burn.

Table 4: Average understory vegetation fuel loading pre-fire and post-fire for plots 1 and 4 to 6.

Site	Average Grass/Herb (ton/ac)						Average Shrub/Seedlings (ton/ac)					
	Pre-Fire			Post-Fire			Pre-Fire			Post-Fire		
	Live	Dead	Total	Live	Dead	Total	Live	Dead	Total	Live	Dead	Total
1	0.005	0.002	0.008	0	0	0	2.667	0.152	2.818	0	0.195	0.195
2	0.001	0.000	0.001				0.261	0.000	0.261			
3	0.001	0.000	0.001				0.085	<0.000	0.085			
4	0.003	0.002	0.004	0	0	0	3.271	0.103	3.374	0	0.151	0.151
5	0.004	0.004	0.008	0	0.001	0.001	7.912	2.691	10.603	0.419	4.091	4.510
6	0.001	0.001	0.002	0	0	0	0.918	0.193	1.110	0	0.494	0.494

Table 5: Average understory vegetation consumption percentage for plots 1 and 4 to 6.

Site	Average Consumption (%)	
	Grass/Herb	Shrub/Seedlings
1	100	93
4	100	96
5	89	57
6	100	56

Surface and Ground Fuel Loading

As considered normal in forested ecosystems, the predominant fuel layer making up the bulk of the total surface and ground fuel loadings was duff, followed by litter (Table 6). Plot 6 is an exception to this, where more litter was measured than duff, probably due to the confusing break points in these strata. The dry site conditions and 14 years since the last fire for all burnt plots also played a role. Loading at the unburned plots 2 and 3 is much higher, showing a difference in the continued reduced fuels from a 14-year old fire. One- and 10-hour fuels contributed only slightly to total fuel loads. Hundred- and 1000-hour fuels were present, but not abundant, except for plot 4, which had about 12 tons/acre of 1000-hour fuels. Fuel bed depths were generally about a half-foot to one-foot, mirroring the relatively low numbers of 1-, 10- and 100-hour fuels. Consumption ranged from moderate to high consumption of surface and ground fuels (Table 7).

Table 6: Average fuel loading and fuel bed depth based on 3 transects per plot, and post-fire data for burned plots 1 and 4 to 6.

Site	Mean Fuel Loading (tons/acre)														Fuel Bed Depth (ft)	
	Duff		Litter		1-hr		10-hr		100-hr		1000-hr		Total load			
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	26.7	4.3	14.9	0.0	0.2	0.0	0.6	0.2	0.4	0.4	3.4	0.0	46.2	5.0	0.5	0.1
2	50.6		16.4		0.5		1.2		0.9		4.1		73.7		0.8	
3	24.5		7.5		0.6		1.5		1.6		5.2		40.8		1.6	
4	12.7	0.0	3.6	0.0	0.4	0.0	1.1	0.1	3.3	0.0	11.8	0.4	32.8	0.5	0.9	0.0
5	19.0	7.1	5.3	1.0	0.3	0.1	0.7	0.6	0.6	0.3	7.0	0.4	32.9	9.5	1.8	0.5
6	3.5	0.0	9.2	0.6	0.6	0.5	0.7	0.6	1.2	0.8	5.8	0.2	20.9	2.6	1.1	0.5

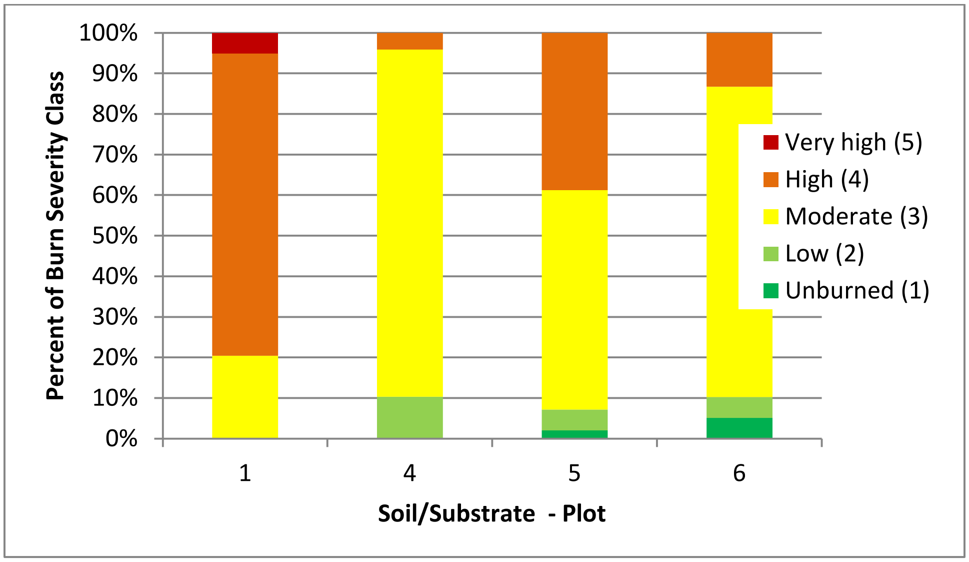
Table 7: Average percent fuel consumption per metric and for plots 1 and 4 to 6 overall (based on Table 6).

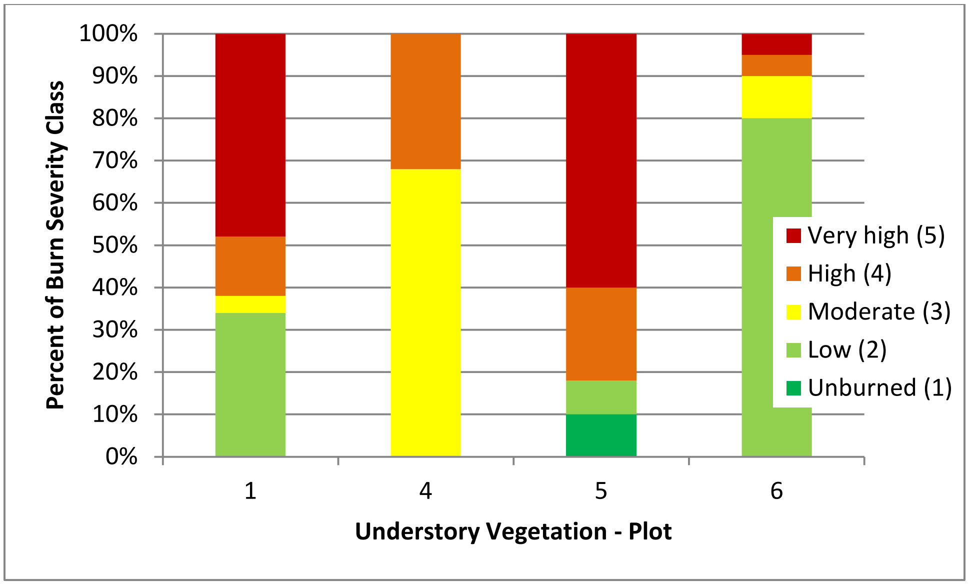
Site	Percent Consumption (%)							Change in Fuel Bed Depth (%)
	Duff	Litter	1-hr	10-hr	100-hr	1000-hr	Total load on site	
1	84	100	91	60	0	100	89	84
4	100	100	97	93	100	96	98	95
5	63	81	63	8	50	95	71	72
6	100	94	12	18	33	97	88	53

Soil and Understory Vegetation Burn Severity

The National Park Service's severity categories were used to assess post-burn soil/substrate and understory vegetation severity along each transect and for the entire plot. Vegetation burn severity is only based on the vegetation that was documented pre-burn. For full descriptions of the categories, please see Appendix B. Substrate severity was mostly moderate in the four burned plots with small pockets of unburned and high severity (Figure 6). Understory vegetation severity was measured as variable based on immediate post-fire conditions (Figure 6), with plots 1 and 6 having lesser understory vegetation severity.

Figure 6: Average post-fire surface soil/substrate (top graphic) and understory vegetation severity rating (bottom graphic) for each plot.





Fire Behavior Observations and Measurements

The narratives below describe fuels and the fire behavior movement through the plot. The metal poles in the video camera's field of view are marked in 1-foot increments; however, often it is difficult to determine how close the flame is to these poles, making flame length estimates approximate. Rate of spread was estimated from the video when possible, by timing the fire progress through a visually-estimated distance. The behavior of the main flame front is generally the behavior described in fire behavior models such as BehavePlus, however, fire spread is rarely that of a simple heading fire as sometimes captured by the video.

Plot 1, Mixed conifer in 2001 North Fork Fire perimeter, dried aerial retardant application area

Plot 1 was located on the upper third of the hill slope below a spur road (7S94B) below Peckinpah Mountain. Many areas bordering the road near the ridge appeared as having previous fuel treatments, but the plot area had not been treated (as recorded in FACTS). The plot was inside the 2001 North Fork Fire perimeter, and many recent dead (orange needle) trees were in the area, with a patchy network of bear clover understory. Most trees had bole char remaining from the previous fire before the Willow Fire burned this site. The video shows mostly low intensity surface fire with isolated periods of moderate intensity. Fire creeped up the boles of trees, but no torching was observed (Figure 7). This plot had moderate fuel loading and consumption compared to the other plots (Tables 6 & 7). The plot was installed near the fire's edge from the day before, in an area that had received aerial retardant, which had already dried. Fire effects indicated that the fire approached from below in the drainage and burned through the plot to the road with varied flame lengths (1 to 6 ft) and spread rates (2 to 4 ch/hr) based on wind gusts/alignment (heading and flanking spread). While surface fuels were mostly to fully consumed, the char and scorch heights on trees were low to moderate. Some scorch and char heights were difficult to estimate post-fire due to previous char and amount of dead foliage on trees before this site burned.

Figure 7. Plot 1 burning, photo captured from video. A four-foot reference pole is visible in right of photo center. The day the site burned is captured on the video, but the time is a time lapse since the video was triggered to record.

Plot 4, Mixed conifer in 2001 North Fork Fire perimeter, edge of 2001 salvage logging

Plot 4 was located on the west/downslope side of a temporary old road (unmaintained) and the main road (8S09 Rd.) within the 2001 North Fork Fire perimeter, above Peckinpah Creek. The area appeared to have thinner tree spacing, potentially due to the salvage logging efforts, and/or being near the main road (hazard tree activities?). Bear clover, manzanita and other understory plants were patchy to thick in areas. Soil disturbance (1 large berm) and understory vegetation patchiness were observed potentially due to previous activities. Fire spread was often in alignment with wind and slope. Video was located above the plot, closer to the road in and low vegetation area. High intensity surface fire with isolated and group torching was observed from video; heavier fuel and steeper slopes were directly down canyon from this site. Fire behavior seems driven more by fuel than by wind speed (Figure 8, and see report cover photos). The consumption within the plot area was near complete, though total loading was low to moderate amount, probably only partially regrown since the last fire and salvage activities. Spread rate ranges from 2 to 20 ch/hr, but as the fire passes through the plot it's mostly from 4 to 10 ch/hr. Flame length variation is similar from 6 in. to 20 or more feet (torching trees), but video observations recorded an average range of 5 to 15 ft. Note fire whirls are visible during several points in the video when winds pick up. Fire whirls range from 4ft to as much as 25ft in length.

Figure 8. Plot 4 burning, photo captured from video. The anemometer and heat sensor box are visible at the left of photo center. The day the site burned is captured on the video, but the time is a time lapse since the video was triggered to record.

Plot 5, Oak woodland and chaparral area, in 2001 North Fork Fire perimeter, below historic road bed
Plot 5 was located on the west/downslope side of a temporary old (unmaintained) and the main road (8S09 Rd.) within the 2001 North Fork Fire perimeter. This site was mostly a few oak trees and some heavy shrub, and was near the dozer line and what appeared to be a temporary/partial safety zone. This plot has the highest understory vegetation loading compared to the other 3 plots that burned. Both plot 5 and 6 (within a quarter mile of each other) were located in a strategic burn out area, and observers/workers reported knowing they were burning out study sites and tried to have the fire spread as natural as possible within their burnout operations only at these 2 plots. This site burned at night, but the video still captured the fire progressing downhill, against the slope. Fire intensity is low (Figure 9). Flame lengths are variable, mostly 6 inches or less, with occasional increases to 1 to 3 feet when the fire moves into heavier fuels. Spread rate is very slow, at an average of less than 1 ch/hr.

Figure 9. Plot 5 backing spread from uphill. The day the site burned is captured on the video, but the time shown is a time lapse since the video was triggered to record.

Plot 6, Mixed conifer in 2001 North Fork Fire perimeter

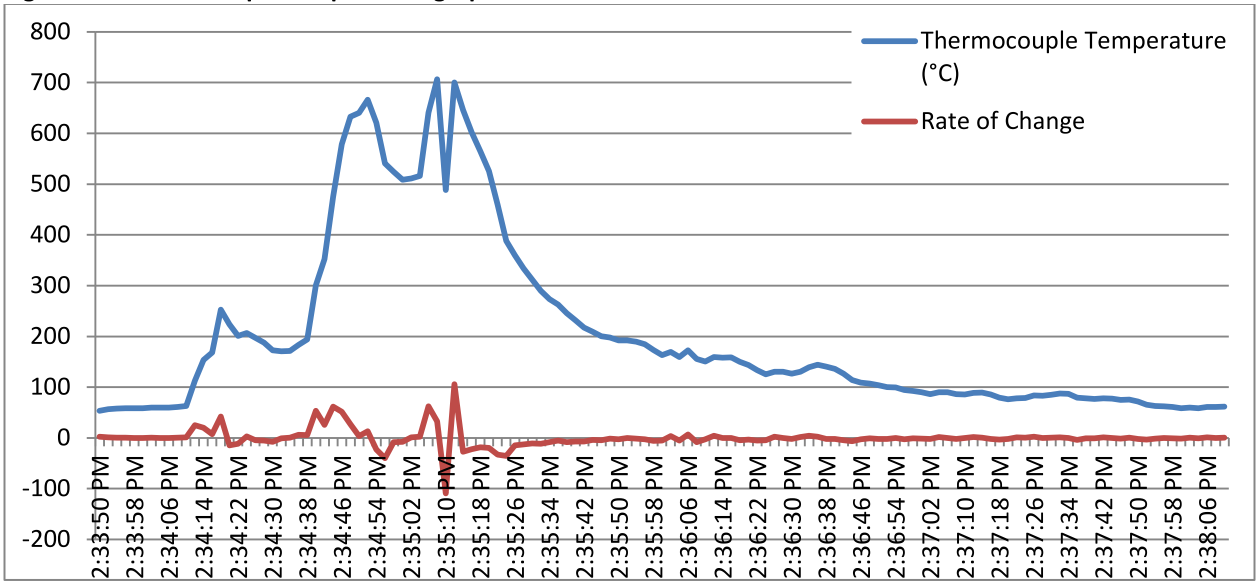
Plot 6 was located on the east/upslope side of the main road (8S09 Rd.) within the 2001 North Fork Fire perimeter. Both plot 5 and 6 (within a quarter mile of each other) were located in a strategic burn out area, and workers reported knowing they were burning these study sites and tried to have the fire spread as natural as possible within their burnout operations at these 2 plots. Fire progression is mostly downhill, backing against the slope. Video shows fire creeping up tree boles, but no tree torching (Figure 10). On the video flame lengths are consistently 1 to 2 ft, except during a few moments of heavier fuels, and spread rates are estimated at about 1.5 ch/hr.

Figure 10. Fire in plot 6 area subsides and torching in distance. The day the site burned is captured on the video, but the time shown is a time lapse since the video was triggered to record.

Rate of Spread and Temperature

Rate of spread and thermocouple temperature data were gathered using five heat resistant data loggers, or sensors, at each plot. One rate of spread calculation can be performed for each triangle formed by three sensors, and rate of spread was calculated for the larger triangles when quality data was recorded and recovered. If more than one triangle of sensors burned, the range of spread rates was reported (figure X placeholder). The temperature sensors logged temperature at 2 second intervals. The north sensor for plot 1 shows a sharp increase in temperature, which marks fire arrival, with a few temperature spikes over a couple of minutes, and then a temperature decay through time (Figure 11). The peak in Figure 11 that is followed by a slow decay in temperature as fuels smolder is typical of most wildfire temperature data.

Figure 11: Thermocouple temperature graph for north sensor at Plot 1.



Fire Type, Flame Length and Duration

In addition to the sensors, fire behavior data can be obtained from the video footage. Table 8 below lists the fire type, flame length, flame angle, and rate of spread (ROS) determined video analysis and the rate of spread sensors.

Differences between fire behavior measurements obtained from video footage and rate of spread sensors were found for plot X (placeholder). The ROS estimate from video is based on what is visible in the camera frame and uses the metal reference poles and anemometer pole, but may not describe the overall rate of spread within the plot area as recorded by the temperature sensors. Further data analysis will tell is there was much spread rate difference as calculated by the temperature (ROS) sensors.

Table 8: Fire behavior data based on the video camera footage and from sensors.

Site	Fire Type	Flame Length (ft)	Flame Angle* (degrees)	ROS (ch/hr) camera	ROS (ch/hr) sensors	Date & Approximate Arrival Time** (2015)	End of Active Consumption
1	surface fire, with isolated moderate intensity, no torching	3 to 6 ft	variable, higher with wind (alignment with fire progression), ranging 10 to 90°	2 to 4		July 29; 14:21 based on ROS sensor	unknown; still active consumption at video end (28 min. later)
4	moderate to high intensity surface fire, with isolated torching	5 to 15 ft, variable	variable, with greater wind speed 0 to 10°, with lower wind speed (perpendicular to fire progression) angle varies from 45 to 90°	Ranges of 2 to 20, mostly 4 to 10		July 31; 07:08 based on ROS sensor	unknown; still active consumption at video end (30 min. later)
5	moderate to low intensity surface fire, no torching	ranges 0.5 to 6 ft, average 2 to 3ft	mostly upright at 90°, occasionally 45° when the log/surrounding fuels are burning	slow, less than 1		July 31 to Aug. 1; 23:11 based on ROS sensor	unknown; still active consumption at video end (1 hr & 4 min. later)
6	low intensity surface fire, no torching	ranges 1 to 3 ft	mostly 45°, leaning uphill, against the wind	average 1.5		July 31; 18:57	unknown; still active consumption at video end (26 min. later)

*Approximate angle from the line between flame tip to center of flame base then to ground surface.
**Time is local.

Energy Transport

Examination of the video from the four burned plots where we collected heat flux data show that plots 1 and 4 involved fire spread towards the sensor (Table 8). In other words, we successfully collected heat flux data at plots 1 and 4 at the Willow Fire. These were low to moderate intensity surface fires, respectively. Because of low flames (plot 1) and wind that sifted from being aligned to being opposed relative to the direction of flame spread (plot 4), the percentage of peak sensor heat flux that was convective was low relative to other measurements where fire spread and wind direction were aligned (see Butler 2014). The heat flux sensors at plots 5 and 6 were not facing the fire spread direction enough to provide quality data, so those data are not reported here. The effects low flame heights are particularly seen in the total energy column of Table 9. Figures showing the time-course of heat flux to the sensors on plots 1 and 4 are shown in Figures 16 and 17, respectively. The lingering convective heating indicates smoldering combustion after the flame fronts had passed.

Table 9. Summary of heat flux and energy transport to heat flux sensors during the Willow Fire consider fully successful data collections. A successful collect occurs when flames spread nearly directly towards heat flux sensor. Convective heat flux to the sensor is approximately the difference between total and radiant. The percentage of peak total heat flux accounted for by convection is shown.

Peak heat flux (kW/m^2)					Energy (kJ/m^2)		
Site	Radiant	Total	Convective	Percent convective	Radiant	Total	Comment
1	34	50	16	32%	1,988	50	Low flames burning uphill with the wind
4	54	73	18	25%	3,054	4,713	Wind shift to downslope as flames spread past sensor

Figure 12. Radiant and total het flux and 10-s average wind for Plot 1 on the Willow Fire. Winds were averaged over 20 minutes until the first rise in heat flux (Table 9). The anemometer cups melted around the time of peak heat flux.

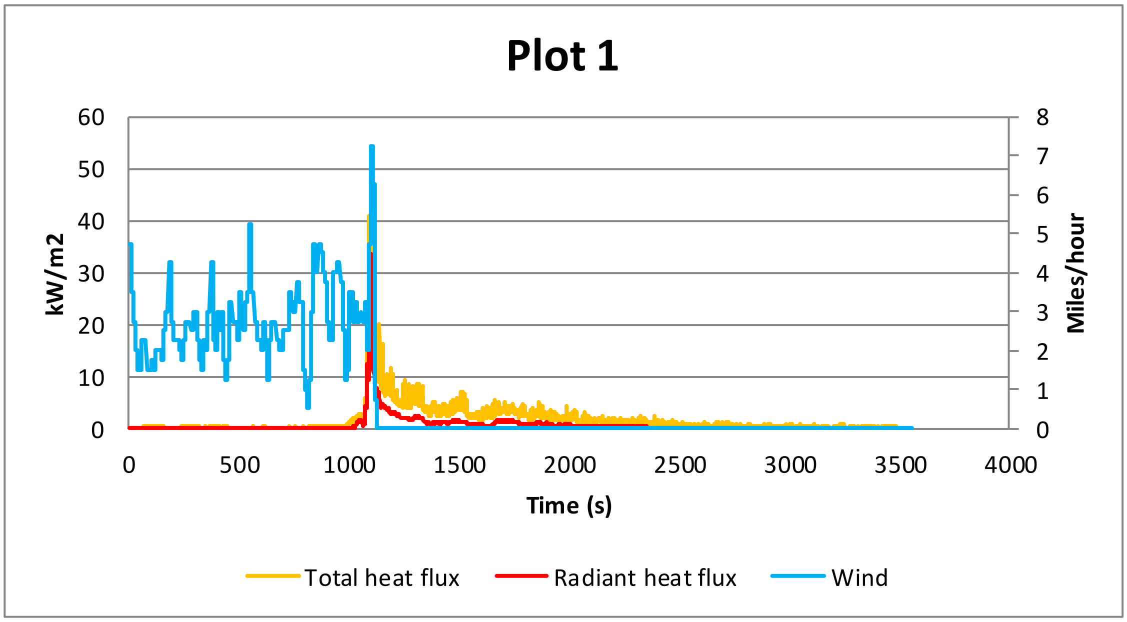
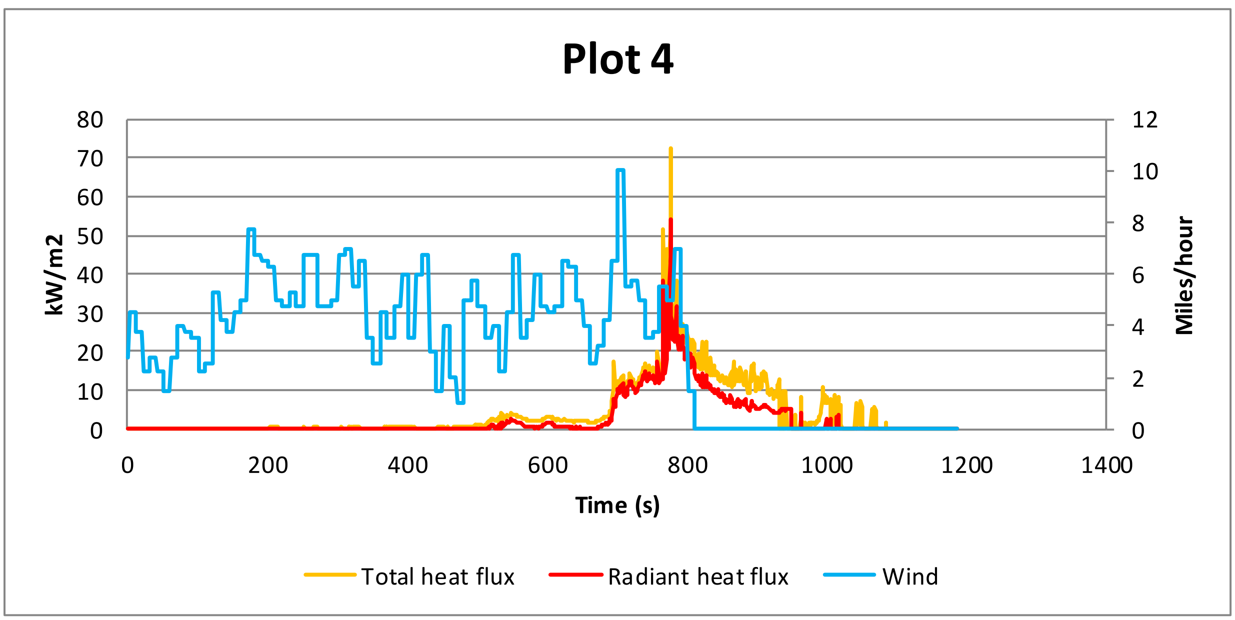


Figure 13: Radiant and total heat flux and 10-s average wind for Plot 4 on the Willow Fire. The wind shift is evident in the early part of the heat flux profile, where there is a slow-down in the rise of sensor heat flux (compare with Figure 12). Winds were averaged over 20 minutes until the first rise in heat flux (Table 9). The anemometer cups melted around the time of peak heat flux.



Plot Wind Speed

Average and peak 5-foot wind speeds over a 20 minute period before fire arrival at the heat flux sensors are shown in Table 10. Winds were modest when fires burned through plots. In part, this can be explained by the location of plots near control lines in areas that were being burned out under moderate conditions. In general, caveats to the data are that they are at 5-foot height (which would approximate mid-flame wind speeds for intense surface fires) and thus, sheltered by any tree canopy that is present. Winds leading up to fire arrival at heat flux sensors and while flames were spreading around sensors are shown for plots 1 and 4 (Figures 12 and 13, respectively).

Table 10: Winds over 20 minutes prior to fire arriving at heat flux sensor and associated anemometer (top of table). The table is sorted by average wind speed. Peak wind speed is from the 10 second moving average.

Site	Wind speed (miles/hr)	
	20 minute average	Peak over 20 minutes
5	1.6	4.5
6	2.7	4.3
1	2.9	5.8
4	3.4	8.3
2 and 3	No heat flux data (unburned)	

Summary

Our objectives were to:

1. Characterize fire behavior and quantify fuels for a variety of fuel conditions, especially in areas with treated fuels. Safety considerations, access, and current fire conditions restrict which areas can be measured and amount of sensors.
2. Gather energy transport data during active burning fires, in conjunction with site characteristics, for the Missoula Fire Lab's safety zone research.
3. Gather and measure representative vegetation to support emission and fire behavior modeling.
4. Assess fire severity and effects based on immediate post-fire measurements.
5. Share the information the FBAT module gathered at the fire.

The FBAT program met its objectives on this incident. We installed and re-visited plots safely, mitigating for risks associated with data collection on active fires. The four plots that burned captured the fuel characteristics and effects of a previous wildfire area being reburned 14 years later. Some of the data were used immediately, and some will be used over the course of the next couple years. FBAT also gathered heat flux data with newly calibrated equipment which will form part of a growing dataset used to develop improved firefighter safety zone guidelines. FBAT also beta-tested a new soil sampling protocol at plot 6 and sent several soil samples off to collaborators at Michigan State University for analysis; this continues steps in integrating soil nutrient and black carbon effects into FBAT protocols. FBAT also collected integrated fuels, consumption, fire effects and fire behavior data which will be used along with data from other fires and years to evaluate and possibly calibrate fire behavior or fire effects models.

The Willow fire burned during drought conditions resulting in high fuel consumption and some areas of intense fire behavior. The data collected by FBAT will be used to improve understanding of fires burning under different conditions.

The information that the FBAT module gathered at the Willow fire is available to all.
See this report at: http://www.fs.fed.us/adaptivemanagement/projects_main_fbat.php
See the video at: http://www.fs.fed.us/adaptivemanagement/amset_videos.php

Acknowledgements

The FBAT program wishes to send a special thanks and appreciation to California Type II South Central Sierra Incident Command Team, David Cooper, Rob Laeng, Taro Pusina, Julie Roberts, and the Sierra National Forest staff such as Van Arroyo, Burt Staler, Mark Smith, and Denise Tolmie, as well as other local fire and fuels managers who hosted and aided FBAT. Thanks to those who have contributed to maintaining FBAT financially, including the USDA Forest Service WO and PSW Regions FAM, JFSP, and others who helped build our FBAT program. We thank the on-call members who make up the FBAT team, past and present – without you, the FBAT team would not exist. Thanks to Dr. JoAnn Fites-Kauffman for starting the FBAT program many years ago. We thank the Missoula Fire Lab and other fire scientists for past, present, and future collaboration and assistance with equipment and methods.

FBAT module at Willow fire standing above Plot 4.

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In Remembrance

A good friend and leader of the FBAT program, **Mike Campbell** (pictured on the right below at 2008 Clover Fire), went to heaven this summer after a bumpy ride with cancer. He was admired and respected in the wildfire community and beloved on the Tahoe NF. In 2012 he turned 57 and retired from the Tahoe NF after making a **career out of leading by example**. This year's FBAT summary reports are *dedicated to Mike and in remembrance of all he gave to the FBAT program* (making it more operational and gear improvements) and to the fire and USFS communities. ***Enjoy the beach Mike! We miss you.***

Appendix A: Representative Paired Photographs from Pre- and Post-Vegetation and Fuel Plots

Plot 1, Transect 1, 0-50ft, pre-fire

Plot 1, Transect 1, 0-50ft, post-fire

Plot 2, Transect1, 0ft to 50ft, **unburned**

Plot 2, Transect 3, 0ft to 50ft, **unburned**

Plot 3, Transect 2, 50ft to 0ft, **unburned**

Plot 3, Transect 3, 0ft to 50 ft, **unburned**


Plot 4, Transect 2, 50ft-0ft, pre-fire


Plot 4, Transect 2, 50ft-0ft, post-fire


Plot 5 Transect 3, 0ft-50ft, pre-fire


Plot 5 Transect 3, 0ft-50ft, post-fire

Plot 6 Transect 1, 0ft-50ft, pre-fire

Plot 6 Transect 1, 0ft-50ft, post-fire

More paired pictures and site pictures are available upon request.

Appendix B: Burn severity coding matrix from the National Park Service

Table 12. Burn severity coding matrix from the National Park Service (USDI 2003).

Code	Forests		Shrublands	
	Substrate	Vegetation	Substrate	Vegetation
Unburned (1)	not burned	not burned	not burned	not burned
Scorched (2)	litter partially blackened; duff nearly unchanged; wood/leaf structures unchanged	foliage scorched and attached to supporting twigs	litter partially blackened; duff nearly unchanged; wood/leaf structures unchanged	foliage scorched and attached to supporting twigs
Lightly Burned (3)	litter charred to partially consumed; upper duff layer may be charred but the duff layer is not altered over the entire depth; surface appears black; woody debris is partially burned	foliage and smaller twigs partially to completely consumed; branches mostly intact	litter charred to partially consumed, some leaf structure undamaged; surface is predominately black; some gray ash may be present immediately after burn; charring may extend slightly into soil surface where litter is sparse otherwise soil is not altered	foliage and smaller twigs partially to completely consumed; branches mostly intact; less than 60% of the shrub canopy is commonly consumed
Moderately Burned (4)	litter mostly to entirely consumed, leaving course, light colored ash; duff deeply charred, but underlying mineral soil is not visibly altered; woody debris is mostly consumed; logs are deeply charred, burned-out stump holes are common	foliage, twigs, and small stems consumed; some branches still present	leaf litter consumed, leaving course, light colored ash; duff deeply charred, but underlying mineral soil is not visibly altered; woody debris is mostly consumed; logs are deeply charred, burned-out stump holes are common	foliage, twigs, and small stems consumed; some branches (0.25-0.50 inch in diameter) still present; 40-80% of the shrub canopy is commonly consumed.
Heavily Burned (5)	litter and duff completely consumed, leaving fine white ash; mineral soil visibly altered, often reddish; sound logs are deeply charred and rotten logs are completely consumed. This code generally applies to less than 10% of natural or slash burned areas	all plant parts consumed, leaving some or no major stems or trunks; any left are deeply charred	leaf litter completely consumed, leaving a fluffy fine white ash; all organic material is consumed in mineral soil to a depth of 0.5-1 in, this is underlain by a zone of black organic material; colloidal structure of the surface mineral soil may be altered	all plant parts consumed leaving only stubs greater than 0.5 in diameter
Not Applicable (0)	inorganic pre-burn	none present pre-burn	inorganic pre-burn	none present pre-burn

Appendix C: About the Fire Behavior Assessment Team (FBAT)

The Fire Behavior Assessment Team (FBAT) operates under the management of the Adaptive Management Services Enterprise Team (AMSET) of the USFS. We specialize in measuring fire behavior and fuels on active wildland and prescribed fires. We utilize fire-resistant sensors and video cameras to measure direction and variation in rate of spread, fire type (e.g. surface, passive or active crown fire behavior), onsite weather, and couple this with measurements of fire effects, topography, and fuel loading and moisture. We measure fuel load changes from fire consumption and compare the effectiveness of past fuel treatments or fires in terms of fire behavior and effects. We are prepared to process and report some data while on the incident, which makes the information immediately applicable for verifying LTAN or FBAN fire behavior prediction assumptions. In addition, the video and data are useful for conveying specific information to the public, line officers and others. We can also collect and analyze data to meet longer term management needs, such as calibrating fire behavior modeling assumptions for fire management plans, unit resource management plans, or project plans.

Since 2003, The FBAT program has built a rich dataset and library of products for fire and fuels managers; fire training and safety; and fuel, fire, and smoke scientific communities. FBAT video has been utilized by the Wildland Firefighter Apprenticeship Program and USFS PSW ecological restoration video series; and FBAT data and program information were shared with the **JFSP crown fire behavior knowledge synthesis project** (p. 41) and a **PSW Research Station project** that estimated carbon stocks and emissions in CA and evaluated FOFEM. Other collaborations to collect and utilize FBAT data are in progress including: supplying data to support fire safety zone research at the Missoula Fire Sciences Laboratory; submitting a JFSP grant proposal with P. Robichaud to create an ash guide for BAER teams; and testing sampling methods for black carbon measurements with Jessica Miesel at Michigan State University.

FBAT is a team of fireline qualified technical specialists and experienced fire overhead. The overhead personnel include a minimum of crew boss qualification, and more often one or more division supervisor qualified firefighters. The team can vary in size, depending upon availability and needs of order, from 5 to 12 persons. We have extensive experience in fire behavior measurements during wildland and prescribed fires. We have worked safely and effectively with over 17 incident management teams. We are comprised of a few AMSET FBAT core members and other on-call firefighters from the USFS and other agencies. We are available to train other interested and motivated firefighters while on fire incidences, as time allows.

We can be ordered from ROSS, where we are set up as “Fire Behavior Assessment Team”, and are in the CA Mobilization Guide (near the BAER Teams). We can be name requested, and we’ll request additional personal to join our team, like a Wildland Fire Module, based on the Module’s availability. Please contact us directly by phone to notify us that you are placing an order, which will speed up the process. You can reach Carol Ewell at 530-559-0070 (cell) or via the Stanislaus NF dispatch (209-532-3671 x212). Or you can reach Alicia Reiner at 530-559-4860 (cell). We may be available if you call dispatch and we are already assigned to a fire. We can work more than one fire simultaneously and may be ready for remobilization. This is the FBAT web page, which has links to most FBAT Incident Summary Reports:
http://www.fs.fed.us./adaptivemanagement/projects/FBAT/FBAT.shtml