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Effectiveness and longevity of fuel treatments in coniferous forests across California

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Integrating science, technology and fire management.
Wildland Fire Management RD&A

Abstract

Longevity of fuel treatment effectiveness to alter potential fire behavior is a critical question for managers preparing plans for fuel hazard reduction, prescribed burning, fire management, forest thinning, and other land management activities. Results from this study will help to reduce uncertainty associated with plan prioritization and maintenance activities. From 2001 to 2006, permanent plots were established in areas planned for hazardous fuel reduction treatments across 14 National Forests in California. Treatments included prescribed fire and mechanical methods (i.e., thinning of various sizes and intensities followed by a surface fuel treatment). After treatment, plots were re-measured at various intervals up to 10 years post-treatment. Very few empirically based studies exist with data beyond the first couple of years past treatment, and none span the breadth of California's coniferous forests. With the data gathered, this research aimed to meet three main objectives:

Objective 1) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior, by*

- **a)** *measuring effects of treatments on canopy characteristics and surface fuel loads over time, and*
- **b)** *modeling potential fire behavior with custom fuel models.*

Objective 2) *Quantify the uncertainty associated with the use of standard and custom fuel models.*
Objective 3) *Assess prescribed fire effects on carbon stocks and validate modeled outputs.*

Results have shown initial reductions in surface fuels from prescribed fire treatments recover to pre-treatment levels by 10 yr post-treatment. Mechanical treatments continue to have variable effects on surface fuels. With the exception of mechanical treatments in red fir, both treatment types resulted in increased live understory vegetation by 8 yr post-treatment relative to pre-treatment. Mechanical treatment effects on stand structure remains fairly consistent through 8 yr post-treatment. Fire-induced delayed mortality contributes to slight decreases in canopy cover and canopy bulk density over time. For both treatment types, overall canopy base height decreases in later years due to in-growth of smaller trees, but it remains higher than pre-treatment. The changes in fuel loads and stand structure are reflected in fire behavior simulations via custom fuel modeling. Surface fire flame lengths were initially reduced as a result of prescribed fire, but by 10 yr post-treatment they exceeded the pre-treatment lengths. Though a low proportion of type of fire, initial reductions in potential crown fire returned to pre-treatment levels by 8 yr post-treatment; passive crown fire remained reduced relative to pre-treatment for the duration. Mechanical treatments showed variable and minimal effects on surface fire flame length over time; however the incidence of active crown fire was nearly halved from this treatment for the duration.

The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) was used to model potential fire behavior for plots treated with prescribed fire to determine the differences in modeled fire behavior using standard and custom fuel models. In general predicted fire behavior from custom versus standard fuel models were similar with mean surface fire flame lengths slightly higher using standard fuel models for all time steps until the 8 yr post treatment. Similarly, custom fuel models predicted a higher instance of surface fire than standard fuel models with the exception of 8 yr post-treatment.

To better understand the impact of prescribed fire on carbon stocks, we estimated aboveground and belowground (roots) carbon stocks using field measurements in FFE-FVS, and simulated wildfire emissions, before treatment and up to 8 yr post-prescribed fire. Prescribed fire treatments reduced total

carbon by 13%, with the largest reduction in the forest floor (litter and duff) pool and the smallest the live tree pool. Combined carbon recovery and reduced wildfire emissions allowed the initial carbon source from wildfire and treatment to become a sink by 8 yr post-treatment relative to pre-treatment if both were to burn in a wildfire. In a comparison of field-derived versus FFE-FVS simulated carbon stocks, we found the total, tree, and belowground live carbon pools to be highly correlated. However, the variability within the other carbon pools compared was high (up to 212%).

Background and purpose

Under the guidance of the National Fire Plan and the 10-Year Comprehensive Strategy, the use of fuel treatments to reduce the likelihood of catastrophic fires has increased over the past decade. The FLAME Act of 2009 and resulting National Cohesive Wildland Fire Management Strategy re-iterated the need to address wildland fire management. One of three core goals of the Cohesive Strategy is to restore and maintain landscapes making them resilient to fire related disturbances. The effectiveness of treatments is a combination of the treatment itself, the behavior of the approaching fire, and the level of fire suppression actions taken (Agee and Skinner 2005, Reinhardt et al. 2008). The most effective treatments alter both canopy fuels and surface fuels, creating a more resilient forest structure by reducing surface and ladder fuels, raising the canopy base, and decreasing the canopy bulk density while preserving large fire resistant trees (Agee et al. 2000, Hessburg and Agee 2003, Agee and Skinner 2005).

Objective 1) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior by measuring effects of treatments on canopy characteristics and surface fuel loads over time and modeling potential fire behavior with custom fuel models*

The short-term effectiveness (1 to 2 yr) of fuel treatments to abate undesirable fire behavior and effects is well studied and known (i.e., Stephens and Moghaddas 2005, Vaillant et al. 2009a,b, Reiner et al. 2009, Fulé et al. 2012, McIver et al. 2012, Safford et al. 2012). Mid- to long-term effectiveness of fuel treatments is not quite as well understood. The longevity of fuel treatment effectiveness to alter potential fire behavior is a critical question for managers preparing plans for fuel hazard reduction, prescribed burning, fire management, forest thinning, and other land management activities. To understand the effectiveness, quantification of fuel treatment impacts on fuel loads and canopy characteristics over time is needed. The primary objective of this research was to determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior by measuring effects of treatments on canopy characteristics and surface fuel loads over time and modeling potential fire behavior with custom fuel models.

Objective 2) *Quantify the uncertainty associated with the use of standard and custom fuel models*

The most reliable test of fuel treatment effectiveness over time is to observe what happens when a wildfire encounters a treated area and determine if fire behavior changed (Pollet and Omi 2002, Finney et al. 2005). In the absence of this information and in necessity for fuel treatment planning, fuel treatment effectiveness is “tested” using fire behavior modeling. Traditionally, the set of 53 standard fuel models (Anderson 1982, Scott and Burgan 2005) are used to characterize treated and untreated fuel loads, which can limit the true representation of the inherent variability of fuels and their response to a fuel treatment.

For instance, long-needle pine is often characterized as a TL8 (188) fuel model pre-treatment and a TL1 (181) post treatment (Cochrane et al. 2011, 2012). The second objective of this research was to compare modeled fire behavior outputs from field-derived custom fuel models to the traditional method of assigning standard fuel models to quantify the differences and explore the uncertainties associated with the use of fuel models.

Objective 3) *Assess prescribed fire effects on carbon stocks and validate modeled outputs*

While fuel treatments result in initial reductions of stand carbon, they have a potential to reduce the severity of wildfires and therefore losses of carbon due to emissions from combustion and decomposition of fire-killed biomass. To date, the majority of publications that quantify fuel treatment effects on forest carbon stocks use empirical data with pre-treatment and immediate or near immediate post-treatment data (i.e., Finkral and Evans 2008, Sorensen et al. 2011, Stephens et al. 2012a). Currently, only three studies go beyond the scope of immediate effects of fuel treatments on carbon stocks with empirical data (Boerner et al. 2008, Hurteau and North 2010, Hurteau et al. 2011). In the absence of empirical data, simulation models can be used to predict the future impact of fuel treatments on carbon pools (i.e., Hurteau and North 2009, Reinhardt and Holsinger 2010, Sorensen et al. 2010). The third objective of this research was to quantify aboveground and belowground (coarse roots) carbon stocks and predicted carbon emissions from simulated wildfire before and up to eight years after treatment, and compare field-derived to simulated values to validate model outputs.

Study description and location

As a part of the Fuel Treatment Effectiveness and Effects Monitoring in the Pacific Southwest Region project (Fites-Kaufman et al. 2007), National Forests in California provided at least one candidate fuel treatment project from 2000 through 2006, which would be treated in the near future. Project monitoring preference was given to optimize likelihood of treatment, compared to random project selections. Up to six permanent plots were randomly placed in each project area before treatment. Two sampling methods were used, "detailed" and "fuels" plots. The detailed plots included data collection on forest floor and surface fuels, understory vegetation, and trees while the fuels plots did not include tree data. The field sampling protocol was based on the National Park Service Monitoring Handbook (USDI National Park Service 2003) with some modifications to optimize sampling efficiency (Vaillant et al. 2009a).

Overstory, pole-size, and seedling tree information were gathered within fixed area nested plots sized 0.1 ha, 0.025 ha, and 0.005 ha, respectively. Tree size categories were: overstory trees ≥ 15 cm diameter at breast height (dbh), pole-sized trees ≥ 2.5 cm to < 15 cm dbh, and seedlings < 2.5 cm dbh. For all overstory and pole-sized trees tag number, vigor (live or dead), species, dbh, and total height were recorded. Live tree measurements included height to live crown base. Seedlings were tallied by species, vigor, and height class. Canopy cover estimates were collected using a canopy sight tube every meter along the understory vegetation transect(s).

Understory vegetation was collected along 50 m transect(s). Shrub data included: species, average height, length along transect, and vigor. Species, height, and cover classes (Daubenmire 1959) by vigor for vascular plants, subshrubs, forbs, and grasses were recorded within five 1 m by 1 m quadrats placed every 10 m along the transect.

Forest floor (litter and duff) and surface fuels (dead and downed woody material) were inventoried following the line intercept method (Van Wagner 1968, Brown 1974) with 15.24 m transects. Litter and duff depths were recorded at 10 equidistant points along each transect. Fuel bed depth, defined as the maximum height from the bottom of the litter layer to the highest dead and down fuel along a vertical plane extending from the fuel transect, was recorded in 10 equidistant intervals.

Plots were grouped into treatment-forest type combinations for analysis (Fig. 1). Prescribed fire (FIRE) treatments were treated with only fire. The mechanical treatment (MECH) included a thinning treatment followed by a surface fuel treatment (mastication, on-site hand or machine piling of materials that may or may not have been burned, or offsite biomass removal). Plots were assigned subjectively to three forest types based on dominant tree species, similarities in fuel characteristics, and expected fire behavior. The forest types include yellow pine (YP) dominated stands, with ponderosa pine, Jeffrey pine, or Coulter pine as the dominant tree species. The red fir (RF) group consisted of short needle conifers dominated by red fir. The mixed conifer (MC) group included the remainder of plots where two or more conifer species share dominance.

All plots were sampled prior to treatment (P00), then 1 yr post (P01), 2 to 3 yr post (P02), 4 to 5 yr-post (P05), 7 to 8 yr post (P08), and 10 yr post-treatment (P10) as possible (Table 1). Some plots do not have data for all post-treatment intervals because not enough time had passed since treatment, the plot was subsequently re-treated or burned in a wildfire, or the interval fell within a two year period (2007 and 2008) where no sampling occurred due to a lack of funding. Plots were re-read post-treatment using the same sampling protocol as the pre-treatment establishment. In 2012, tree data was collected for the first time in "fuels" plots which were all P08 to better fill out desired data metrics.

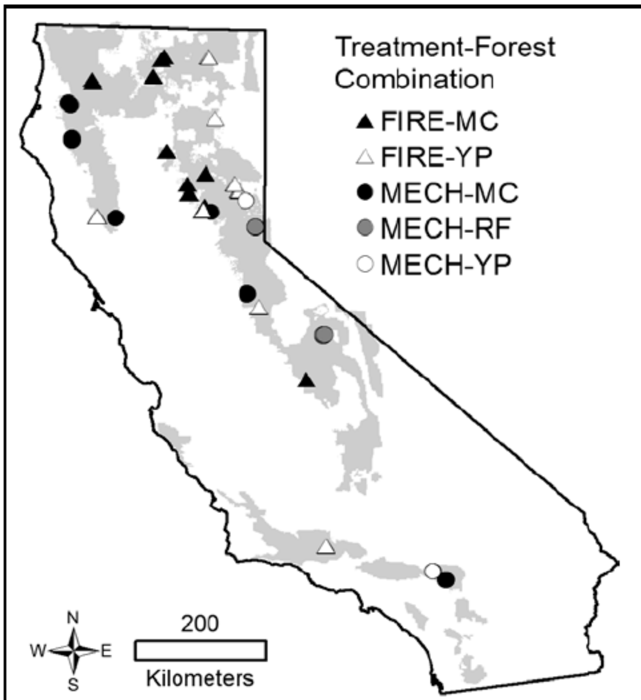

Figure 1. Location of all plots depicting treatment-forest combinations with National Forest lands shown. FIRE – fire-only treatment, MECH – mechanical treatment, MC – mixed conifer forest, YP – yellow pine dominated forest, RF – red fir dominated forest

Table 1. Number of plots and fuel treatment sites by treatment-forest type for each time period. Sites can exceed the 28 visited because some contained more than one forest type.

Treatment-forest type	P00		P01		P02		P05		P08		P10	
	Plots	Sites	Plots	Sites	Plots	Sites	Plots	Sites	Plots	Sites	Plots	Sites
FIRE-MC	25	11	24	10	25	11	4	3	18	8	6	3
FIRE-YP	22	9	20	9	18	8	8	4	11	6	7	3
MECH-MC	24	8	24	8	19	7	19	7	17	8	2	1
MECH-YP	6	3	6	3	6	3	5	3	6	3	0	0
MECH-RF	11	2	11	2	10	2	2	1	5	2	0	0

Objective 1a) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior* *by measuring effects of treatments on canopy characteristics and surface fuel loads over time*

The Fire and Fuels Extension (FFE-FVS, Reinhardt and Crookston 2003, Rebain 2010) for the Forest Vegetation Simulator (FVS, Crookston and Dixon 2005) was used to calculate tree density, quadratic mean diameter, canopy height, canopy base height, canopy cover, and canopy bulk density for pole and overstory trees, as well as for seedlings ≥ 1.8 m tall. The FFE-FVS uses geographically derived equations called "variants" to model tree growth and fuel accumulation and decomposition over time. The plots are within four variants: Western Sierras, Southern Oregon/Northeast California, Klamath Mountains, and Inland California/Southern Cascades. Surface fuel and forest floor loads were calculated from field data with coefficients specific to the Sierra Nevada range (van Wagtendonk et al. 1996, van Wagtendonk et al. 1998). Live herbaceous plant and shrub biomass and was calculated using the FIREMON methodology and bulk density values (Lutes et al. 2006). Biomass from live tree branches and foliage of seedlings < 1.8 m tall was calculated in FFE-FVS, and then included with the live understory vegetation.

Objective 1b) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior* *by modeling potential fire behavior with custom fuel models*

Custom fuel models were used as inputs to model fire behavior to evaluate fuel treatment effectiveness and longevity using Nexus 2.0 (Scott 1999, Scott and Reinhardt 2001). The results from the calculations for fuel biomass and canopy metrics in FFE-FVS described above (Obj. 1a) were used as input values to create custom fuel models. We chose to produce custom fuel models rather than assign standard ones after evaluating the uncertainty associated with custom fuels (see Obj. 2) and generally finding that they predict similar trends in fire behavior as standard fuel models but more adequately capture the variability of fire behavior from changes in fuel loading. Candidate RAWS (weather stations), provided by the fuels staff on each Forest, were used to determine 90th percentile fuel moistures and wind gust speeds. Two simulations were run: 1) surface fire only for all plots; and 2) with crown fire enabled for detailed plots.

Objective 2) *Quantify the uncertainty associated with the use of standard and custom fuel models*

A subset of the FIRE plots was used to address this objective. The FFE-FVS was used to model fire behavior using both standard and custom fuel models. To assign standard fuel models from fuel loads, the FFE-FVS model first narrows the selection of fuel models based on fuel and climate type and then compares fuel bed characteristics (fine fuel load, characteristic surface area to volume, bulk density) to standard fuel models. The standard fuel model that is least different is chosen. To create custom fuel models, the FFE-FVS uses the fuel loads input by the user with modeled loads for live vegetation and weights the contribution of live and dead fuel loading to represent bulk density and fuel bed depth (Rebain 2010). The result are custom fuel models that include fuel load by size class and category; live woody and live herbaceous loading; surface area to volume; fuel bed depth; dead fuel moisture of extinction; and heat content of live and dead fuels. The standard default values were used for custom fuel modeling for surface area to volume, mineral content, and fuel particle density. Potential fire behavior was simulated in FFE-FVS using fuel moisture and wind speeds (maximum 1-minute wind speed and maximum momentary wind gust speed) observed historically during large wildland fire events close to each fuel treatment project. Surface fire flame length and type of fire was simulated for each plot.

Objective 3) *Assess prescribed fire effects on carbon stocks and validate modeled outputs*

A subset of the FIRE plots was used to address this objective. The FFE-FVS was used to calculate carbon stocks for all time periods for: aboveground live tree carbon, standing dead carbon, belowground carbon (live and dead coarse roots), dead down wood, forest floor, and herbs and shrubs (Rebain 2010, Hoover and Rebain 2011). Biomass values for dead down wood and forest floor were calculated outside of the program using methods outline above (Obj. 1a) and multiplied by the appropriate factor to determine the carbon stocks (Penman et al. 2003, Smith and Heath 2002). Herb and shrub biomass was calculated from the field data as described above (Obj. 1a), and then divided in half to determine carbon stocks matching FFE-FVS methods. The FFE-FVS was also used to predict carbon emissions from a simulated wildfire for all time periods to compare net carbon changes from treatment followed by reduced wildfire emissions to P00. The FFE-FVS was used to project carbon stocks into the future using the P00 data, applying a prescribed fire treatment to each plot, and then grown forward through P08 to match the field data. No further controls on fuel accumulation and decomposition or snag changes were used, allowing the program to control these factors. Simulated values for P01, P02, and P08 were then compared to field-derived estimates.

Key findings

Objective 1a) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior* *<u>by measuring effects of treatments on canopy characteristics and surface fuel loads over time</u>*

Fire-induced delayed mortality contributes to slight decreases in canopy cover and canopy bulk density over time. In order to fully understand the impact of FIRE treatments on tree mortality, monitoring needs to extend beyond the first year or two after the burn. We found trees continued to die and fall over through the P10 read at some of our sites (Fig. 2). van Mantgem et al. (2011) had similar findings of delayed mortality elsewhere in the Sierra Nevada as a result of prescribed fire six years after treatment.

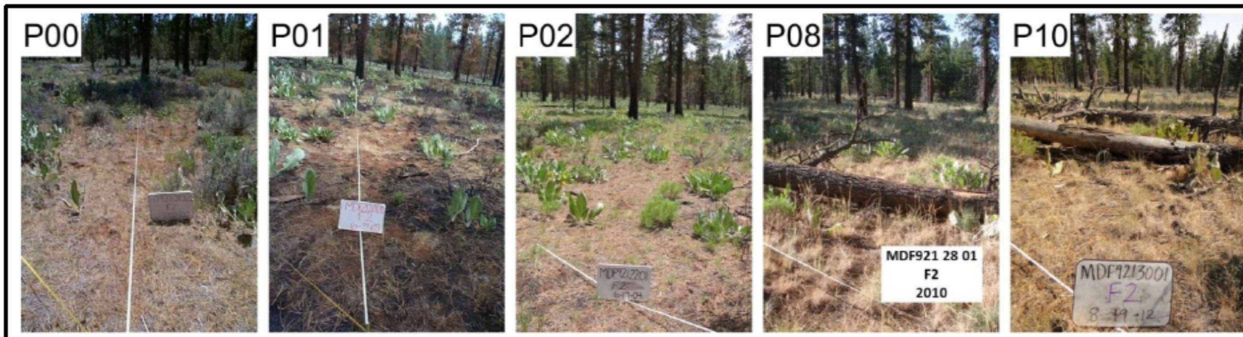

Figure 2.Time series of photos from one of the prescribed fire plots on the Modoc National Forest showing the delayed mortality and falling of large Jeffrey pine trees after treatment.

A great deal of spatial and temporal variability in fuel loads between and within treatment-forest combinations were found. Our dataset indicated large variability; the lack of clear fuel reduction or accumulation trends were apparent in our time series for a few fire-only and most mechanical treatment metrics (Fig. 3). The inconsistent trends are common given the spatial variability in surface fuels, and the overall variability within one project area and across similar treatment and forest types (Keane et al. 2012). Chiono et al. (2012) also did not find temporally consistent trends but rather even more variability where the post 5 to 7 yr period was often higher or more typically lower than prior and latter sampling periods. A large part of our temporal variability had to do with uneven sample sizes; both P05 and P10 have a very low number of plots (see Table 1).

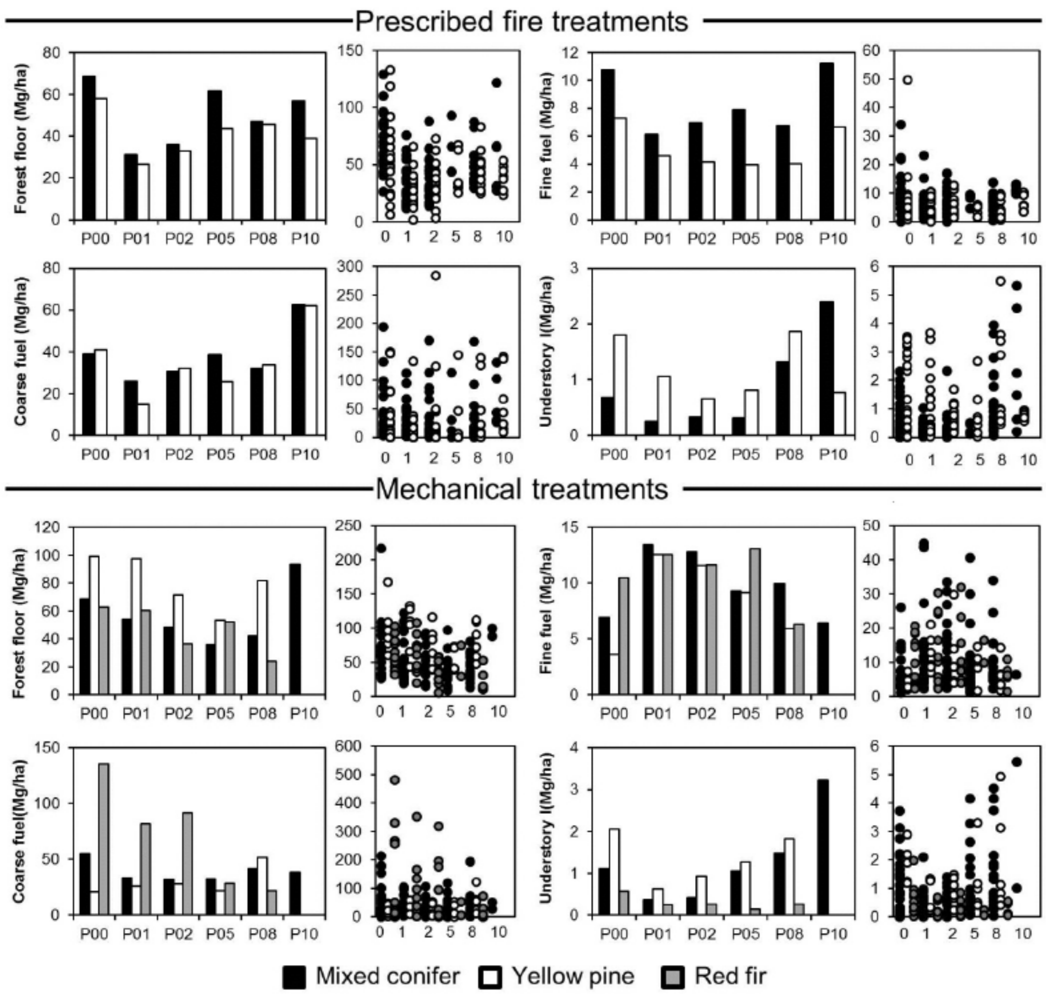

Figure 3. Fuel loads for different classes for FIRE (upper) and MECH (lower) treatments by forest type and time period. For each panel the chart on the left is the mean value, and the chart on the right is the value for each plot. Only 2 plots are available for the MECH treated fuels P10, leading to non-uniform trends.

With the exception of MECH-RF, understory live fuel load exceeded P00 levels by P08 if not sooner in FIRE and MECH treatments. Live understory fuel load recovered to or exceeded that of P00 for the MC and YP forest types regardless of treatment type by P08 which could lead to higher fire hazard in later years as these shrubs become more decadent (Fig. 3). The composition of the understory vegetation (proportion of dead versus live material and ignitability), and height will both impact potential fire behavior. Although using a different method of quantifying potential ladder fuels, Chiono et al. (2012) found shrub cover in treated stands to exceeded non-treated controls 2 to 4 yr after treatment in both Jeffrey pine and mixed conifer stands. Small sample size, results in the P10 decrease in FIRE-YP (see the right hand panel in Fig. 3).

MECH treatment removed trees of all size classes whereas FIRE treatment primarily impacted smaller diameter trees. MECH treatments reduced tree density greater than FIRE treatments in most size classes (Fig. 4). MECH treatments removed trees of all size classes, and the reductions were fairly stable over time. FIRE treatment reduced both seedling and pole-sized trees but did not impact overstory tree density much between P00 and P01. Overstory density decreased through P05 as a result of delayed mortality for both forest types, but for P08 and P10 the trends were different for MC and YP overstory trees treated with FIRE. Seedling recruitment spiked P02 in FIRE treatment but then decreased.

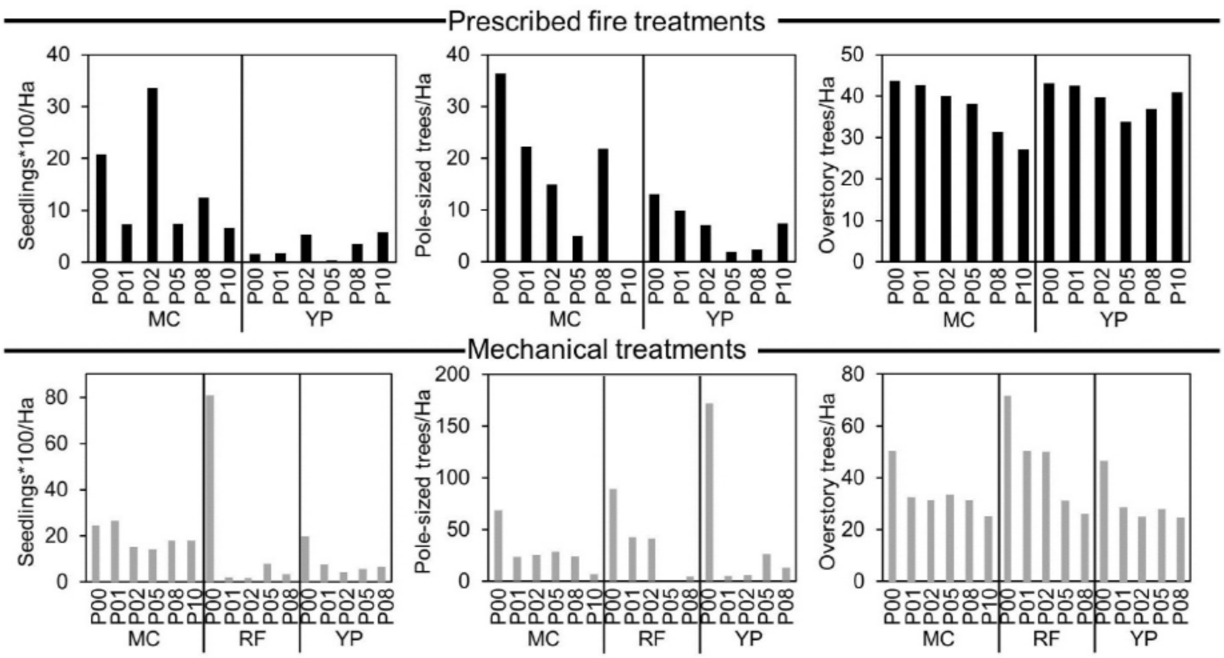

Figure 4. Seedling, pole-sized, and overstory tree density for FIRE (upper) and MECH (lower) treatments by forest type and time period. Only 2 plots are available for the MECH treated fuels P10, leading to non-uniform trends.

Canopy characteristics were affected more by MECH treatments than FIRE treatments. As with the surface fuels, a large part of our temporal variability had to do with uneven sample sizes; for instance, both P05 and P10 have a very low number of plots (see Table 1). Mechanical treatment effects on stand structure remains fairly consistent overtime with the exception of low sample years (P05 and P10, Fig. 4 and 5). In general, CC, CBD, and tree density were reduced; CBH and QMD increased. Canopy height was reduced for MC and YP forest types, and increased for RF. A similar trend existed for the influence of FIRE on CBD and tree density. Both CBH and QMD increased as a result of fire but the trend was not consistent. It is likely that the continued changes over time to the canopy characteristics are partially attributed to delayed mortality from FIRE.

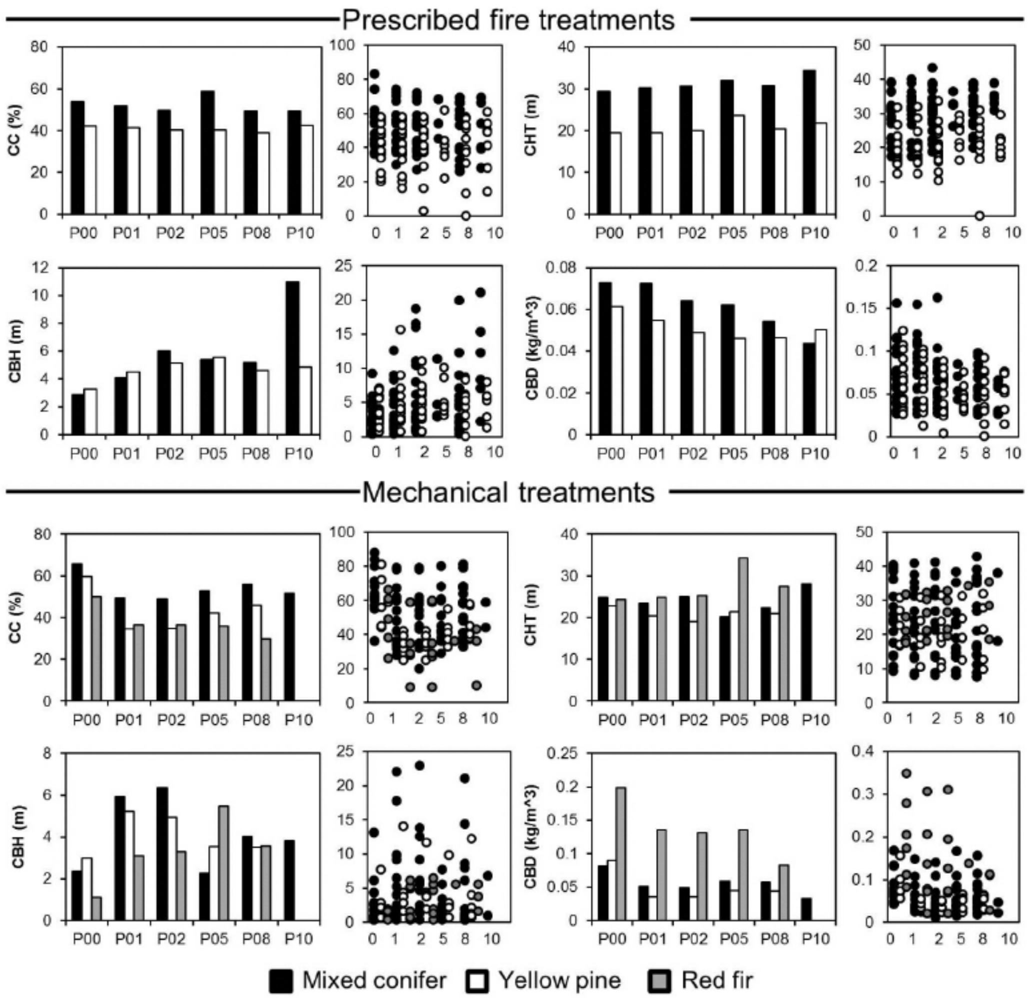

Figure 5. Canopy cover (CC), canopy height (CHT), canopy base height (CBH), and canopy bulk density (CBD) for FIRE (upper) and MECH (lower) treatments by forest type and time period. For each panel the chart on the left is the mean value, and the chart on the right is the value for each plot. Only 2 plots are available for the MECH treated fuels P10, leading to non-uniform trends.

For both treatment types CBH decreases in later years, but it remains higher than P00. Canopy base height increases from treatment (P01) then continues to increase through P02 for all treatment-forest combinations (Fig. 5). This increase then declines for P05, P08 and P10 except for FIRE-MC where P10 CBH is extremely high. This peak can again be explained by the small sample size in P10. The fact that CBH is continuing to decrease could have implications for crown fire activity; if CBH is low enough, the stands have a potential for increased passive crown fire in later years relative to P01 and P02. Chiono et al. (2012) found similar increase followed by a decrease in CBH in Jeffrey pine stands, however, the decline did not start until more than 8 yr after treatment. Stephens et al. (2012) had similar findings as Chiono et al. (2012) in stands treated mechanically.

Objective 1b) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior* *<u>by modeling potential fire behavior with custom fuel models</u>*

MECH treatments showed variable and minimal effects on surface fire flame length over time; however the incidence of active crown fire was about halved from treatment for the duration. Because the P10 sample size is so small (n=2) the results are not discussed for any trends (Fig. 6). Total fuel load (sum of litter, 1-hr, 10-hr, 100-hr, and live fuels used for building the custom fuel models) show slight increase from treatment (P01), reflecting an increase in the 10-hr and 100-hr fuel loads, and the range of MECH treatments. Total fuel load continues to slowly increase over time, but results are variable. Surface fire flame lengths slightly decrease in P01 relative to P00 likely reflecting the slight decrease of litter loading post-treatment and do not exceed P00 until P08. We found initial increases in canopy base height starting to decrease by P05, likely due to recruitment of smaller soft and hardwood trees. The incidence of potential passive crown fire follows the same trend. The decrease in canopy bulk density post-treatment is still found P08, resulting in reduced active crown fire potential for P01 through P08.

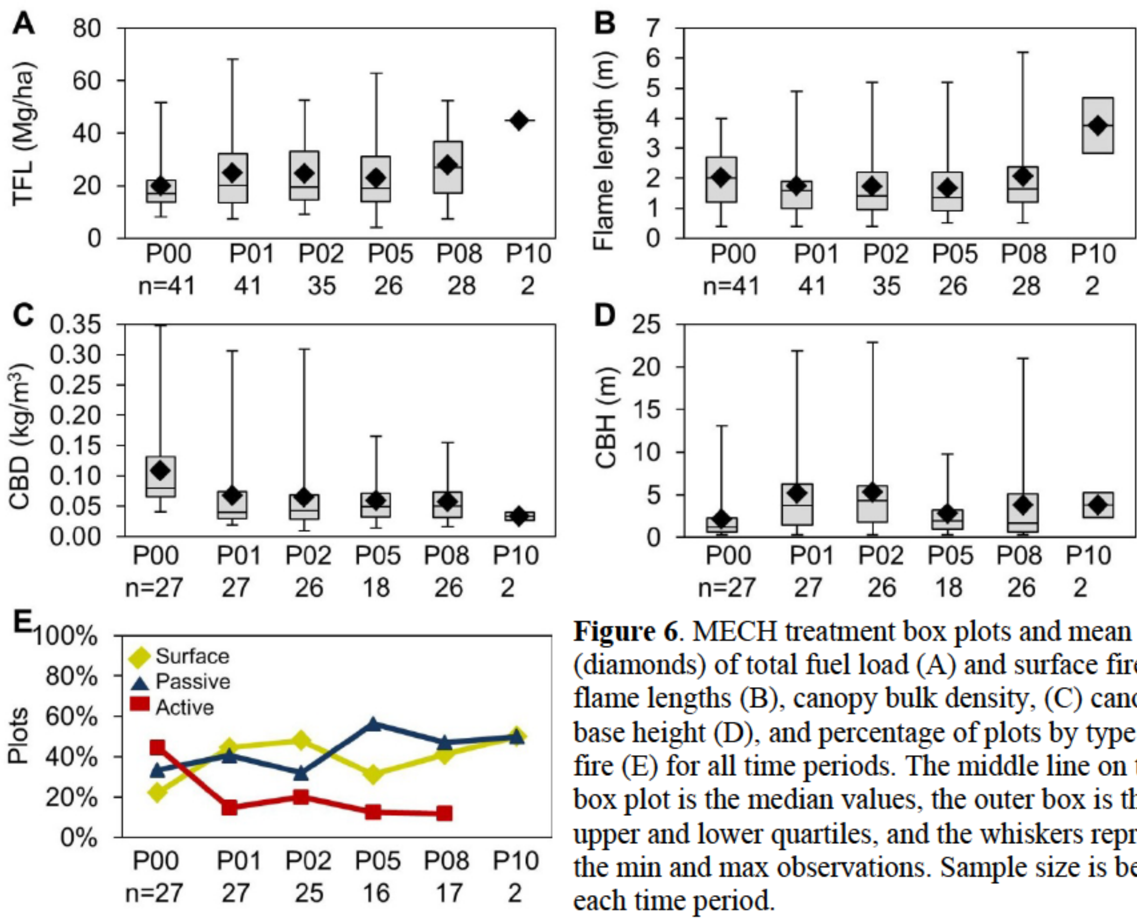

Figure 6. MECH treatment box plots and mean value (diamonds) of total fuel load (A) and surface fire flame lengths (B), canopy bulk density, (C) canopy base height (D), and percentage of plots by type of fire (E) for all time periods. The middle line on the box plot is the median values, the outer box is the upper and lower quartiles, and the whiskers represent the min and max observations. Sample size is below each time period.

Total fuel load and surface fire flame lengths were initially reduced as a result of FIRE treatments, but by P10 they exceeded the P00 levels. Initial reductions in potential crown fire returned P00 levels by P08; passive crown fire remained reduced relative to P00 for the duration for FIRE treatments. We found total fuel loads sharply decline P01 as a result of the FIRE treatment, and start to increase between P05 and P08 treatment, exceeding pre-treatment levels P10 (Fig. 7). The initial decrease in surface fire flame lengths from treatment P01 and P02 started to increase around P05. By P08 the surface fire flame lengths matched P00 and exceeded P00 by P10. In contrast, by 7 yr after treatment Stephens et al. (2012) found flame lengths continued to decline from fire-only treatments when standard fuel models were used to model potential fire behavior rather than custom fuel models. We found initial decrease in passive crown fire as a result of increased canopy base height from treatment (P01 and P02) until about P05 to P08 when canopy base height slightly declines and surface fuel loads also increase (Fig. 6). The trend toward more surface and less active and passive crown fire continues for P10. Given the small sample size for P05 and P10, the interpretation of these results is variable and caution must be applied when interpreting the longevity of prescribed fire treatments for these time periods.

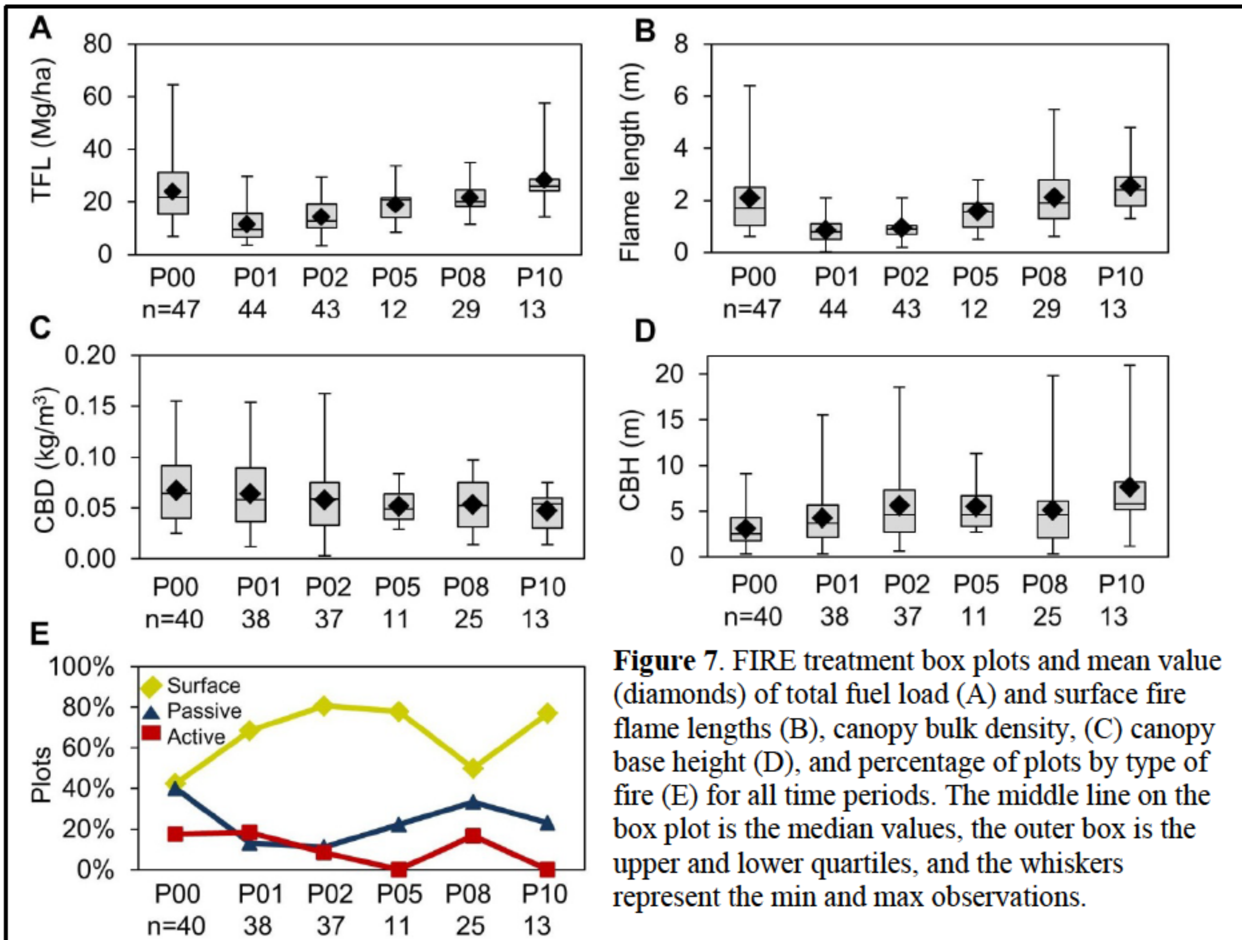

Figure 7. FIRE treatment box plots and mean value (diamonds) of total fuel load (A) and surface fire flame lengths (B), canopy bulk density, (C) canopy base height (D), and percentage of plots by type of fire (E) for all time periods. The middle line on the box plot is the median values, the outer box is the upper and lower quartiles, and the whiskers represent the min and max observations.

Objective 2) *Quantify the uncertainty associated with the use of standard and custom fuel models*

Predicted fire behavior from custom versus standard fuel models was similar, with similar trends through time. We generally found good agreement between modeled fire behavior using custom and standard fuel models with the methods presented in this analysis. Mean predicted surface fire flame length was higher for standard fuel models than custom fuel models for post-treatment time periods until P08 (Fig. 8). Although modeled surface fire flame lengths were variable for both fuel model types, the greatest variability in was seen from custom fuel models in P00, reflecting the pre-treatment variability in fine fuels. In addition, users that apply their own surface area to volume ratios or calculated values for bulk density for custom fuel models may find that their results will have greater variability than results shown here.

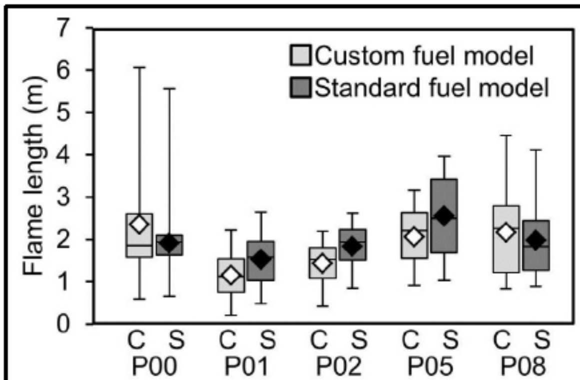

Figure 8. Predicted surface fire flame lengths modeled with maximum momentary gust speed for all time periods for standard fuel models (S) and custom fuel models (C). Mean value (diamond), and box plots where the middle line on the box plot is the median values, the outer box is the upper and lower quartiles, and the whiskers represent the min and max observations.

Predicted fire type (surface or crown) is very similar using either custom or standard fuel models for all time periods. Regardless of the type of fuel models used, prescribed fire treatments reduced the potential for crown fire behavior (passive, conditional, and active, Fig. 9). For all time periods except P08, there was only a one plot difference in the prediction of crown fire. By P08 the difference was larger, although still only a 4 plot difference, with custom fuel models having a higher crown fire hazard. The initial reduction in predicted crown fire from treatment is consistent with most studies (i.e., Stephens and Moghaddas 2005, McIver et al. 2012), and the prolonged reduction is also seen in Stephens et al. (2012).

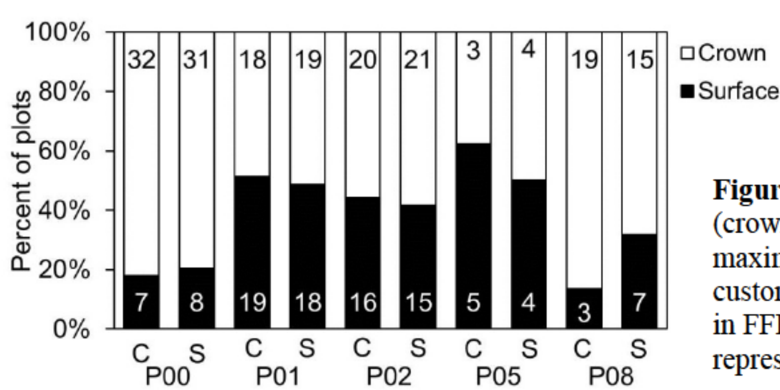

Figure 9. Predicted percent of type of fire (crown or surface) modeled with maximum momentary gust speed for custom (C) and standard (S) fuel models in FFE-FVS. The numbers in each bar represent the sample size.

Modeled live fuel loads generated from FFE-FVS did not match field-derived values. The field-derived live fuel load is typically higher than the FFE-FVS-derived load (Fig. 10). At this time a known weakness of FFE-FVS for fire behavior modeling is the lack of the ability to input live fuel loads (Rebain 2010). Rather FFE-FVS uses the location information and tree list data to estimate the loading. Interestingly, over 30% of the standard fuel models selected to represented P01 and P02 fuel loads have live fuels represented; they are a shrub (SH), grass-shrub (GS) or grass (GR) fuel model, whereas field derived values for live loads on average were less than 1 Mg/ha for those time periods (Fig. 9). Five years after treatment, no more than 15% of selected standard fuel models have live loading represented; mostly timber litter (TL) and slash-blowdown (SB) models were chosen, even though the field-derived values for live fuels start to increase. When live fuels are present in higher proportions for the later time periods, the standard fuel models that were selected by FFE-FVS did not represent these fuel strata very adequately. Users that have plots with a considerable portion of live fuel loading should apply the fuel model logic in FFE-FVS with caution; understanding the limitations of using modeled live fuel loads for custom fuel modeling.

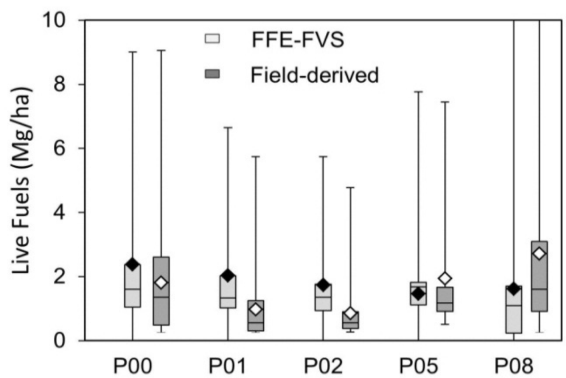

Figure 10. FFE-FVS-derived and field-derived live fuel loads before and after treatment. Mean value (diamond), and box plots where the middle line on the box plot is the median values, the outer box is the upper and lower quartiles, and the whiskers represent the min and max observations.

Objective 3) *Assess prescribed fire effects on carbon stocks and validate modeled outputs*

By P08 most carbon pools exceeded both the P01 and P02 stocks, and total stand carbon returned to almost 97% of the P00 level. Our carbon recovery was primarily due to increases in the tree and snag stocks; surface fuels and forest floor also increased over time (Table 2). We found that the year following the prescribed fire treatment (P01), modeled wildfire emissions were reduced to about half of the P00 emissions. However, for P01and P02, the combined carbon sources from both the FIRE treatment and a modeled wildfire exceed the emissions from a modeled wildfire without treatment (P00). By P08, enough carbon recovered in the stands and the modeled wildfire emissions were still reduced from treatment, creating a carbon sink relative to P00. The gain we found in such a short time period is promising for forest managers in forest types similar to our research area who apply FIRE treatments.

Table 2. Mean (SE) values of field-derived carbon stocks for various pools.

Carbon pool	P00	P01	P02	P08
	--Mg/ha---------------------------------			
Total stand carbon	204.0(21.1)	177.9(21.2)	181.8(20.7)	197.1(22.2)
Trees	123.0(15.5)	120.9(15.5)	117.8(15.4)	127.1(17.0)
Snags	2.0(0.8)	2.5(0.7)	4.8(1.2)	4.7(1.3)
Herbs and shrubs	0.7(0.1)	0.4(0.1)	0.3(0.1)	0.8(0.1)
Surface fuels	26.0 (5.2)	15.7(3.8)	18.5(4.5)	19.0(4.3)
Forest floor	24.8(2.2)	11.1(1.3)	12.0(1.2)	16.4(1.1)
Belowground live	27.2(3.4)	26.2(3.2)	27.9(3.5)	27.6(3.6)
Belowground dead	1.3(0.6)	1.2(0.4)	1.8(0.4)	1.6(0.4)
Wildfire emissions	34.7(3.6)	19.0(2.4)	20.5(2.4)	23.0(2.0)

Although the mean total carbon differences between field-derived and simulated carbon stocks were minimal (2%), the variability within different carbon pools was large (up to 212%). Compared to field-derived values, FFE-FVS over predicted mean carbon stocks for snag, herbs and shrubs, forest floor, and belowground dead, and under predicted tree, surface fuels, and belowground live carbon stocks (Fig. 11). High correlation was found between the field-derived and simulated values for the total, tree, and belowground live carbon pools. The herb and shrub data showed a great deal of variation and little correlation between field-derived and simulated values, which are expected because FFE-FVS does not include this as an input. Many field plots had no snags, however simulated snags were rarely zero which accounts for the over prediction of both snag and belowground dead carbon. The scatter seen in the forest floor and surface fuels carbon pools highlight the variability found in the field.

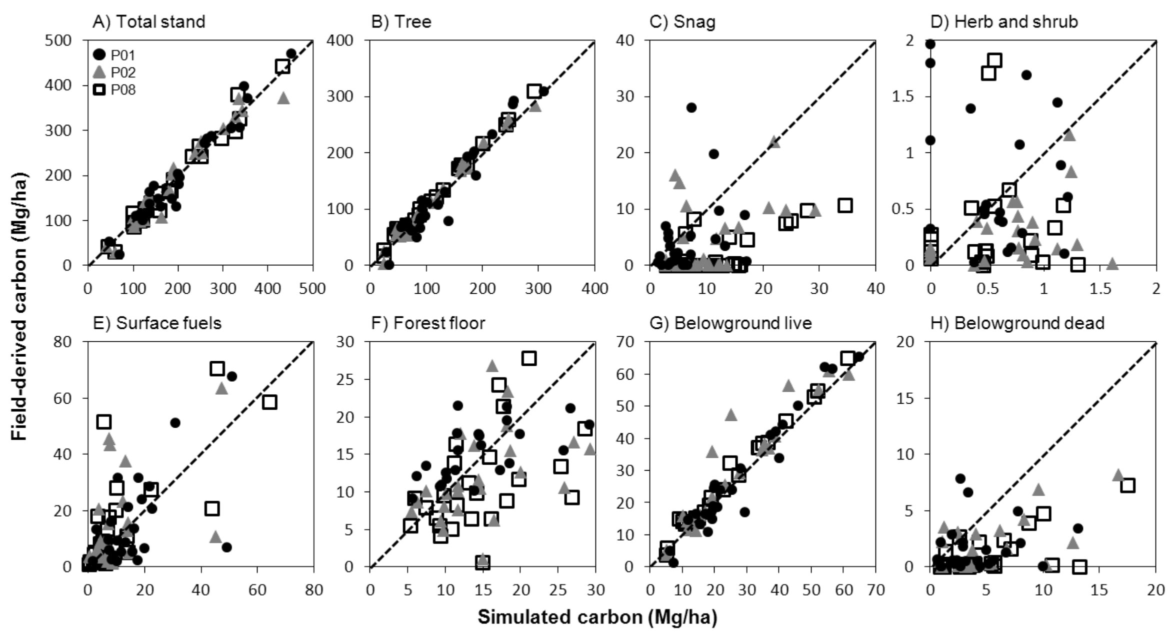

Figure 11. Field-derived carbon stocks versus simulated carbon stocks (Mg/ha) for P01, P02, and P08 for total stand (A), tree (B), snag (C), herb and shrub (D), surface fuels (E), forest floor (F), belowground live (G), and belowground dead (H) pools.

Management implications

Need for more long term monitoring

More monitoring of fuel treatment effects is needed before and after treatment to better understand how fuels accumulate and forest structure changes over time (i.e., Evans et al. 2011, van Mantgem et al. 2011). Cohesive monitoring does not exist across most federal agencies managing forest structure and fuel loading. Monitoring needs are high, especially to determine treatment effectiveness over time. Given the variability we found between our plots, larger sample sizes would also aid in more effective documentation of post-treatment trends. Below are some suggestions from our lessons learned during the Fuel Treatment Effectiveness and Effects Monitoring in the Pacific Southwest Region and JFSP projects:

Plot and transect relocation: Every visit verify driving directions and update as needed. For the plots: 1) make a map noting rebar locations, 2) bring GPS coordinates, and 3) bring data and photos to help locate plots and rebar within.

Plot type: Having two plot types (detailed and fuels) was initially faster and covered more project area spatially. The fuels plots which were lacking tree data lowered our sample size for canopy characteristic comparisons, and hindered our ability to fully model fire behavior in those plots. To remedy this, tree data was collected on all plot types towards the end of the project.

Trees: To help improve tree measurement accuracy and consistency: 1) always bring previous years data, and 2) emphasize appropriate sampling techniques. At the end of the field season input and validate all data and check for species changes and anomalies for growth and changes in status.

Litter and Duff: We recommend measuring them together as 'forest floor' and assigning a percentage to each to minimize sample error. Refresh field crews on the difference between the layers.

Fuel bed depth: We found that it is imperative to refresh field crews annually on the true definition of fuel bed depth (from the bottom of the litter to the highest dead fuel particle).

Grass/herb: We recommend trying to visit plots at the peak of flowering for the majority of species to aid in identification of plants.

Photos: The photos will match through time better if the previous years' photos are in hand.

Objective 1a) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior* *<u>by measuring effects of treatments on canopy characteristics and surface fuel loads over time</u>*

The ability of a fuel treatment to maintain effectiveness in reducing fire behavior and effects depends on the accumulation rates and distribution of fuels, which are used as metrics to judge treatment longevity. Surface and understory fuel loading trends help inform managers' initial treatment and maintenance timelines, priorities, and adaptive management prescriptions. FIRE treatments showed reduced fuel loads, followed by increases accumulating back to about 75% of pre-treatment levels by P08 and matching P00 levels through P10; indicating potential need for re-treatment. This hazard might be offset by some changes in the canopy characteristics (see below). MECH treatments initially increased fine fuel loads (1- to 100-hr) and decreased other categories (forest floor, 1000-hr, live understory), then loading continued to increase through P08, but trends over time were mixed. This is partially due to sample sizes and grouping all mechanical treatments together. MECH usually did not impact the P00 surface fine fuel loads, such as litter loading, amendable to fire spread. MECH treatments would benefit from broadcast/prescribed fire follow-up or secondary treatments to reduce the elevated surface fuel loads.

Stand and canopy structure trends help inform both fuel and silviculture integrated objectives and prioritizations. FIRE treatments generally had minimal impacts on canopy metrics. The biggest changes were increased CBH and reduced smaller diameter tree density relative to P00 through P10. MECH treatments had a larger impact on canopy metrics than FIRE treatments, and the changes were fairly stable over time. Both treatment types created positive stand structure changes through reductions in seedling and pole size trees through P08 resulting in positive increases in CBH and overall reductions in tree density and CBD.

Despite extensive variability between plots, overall trends for treatment-forest combinations exist. Variability was minimized by grouping data by treatment type and dominant forest type, especially with the FIRE treatments. Live understory fuels exceeded the P01 levels by P08 and indicate potential need for retreatment (except in RF plots). CBH returned to lower levels again through P08 (except MECH-RF in P08 had different trends, potentially due to low sample size). When adding up our results, they seem to be to be in alignment with past studies that concluded that most effective treatments alter both canopy fuels and surface fuels, creating a more resilient forest structure to high severity wildfire by reducing surface and ladder fuels, raising the height to the live crown base, and decreasing the crown bulk density. For example, FIRE treatments reduced total fuel loads and therefore flame lengths but had limited changes to canopy fuels, and MECH treatments effects on surface and understory loading were variable, but affected stand structure in a positive way with a reduction in CBD and increase in CBH resulting in reduced crown fire potential.

Objective 1b) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior* *<u>by modeling potential fire behavior with custom fuel models</u>*

Changes to modeled surface fire after FIRE treatment included an initial decrease in surface fire flame lengths, then an increase starting around P05. Surface fire flame lengths match P00 flame lengths by P08 and exceed them by P10. Modeled crown fire found an initial decrease in passive crown fire until P05 to P08, when the proportion of passive and active crown fire start to increase, but not to P00 levels. The P05 and P10 treatment time sequence made up the smallest sample sizes, so conclusions are cautiously implied for longevity for these time periods. However, the increase in surface fire flame length and increase in proportion of crown fire indicate that treatment longevity might be less than 10 yr from FIRE treatments in our study area.

Overall, modeled fire behavior in MECH treatments showed that goals of reduced fire behavior were initially reached, then began diminishing around P05 to P08, with some positive changes still apparent through P08. MECH treatments reduced modeled surface fire flame lengths P01 and do not exceed P00 flame lengths until P08, but results are variable. Modeled crown fire was decreased P01 with a continued trend of less active crown fire through P08. The MECH treatments effectively reduced CBD and increased CBH which continued to reduce the potential for crown fire hazard through P08. However, the increasing total fuel loads and therefore surface fire flame lengths indicate that MECH treatments would benefit from broadcast/prescribed fire follow-up or secondary treatments to reduce the elevated surface fuel loads.

Objective 2) *Quantify the uncertainty associated with the use of standard and custom fuel models*

In general, predicted fire behavior from custom versus standard fuel models was similar. Both custom and standard fuel models resulted in similar enough output to suggest that both are adequate options to evaluate fuel treatment effectiveness. However, custom fuel models were able to represent fine fuel loading associated with FIRE treatments and the accumulation of fine fuels after treatment better than standard fuel models. Using FFE-FVS for custom fuel modeling is a viable approach for managers with measured fuel loads, but the FFE-FVS is less reliable for areas with considerable live fuels.

Objective 3) *Assess prescribed fire effects on carbon stocks and validate modeled outputs*

Prescribed fire treatments reduced total stand carbon by about 13%, and total stand carbon stocks returned to 97% of P00 levels after P08. The combined carbon recovery and reduced wildfire emissions allowed the initial carbon source from wildfire and treatment to become a sink by P08 relative to P00. The gain we found in such a short time period is promising for managers in forest types similar to our research area who apply prescribed fire treatments. However, it should be noted our carbon accounting did not include soil carbon, vehicles, smoke, or ash deposits.

Although the total stand carbon differences between field-derived and FFE-FVS simulated carbon stocks are minimal, the variability within different carbon pools varied greatly. If total carbon accounting from FFE-FVS is used the model predictions are very close to those seen in the field. However, caution must be used if values from the individual carbon pools are reported because FFE-FVS over and underestimates the individual pools by up to 212%.

Relationship to other recent findings and ongoing work

Objective 1a) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior <u>by measuring effects of treatments on canopy characteristics and surface fuel loads over time</u>*

Few studies have quantified the effect of fuel treatments on canopy characteristics and surface fuels beyond the first couple of years after. Keifer et al. (2006) reported forest floor and surface fuel loads before and up to 31 yr after prescribed fires in Yosemite and Sequoia and Kings Canyon National Parks, in multiple forest types. Chiono et al. (2012) retrospectively sampled fuel loads and canopy characteristics in mixed conifer and Jeffrey stands of the Sierra Nevada treated with mechanical mean for multiple post-treatment periods. Stephens et al. (2012b) reported fuel loads and canopy characteristics from Sierra Nevadan mixed conifer stands treated with fire, mechanical means, or a combination stands prior to, 1 yr, and 7 yr after treatment.

Fire-only treatments showed total fuel load (litter, duff, and coarse woody debris) reductions were more drastic (85 to 99%) in Keifer et al. (2006), than FIRE sites (46 to 53%) in this study. We believe because our initial reductions were not as extreme, our total fuel load recovered to a higher percentage of pre-treatment values sooner (8 yr vs. 10 yr) than Kiefer et al. (2006). Like Chiono et al. (2012), inconsistencies in fuel accumulation trends over time was apparent in our study for both FIRE and MECH (most metrics). Non-uniform trends over time were apparent in stand metrics for Chiono et al. (2012), as are common with the MECH, but not FIRE treatments in this study. Continued reductions for tree density and CBD and increases for CBH from FIRE treatment, through P08 and 7 yr post were similar between Stephens et al. (2012b) and our work. Not surprisingly, within mechanical treatments initial declines in tree density were maintained in both studies through later site visits. Stephens et al (2012b) found initial reductions in forest floor and surface fuel loads from fire-only treatments started to recover 7 yr after treatment; although less than about 50% of pre-treatment. For our FIRE-MC sites, we had greater recovery, 72% of pre-treatment, of the forest floor and surface fuels by P08. Fine fuels were increased as a result of mechanical treatments relative to pre-treatment 1 yr after treatment for both studies, but Stephens et al. (2012) declined by 7 yr post-treatment, where we found MECH-MC continued to increase.

Objective 1b) *Determine the length of time that fuel treatments are effective at maintaining goals of reduced fire behavior* <u>*by modeling potential fire behavior with custom fuel models*</u>

Very few studies have modeled the effectiveness of fuel treatments using empirical data beyond the first couple of years after treatment. The only study from a similar vegetation type that included both mechanical and prescribed fire treatments is Stephens et al. (2012b); however, the fire simulations use standard fuel models and are specific to one location in the Sierra Nevada Mountains. To our knowledge this is the first body of work to used custom fuel models from field-derived metrics to model potential fire behavior before and through 10 yr after treatment.

Objective 2) *Quantify the uncertainty associated with the use of standard and custom fuel models*

Cruz and Alexander (2010) suggested that error is introduced when predicting crown fire with the use of un-calibrated custom fuel models. This study applied uncalibrated custom fuel models to evaluate fuel treatment effectiveness. We addressed the limitations described in the Cruz and Alexander (2010) critique of U.S. fire behavior modeling systems in a number of ways. First, we simulated only surface fire behavior and reported only *surface* fire flame lengths in order to remove the effect of using a different algorithm tied to crown fire behavior to predict crown fire flame lengths (Thomas 1963). Subsequently, only surface fire flame lengths derived from a well-established fire model (Byram 1959) were compared to assess fuel treatment effectiveness over time. Secondly, we acknowledged the limitations of using custom fuel models and compared them to predicted fire behavior as a result of one of the standard 53 fuel models. We found that trends with predicted fire behavior, regardless of using uncalibrated custom or standard fuel models were similar enough that either method would be appropriate as long as the assumptions and limitations were fully disclosed. Last, we acknowledge that there are some well known limitations with the current fire behavior models especially for crown fire, but until another model is created based on sound physics of fire combustion and transfer (Finney et al. 2012), the current operational fire models in the U.S. (i.e., Rothermel 1972, 1991, Scott and Reinhardt 2001, Van Wagner 1977) are the 'best available science' to do these types of fuel treatment effectiveness evaluations.

Objective 3) *Assess prescribed fire effects on carbon stocks and validate modeled outputs*

To date, three studies have quantified the effect of fuel treatments on carbon stocks beyond the first couple of years using empirical data (Boerner et al. 2008, Hurteau and North 2010, Hurteau et al. 2011). Boerner et al. (2008) conducted a meta-analysis of 12 study sites before and up to 4 yr after treatment across the US that were treated with fire, mechanical means, or a combination. Hurteau and North (2010) reported immediate and 7 yr post-treatment changes to carbon within trees, snags, and shrubs in a California mixed conifer forest. Hurteau et al. (2011) reported carbon stocks before and 5- to 6 yr after combined thinning and prescribed burn treatments were conducted in ponderosa pine dominated stands in Arizona. One commonality among the results, which our data also supported, was that carbon removed from less intense fuel treatments, like prescribed fires, that impact primarily surface fuels, recovers faster.

No direct comparisons between field-derived and FFE-FVS simulated carbon stocks have been completed. However, Hummel et al. (2012) completed an assessment of the accuracy of estimates made by the FFE-FVS predictions through comparisons between model outputs and measured post-fire conditions for a wildfire in Washington. They also completed a sensitivity analysis of model outputs to weather, disease, and fuel inputs.

Future work needed

Need for more long-term monitoring

Cohesive monitoring does not exist across most federal agencies managing forest structure and fuel loading (Hunter 2007), so monitoring needs are high, especially to determine treatment effectiveness over time.

- Continued monitoring of the sites involved in this study, and some additional sites would increase the sample sizes and time sequences. This would further help to assess fuel treatment effectiveness, longevity, implications of predicted fire behavior, appropriate fuel model choices, and changes to carbon stocks across large areas of California and areas with similar vegetation and/or fuel treatment methods. For example, the variability of the treatments that were grouped in the mechanical category in this study, after an increased sample size, should be sub-divided into more specific thinning and follow up surface fuel reduction groups that enable clearer findings and management implications.

- Although no set monitoring protocol is in place for the Collaborative Forest Landscape Restoration Program (CFLRP, Schultz et al. 2012), one could be adapted from this study to populate a nationwide dataset that could assess fuel treatment effectiveness on different spatial scales.

- Once established, the data needs to be archived and available to managers and researchers. We suggest the use of the FFI (FEAT/FIREMON Integrated) tool. The dataset from this study is available in FFI for future use and comparisons.

- Establishing plots that have both a mechanical and prescribed fire treatment, and monitoring these over time would help establish how a dual treatment approach changes potential fire behavior, fuel loads, and canopy characteristics over time.

Understanding the ecological impacts of fuel treatments

Very little research has been completed on the ecological impacts of fire and non-fire fuel treatment types. A better understanding of the effects on species diversity, regeneration and mortality, insects and pathogens, and wildlife is needed.

Modeling potential fire behavior to assess treatment effectiveness and longevity

True representation of the inherent variability of fuels and their response to a fuel treatment (or wildfire) are limited by using the 53 standard fuel models to characterize treated and untreated fuel loads and predicted fire behavior. A true sensitivity analysis evaluating how fuels are characterized would be beneficial. For instance, most often the ‘average’ is derived from field measured values to represent biomass on a plot-level, but averages rarely are what truly impact realistic fire behavior. Efforts to better capture the inherent variability of fuels, and modeling that variability to predicted fire behavior maybe more informative concerning thresholds of when fire transitions from surface to canopy.

- Creating and improving the tools available to use field-derived surface and understory fuels as inputs into fire simulation models are needed. For example, at the present time it is not possible to input live fuel loads in FFE-FVS, and no consistent way exists to sample, quantify, or model masticated or chipped materials.

- More empirical data is needed to compare modeled to actual fire behavior for prescribed or wildfire events (active wildfire season vs. cooler/wetter season burning) as related to fuel treatment effectiveness.

- Exploring the threshold with field-derived data between the benefits of fuel treatments that focus on surface fuel reduction, canopy fuels, or a combination and their effects on actual fire behavior (surface or crown fire changes) would help assist managers with treatment prioritizations.

Estimating prescribed fire impacts on carbon stocks in FFE-FVS

Many studies that assess carbon stocks with respect to fuel treatments and wildfires use the FFE-FVS because of the integration of carbon stock calculations, ability to model fuel treatments, fire simulation capabilities, and the capacity to model changes over time. The variability between field-derived and simulated carbon pools indicates a need for further such comparisons between empirical data and simulated results and possible updates to the model assumptions.

Deliverables

Results will be shared with managers via several means including: 1) website; 2) managers' summary; 3) presentations at multiple regional or national fire conferences; and 4) two or more refereed publications.

Table 3. Deliverables crosswalk table with proposed deliverables and current status.

Deliverable	Description	Status
Website	Creation and maintenance of project website	Completed www.fs.fed.us/adaptivemanagement/pub_reports/JFS_vaillant2.shtml
Interactive dataset	Creation of an interactive database linked to the project website. People would be able to click on the individual treatments and retrieve the plot level data.	In progress Links to FVS-ready databases and project specific information will be added by the end of March 2013.
Data Archive	Out data will be archived and available at through FFI (www.frames.gov/partner-sites/ffi/ffi-home/)	Completed This was an additional deliverable.
Workshops	Present findings and conduct a workshop session at the Region 5 Vegetation Management Workshop (occurs annually)	Not completed, no longer possible the workshop does not exist. In lieu of this we propose giving a project synthesis webinar for the CA Fire Consortium and a presentation for the R5 California Fuels Committee.
Conferences	Present findings in oral presentation	Completed See list of presentations below
Managers' summary	Create and mail a managers' summary based on the findings. This will include the Final Report, FVS-ready database, summarized data, maps, plot locations and photos for each project. All the above information will be saved to thumb-drives and sent to the applicable forest and district contacts for their own use.	In progress To be mailed by end of March 2013
Refereed publications	Two or more refereed publications	In progress See status below

Presentations

Vaillant, N., E. Noonan-Wright, A. Reiner. 2012. Fuel loading succession following fuel treatments in California. Abstract, pg. 79 in Program, Southwest Fire Ecology Conference – Fire Landscapes, Wildfire & People: Building Alliances for Restoring Ecosystem Resiliency. Santa Fe, New Mexico, USA, February 27 –March 1, 2012.

Noonan-Wright, E., and N. Vaillant. 2012. The efficacy and limitations of custom fuel modeling using FFE-FVS. Abstract, pg. 19 in Program The Fourth Forest Vegetation Simulator Conference. Ft. Collins, Colorado, USA, April 17-19, 2012.

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Noonan-Wright, E., N. Vaillant, A. Reiner, C. Ewell, S. Dailey. 2013. The effectiveness and longevity of fuel treatments in coniferous forests across California. Abstract 47, pg. 71-72 in IAWF 4th Fire Behavior and Fuels Conference – At the crossroads: Looking toward the future in a changing environment. Raleigh, North Carolina, USA, February 18-22, 2013.

Vaillant, N., E. Noonan-Wright, A. Reiner, C. Ewell, S. Dailey, J. Fites-Kaufman. 2013. Fuel accumulation rates following hazardous fuel reduction treatments throughout California. Abstract 59, pg. 78 in IAWF 4th Fire Behavior and Fuels Conference – At the crossroads: Looking toward the future in a changing environment. Raleigh, North Carolina, USA, February 18-22, 2013.

Reiner, A., N. Vaillant, E. Noonan-Wright, S. Dailey, C. Ewell, J. Fites-Kaufman. 2013. Fuel treatment effectiveness over 10 years in California forests, USA. Abstract P59, pg. 118-119 in IAWF 4th Fire Behavior and Fuels Conference – At the crossroads: Looking toward the future in a changing environment. Raleigh, North Carolina, USA, February 18-22, 2013.

Ewell, C., N. Vaillant, A. Reiner, E. Noonan-Wright, S. Dailey, J. Fites-Kaufman. 2013. Fuel treatment impacts on forest structure and fuel loads in California. Presented at the CFLRP Cornerstone Project Monitoring Meeting. Sutter Creek, California, USA, February 26, 2013. The audience was interagency and public collaborators/representatives, focusing on our study's preliminary monitoring results and methods application to upcoming Cornerstone monitoring efforts.

Publications

Noonan-Wright, E., N. Vaillant, A. Reiner. Accepted pending minor revisions. The Efficacy and Limitations of Fuel Modeling using FFE-FVS. Forest Science.

Vaillant, N., E. Noonan-Wright, A. Reiner, C. Ewell, S. Dailey. In prep. The effectiveness and longevity of fuel treatments in coniferous forests across California.

Vaillant, N., A. Reiner, E. Noonan-Wright, C. Ewell, S. Dailey, B. Rau, J. Fites-Kaufman. In prep. Mid- to long-term fuel treatment impacts on forest structure and fuel loads in California.

Vaillant, N., A. Reiner, E. Noonan-Wright. In prep. Prescribed fire effects on field–derived and simulated forest carbon stocks over time.

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