Tradeoffs in Fire Hazard versus Societal Benefits in Wildland-Urban Interface Communities

Project Title:
Tradeoffs in Fire Hazard versus Societal Benefits in Wildland-Urban Interface Communities

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I. Abstract

A paradox, vegetation is both an asset and a liability to residents living in the wildland-urban interface (WUI). The same vegetation that provides both tangible and intangible benefits to society is regularly prone to burn with great intensity and destruction. Therefore, great emphasis is regularly given to vegetation clearance to reduce wildfire risk. However, while fuel reduction treatments may moderate fire risk to residents living in the WUI, they simultaneously impact ecosystem services such as air pollution removal and carbon sequestration that vegetation provides.

To investigate this seeming quandary, we quantified surface and canopy fuel characteristics and subsequent potential fire behavior (fireline intensity, rate of spread, etc.) versus multiple ecosystem services (air pollution removal, carbon storage and sequestration) that vegetation provided in treated and untreated WUI communities in the central Sierra Nevada Mountains and the Klamath Mountains of California. The i-Tree Eco (formerly the Urban Forest Effects) model was used to assess ecosystem services while various fire behavior prediction systems were utilized to assess potential fire behavior across a given landscape under both average and extreme weather scenarios.

In general, at both the Klamath and Sierra Nevada sites, distinct fuel treatment types (prescribed fire, thinning, mastication, etc.) differentially impacted various components of the fuel strata and subsequent potential fire behavior compared to untreated controls. Treatment-induced reduction in potential fire behavior was diminished during extreme fire weather events for all treatment types. Vegetative ecosystem services of air pollution removal and carbon storage did not significantly change following treatment. Annual carbon sequestration rates, however, generally decreased immediately following treatments, but are expected to quickly return to pre-treatment levels as new vegetation begins to occupy the site. The techniques used here provide new options for land managers when evaluating the various impacts of WUI fuel treatments. That said, users must be cognizant of the assumptions and limitations of the models utilized here, particularly difficulties associated with evaluating non-tree vegetation.

II. Background and Purpose

Reducing fire hazard while maximizing the aesthetic and social values that vegetation provides are seemingly conflicting objectives to those living in highly fire-prone areas with elevated population densities. There is legitimate concern for both fire safety and loss of native vegetation as populations increasingly move to the wildland-urban interface (WUI). It is largely expected that continued immigration to highly fire-prone areas in California will likely continue unabated in the near future.

Often it seems, immigrants to the WUI expect the same level of fire protection that they experienced in urban settings, which may lead to a lack of personal responsibility in modifying the hazard on their property. However, there is a legitimate need to modify WUI vegetation so that radiant heat during a wildfire is reduced, thereby moderating risk to structures (Cohen and Butler 1998) and firefighters (Butler and Cohen 1998, Scott 2003).

However, with increasing development, there is also a justifiable concern about inherent losses of native vegetation and the subsequent ecosystem services that they provide. Development-induced losses in tree and shrub canopy cover cost society in many direct and indirect ways. Fuel treatments will only serve to further reduce vegetative cover and the inherent ecosystem services that it provides. Any loss of vegetative diversity and structure impairs healthy ecosystem function for both plants and animals. Further, lost canopy cover translates into direct, measurable social losses.

It is intended that the research here will lead to fuel reduction treatments that successfully mitigate fire hazard while being compatible with community environmental standards. To that end, the specific objectives for this project were to

1. Quantify changes to fuel parameters (loading by size class, fuelbed depth, fuel configuration, etc.) after various fuel treatments in 2 ecotypes.

2. Quantify changes to potential fire behavior (fireline intensity, rate of spread, flame length, etc.) after various fuel treatments in 2 ecotypes.

3. Quantify changes to ecosystem services (air pollution removal, carbon storage and sequestration) after various fuel treatments in 2 ecotypes.

4. Develop multiple instruments to effectively illustrate how fuels, fire behavior (under given weather and topography scenarios), and ecosystem services change as stand composition and structure are modified in 2 ecotypes.

5. Disseminate results in multiple forums and mediums to maximize impact to scientists, land management professionals, and WUI residents.

In completing these objectives, we hope to aid WUI land managers and communities in understanding the potential tradeoffs in fire hazard versus other social values when implementing potential fire mitigation actions.

It should be noted that sustainable WUI management requires several critical elements, including proper construction standards and sound community planning (Dicus 2006a,b). Our research cannot address all WUI issues, nor can it address how to minimize embers, which is also extremely important to structure ignition (Cohen 2000). However, we hope that it will greatly serve to increase the fundamental knowledge of WUI fire management and foster collaboration between land managers, WUI residents, and activist groups that have conflicting worldviews, which is essential for effective fire management in the WUI (Dicus and Scott 2006).

III. Study Description & Location

III.a. Study sites

We originally intended to quantify treatment-induced changes to fuels, fire behavior, and ecosystem services in a mixed-conifer forest in the central Sierra Nevada Mountains and in southern California chaparral. During data analysis of the chaparral ecotype, however, we experienced multiple complications for both fuels and ecosystem services; therefore, we eliminated analysis (at present) in that ecotype and instead analyzed treatment-induced changes in mixed-conifer forests in the Klamath Mountains of northern California. It is intended that the chaparral data will soon be reexplored.

Specific fuel treatments at each study site in which data were collected included

- Klamath Mountains mixed-conifer forest (all treatments within the Klamath National Forest, Salmon River Ranger District)
  - Fire-Only
  - Thin-Only
  - Thin+Fire
  - Thin+Pile&Burn

- Sierra Nevada mixed-conifer forest (Sierra and Stanislaus National Forests; Yosemite National Park)
  - Fire-Only
  - Thin+Fire
  - Thin+Pile & Burn
  - Thin+Mastication

- Southern California chaparral (Cleveland National Forest)
  - Fire-Only
  - Lop&Scatter+Fire
  - Goats
  - Mastication

We identified all of our study sites under advisement from local managers. Specific sites were selected so as to minimize variability in slope, aspect, elevation, soil productivity, pre-treatment composition, and stand age. Further, we limited data collection to sites that had been treated within 2 years (excluding non-treated controls).

III.b. Methodology

In the mixed-conifer forest sites of the Klamath and Sierra Nevada study sites, surface fuel loading and depth characteristics were collected per Brown et al. (1982) and then quantified with JFiremon (formerly FIREMON; Lutes et al., 2006). Surface fuel outputs included 1-hr (0-0.64 cm), 10-hr (0.64-2.54 cm), 100-hr (2.54-7.62 cm), 1000-hr (>7.62 cm) fuel loading (Mg ha^{-1}), litter and duff loading (Mg ha^{-1}), litter and duff depth (cm), and fuelbed depth (m).

Basic stand structural characteristics (basal area [m^2 ha^{-1}]; canopy cover [%]; trees ha^{-1}; quadratic mean diameter [QMD; cm]; stand height [average height of the 40 tallest trees; m]) and canopy fuel loading variables (canopy base height [CBH; m]; canopy bulk density [CBD; kg m^{-3}]), were calculated with the appropriate variant of the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS; Reinhardt and Crookston, 2003; Rebain, 2009). Due to the fact that FFE-FVS does not provide available canopy fuel loading (ACFL), a required canopy fuel input for NEXUS 2.0 fire modeling software (Scott, 1999), live foliage biomass (Mg ha^{-1}) from the FFE-FVS All Fuels Report was substituted (Brown and Johnston, 1976; E. Reinhardt, Missoula Fire Sciences Laboratory, personal communication). The substitution meant that the fraction of 0.0 to 0.6 cm branchwood typically included as part of ACFL was not part of these fire behavior calculations.

Modeling of potential fire behavior was conducted with NEXUS 2.0, which combines Rothermel's (1972) surface fire spread equations and Van Wagner's (1977) crown fire initiation equations in order to simulate stand-level fire spread and intensity (Scott and Reinhardt, 2001). Custom surface fuel models were created in BehavePlus Version 4.0.0 (Andrews, 2009; Andrews et al., 2008). Based on site conditions and experience, custom fuel models were initialized from standard fuel model TL5 (Scott and Burgan, 2005) and then adjusted using mean JFiremon surface fuel loading outputs specific to each combination of experimental unit and condition (untreated or treated). In all custom fuel models, litter load was added to the 1-hr fuel load. For the Mastication sites, 1-hr fuel surface area-to-volume (SA V^{-1}) ratio was modified from the default 6,562 m^2 m^{-3} (2,000 ft^2 ft^{-3}) to 8,202 m^2 m^{-3} (2,500 ft^2 ft^{-3}) to better reflect the characteristics of this novel fuelbed type (M. Battaglia, USFS Rocky Mountain Research Station, personal communication).

Mean (50th percentile) and extreme (90th and 97th percentile at the Sierra and Klamath sites, respectively) fire weather data from pertinent, nearby weather stations in the study areas were obtained using FireFamily Plus (v. 4; Bradshaw and McCormick, 2000).

For NEXUS modeling purposes, foliar moisture content (FMC) was held constant at the default value of 100%, as the range of old-foliage FMC values for most species straddles 100%, and site-specific FMC data were not available (Scott and Reinhardt, 2001). Slope was held constant at 20% in NEXUS, as this was close to the average value across all plots. Wind direction was upslope and a wind reduction factor of 0.3 was used. These inputs were then used in conjunction with the custom fuel models from BehavePlus to obtain potential fire behavior outputs including flame length (m), rate of spread (km hr^{-1}), fireline intensity (kW m^{-1}), torching index (km hr^{-1}), and crowning index (km hr^{-1}).

Stand-level leaf area, air pollution removal, and C storage and sequestration were calculated with the USFS Northern Research Station's i-Tree Eco program, Version 3.0.9 (formerly known as UFORE; Nowak and Crane, 2000). Eco uses forest inventory data in combination with local hourly air pollution and meteorological data to quantify urban forest structure and ecosystem services.

Required Eco inputs that were not sampled in the field were derived from other sources. Crown width for each tree was calculated using the Western Sierra variant of the Fire and Fuels Extension to the Forest Vegetation Simulator (WSVAR FFE-FVS; Reinhardt and Crookston, 2003; Rebain, 2009). Percent crown missing, percent dieback, and crown light exposure data for the Sierra and Stanislaus National Forests were obtained from Karen Waddell of the USFS Pacific Northwest Regional Forest Inventory and Analysis (FIA) office. For the Sierra Nevada site, averaged Sierra and Stanislaus National Forest FIA data were used for the Yosemite National Park stands.

IV. Key Findings

1. **Fuel treatments significantly changed multiple surface and canopy fuel characteristics, but the specific characteristics affected and the degree of impact varied by treatment type.**

- Klamath site

Compared to the untreated control, patterns of changes to surface fuel loading were similar across all treatment types. 1-hr timelag fuel loading did not significantly vary (α=0.10) between the untreated control and any other treatments, which might be the result of rapid accumulation of fine fuels that occurred between treatment implementation and data collection (vs. no impact from treatment). Fuel treatments that involved broadcast burning (Fire-Only, Thin+Fire) significantly lowered litter and 10-hr, 100-hr, 1000-hr timelag surface fuel loading compared to the untreated control and to the Thin-Only and the Thin+Pile&Burn fuel treatments.

Thin-Only resulted in an increase in several categories, particularly the coarser fuels, which is likely due to an increase in slash from the mechanical operations as seen in other studies (Agee and Skinner,2005; Graham et al., 2004). The Thin+Pile&Burn treatment slightly reduced the 10-hr and 1000-hr fuels, but its effect on litter load was negligible, which is likely due to the scattered and localized location of burn piles.

Crown Base Height (CBH) was significantly increased only in the Thin+Fire treatment compared to the untreated control (280% increase). Neither Canopy bulk density (CBD) nor Available Canopy Fuel Load (ACFL) significantly varied between the untreated control and any of the treatment types.

- Sierra Nevada site

Compared to the untreated control, the Fire-Only treatment significantly reduced surface fuel loading in all size classes except 10-hr fuels. Thin+Pile&Burn significantly reduced 100-hr and litter fuel loading (but no other surface fuel categories), while Thin+Fire significantly reduced 1-hr and litter fuel loads. In contrast to the other treatments, the Mastication treatment significantly increased surface fuel loading in all size classes, which generally mirror other studies in the region (Stephens and Moghaddas, 2005a; Kobziar et al., 2009). Significant results were not found for 1000-hr fuels in any treatment type.

Comparing treatment types, changes to 1-hr fuel loading significantly varied only between the Thin+Fire and Mastication treatments. 10-hr fuel loading only varied between the Fire-Only and Mastication treatments. 100-hr and litter fuel loading varied between Mastication and all other types.

The Thin+Fire treatment significantly reduced CBD and increased CBH, while Mastication significantly reduced CBD, which is similar to the results found by Stephens and Moghaddas (2005a) and Schmidt et al. (2008). However, in contrast to the findings of the aforementioned studies, the Mastication treatment did not significantly increase CBH, while Fire-Only did significantly affect both variables. Thin+Pile&Burn did not have significant effects on either variable.

2. **Fuel treatments significantly changed multiple fire behavior characteristics, but the specific degree of impact varied by treatment type and by ecotype.**

- Klamath site

At 50th percentile weather, Crown Fraction Burned (CFB) was significantly lower in all treatments compared to the untreated control, and did not vary between treatment types. Further, fireline intensity (FLI), heat per unit area (HPUA), and flame length (FL) were significantly lower in the Thin+Fire treatment (but no other treatments) compared to the untreated control. Rate of spread (ROS) was not significantly affected by any treatment type.

At 97th percentile weather, FLI was significantly lower in the Thin+Fire treatment compared to the untreated control and all other treatments. All other fire behavior parameters did not vary between the treatments and the untreated control. Under extreme weather conditions, characterized by high winds and low relative humidity, it is unlikely that the reduced fuel loads will stop a fire (Fernandes and Botelho, 2003) due to fire spread characteristics. The high winds can push flaming embers from the fire front over a treated area igniting more fires that continue to spread (Keeley et al., 2004). However, fuel treated areas are not intended to stop an advancing fire front, but rather is to reduce fire behavior and subsequent fire severity (Reinhardt et al., 2008) and also to potentially allow suppression resources a higher chance of success (Agee et al, 2000; Finney and Cohen, 2003; Graham et al., 2004; Schmidt et al, 2008).

The four treatment types examined in this study were successful at reducing fireline intensities to a level where ground suppression forces could contain them, but only under the 50th percentile weather conditions. Under more extreme fire weather scenarios, even the treated stands were burning at levels near or beyond suppression capabilities. The Thin+Fire treatment was the only simulation that kept fireline intensity near the 10,000 kW/m threshold under the most extreme (97th percentile) weather conditions considered.

- Sierra Nevada site

Significant changes were not found for ROS or FLI under either fire weather scenario, which was unexpected and potentially influenced by the high degree of natural variability between the stands and the underlying algorhythms of the fire prediction equations. That said, FL in treated stands was significantly lowered in the Thin+Pile&Burn and Thin+Fire treatments under both weather scenarios. Fire-Only significantly reduced flame length only under 90th percentile conditions. The Torching Index (TI) was significantly increased by the Thin+Fire treatment, while crowning index (CI) was significantly increased by all treatments except Thin+Pile&Burn.

All treatment types would be effective at keeping flame lengths low until wind speeds of approximately 41 km hr^{-1} (50th percentile conditions) or 35 km hr^{-1} (90th percentile conditions) were experienced. Thin+Fire had the greatest impact on predicted flame length, and on fire behavior overall, significantly decreasing flame length and increasing TI and CI under both weather scenarios.

Treatments affected flame length, TI, and CI, but not spread rate or fireline intensity. The absence of significant effects on spread rate and fireline intensity is at odds with the results reported by Stephens and Moghaddas (2005a). Their Mechanical Only treatment was found to significantly increase both of these variables under moderate (80th percentile) and high (90th percentile) fire hazard scenarios, while Mechanical & Fire and Fire-Only significantly reduced them.

With the exception of significantly increasing crowning index values, the mastication treatment was not found to have statistically significant effects on predicted fire behavior in the current study.

3. **Fuel treatments had minimal impact on vegetative carbon storage and air pollution removal capacity. The combination of thinning and burning significantly lowered annual carbon sequestration rates (at least in the short term); all other treatment types had no impact on carbon sequestration.**

- Klamath site

Annual air pollution removal (CO, O_3, NO_2, SO_2, PM10) did not vary between the untreated control or between any of the treatments. Similarly, carbon storage did not significantly vary between the untreated control or between treatments. Lack of statistical significance may be a result of small sample size (n = 15) and a resulting high degree of variability that made treatment effects difficult to identify.

However, annual carbon sequestration rates were significantly lower in the Thin+Fire treatments compared to the untreated control. This difference can be explained by considering the trees targeted in the fuel treatments. Larger diameter trees, which contribute more to the total carbon storage, were not greatly reduced under any of the treatments. However, smaller diameter trees, which contribute more to the rates of carbon sequestration, were reduced in the Thin+Fire treatment.

- Sierra Nevada site

Similar to the Klamath site, neither air pollution removal nor carbon storage significantly varied from the untreated control. Also akin to the Klamath site, annual carbon sequestration was significantly lowered by the Thin+Fire and Thin-Only treatments. In contrast, North et al. (2009b) and Stephens et al. (2009b) did find significant treatment-related reductions in stand C storage. The present statistical analysis was likely hampered by high variability in the data and small sample size, concerns that were exacerbated by the removal of one experimental unit due to data quality concerns. While the i-Tree Eco software proved capable of calculating air pollution removal and live-tree C pool characteristics in the study's WUI mixed-conifer stands, differences between C results reported by Eco and an additional analysis by FFE-FVS demonstrate that the selection of methods used in modeling has a strong influence on the outcomes obtained.

V. Management Implications

Our methodology provides a practical mechanism for managers and policy makers to better assess management options for WUI vegetation so as to simultaneously evaluate the risk of fire losses and potential environmental impacts. Unfortunately, the i-Tree Eco software does not currently estimate C storage and sequestration for all non-tree vegetation or air pollution removal afforded by grasslands . This inability to adequately calculate benefits in shrublands and grasslands is problematic, especially in areas where trees are not the dominant vegetation type (e.g., Dicus and Zimmerman 2007). That said, this methodology provides a sound mechanism to evaluate relative differences in benefits for various vegetative communities and for assorted fuel treatment alternatives, especially in landscapes in which trees are the dominant vegetation type (Dicus et al. 2009).

Management implications for the specific study sites follow.

- Klamath site

Treatments to reduce potential fire behavior must follow address three important criteria: a reduction in surface fuels, an increase in canopy base height, and a reduction in crown density (Agee and Skinner, 2005). Combinations of these objectives will affect surface fire, crown fire initiation (torching) and active crown fire spread. The four treatments considered in the present study used different methods to affect the fuels complex to various degrees, with reductions in fire behavior reflected in their overall impact on different components of the fuel complex.

Thin-Only treatments do not greatly affect fine surface fuels with the exception of compaction resulting from the use of equipment, and can potentially contribute to an increase in fuel loads depending on the method of tree removal (Agee and Skinner, 2005; Graham et al., 2004) which can result in an increase in surface fire behavior (Graham et al., 1999). Fire-Only treatments can affect multiple fuelbed characteristics by consuming lower ladder fuels and killing lower branches on trees thereby raising the canopy base height (Graham et al, 2004); however, it has the greatest impact on reducing surface fuel loads (Van Wagtendonk, 1996; Schmidt et al, 2008). Thin+Pile&Burn treatments do not treat surface fuels over the entire site, but rather only reduce those in the vicinity of the burn piles.

Post-treatment wildfire intensity and severity in thinned stands will be most effective when surface fuels also reduced (Graham et al., 1999, 2004). The most effective fuel treatment strategy is to thin the understory vegetation, which decreases canopy bulk density and increases canopy base height, followed by a method to reduce surface fuels such as prescribed fire, piling and burning coarse surface fuels, or mastication (Graham et al, 2004) as was found in this study.

Data from this study indicate that the Thin+Fire treatment had the greatest reduction in potential fire behavior under both average and extreme weather scenarios due to its effect on canopy base height from the mechanical component and its reduction of surface fuels through the burn component. Although the other treatment options considered resulted in a noticeable reduction in fire behavior, their impacts were lessened due in part to the remaining canopy and surface fuel loads. This illustrates the effect different levels of the fuel complex (surface, ladder, and canopy) have on fire behavior and the importance of choosing treatment options that manipulate the entire complex to achieve fire behavior reduction goals under various weather components.

It is important to consider the overall goal of any fuel treatment project, and the weather conditions under which they may be subjected. Under the 50th percentile conditions for this area, all treatment types kept intensities to a level where ground suppression crews could safely take action and protect any values at risk. However, under the 97th percentile conditions, fire intensities in three of the four treatments would likely exceed all suppression capabilities. This does not indicate a success of one type of treatment over another, but rather illustrates the importance of setting clear and realistic goals when planning fuel reduction projects for the purpose of wildfire hazard mitigation.

Fuel reduction treatments will subsequently reduce ecosystem services that a stand provides dependent on the pretreatment composition and structure of the stand and on the type and intensity of the treatment. The extent of this effect will be determined by the targeted vegetation, such as smaller versus larger trees. The loss of ecosystem services by fuel treatments should therefore be weighed against the potential benefits of fire hazard reduction to justify specific management actions.

- Sierra Nevada Site

Similar to the Klamath site, treatments involving broadcast burning are most likely to effectively reduce surface fuels and thus surface fire intensity while also restoring a critical ecosystem function, and under some circumstances they may also reduce ladder fuels and canopy bulk density, especially as regards smaller trees (Peterson et al., 2005). Nonetheless, they can be difficult to implement due to public concerns over smoke production and the risk of escaped fire, and multiple entries are often required within a decade, compounding these difficulties (McCandliss, 2002).

In contrast, mechanical treatments are generally more effective at thinning out dense forest canopies and allow for greater precision (i.e., targeting certain stand components but not others) than prescribed fire (Stephens and Moghaddas, 2005a). Furthermore, because the risk of unintended treatment effects (such as escaped fire) is perceived as being lower with mechanical treatments than with prescribed burning, mechanical treatments are often preferred in the WUI (Schoennagel et al., 2009). However, because mechanical treatments commonly increase surface fuel loading, follow-up treatments such as prescribed fire or pile burning are often required in order to mitigate the elevated fire hazard resulting from the initial treatment (Graham et al., 2004). Fuel treatments that combine mechanical methods with prescribed fire have typically been found to be most effective at creating a fire-resilient forest structure (fewer but larger-diameter trees), reducing surface fuels, and increasing understory species richness in dry, mixed-conifer forest stands such as those of the central Sierra Nevada (Schwilk et al., 2009).

As with any forest management activity that removes biomass, a fuel treatment has the potential to affect forest productivity (Campbell et al., 2009) and therefore, the ability of a given stand's ecological components to perform various ecosystem services. Air pollution removal capacity is dependent in part upon leaf area (Nowak et al., 2006). The leaves of trees and shrubs take in gaseous pollutants via their stomata, and intercept particulate matter on their leaf surfaces. In a study of urban forest air pollution removal, Nowak et al. (2006) noted that although average percent air quality improvement due to trees is relatively low (less than one percent), the improvement is for multiple pollutants and the actual magnitude of pollution removal can be significant, in the hundreds to thousands of Mg (metric tons) of pollutants per city per year. For example, the urban forest in Sacramento, California was estimated to have removed 378 Mg of airborne pollutants in the year 1994, at a total value of over $2.1 million (Ibid.).

Whether or not the lifespan of a given fuel treatment outlasts the C recovery period is dependent upon site-specific factors; however, based on their research in the central Sierra Nevada, Hurteau and North (2010) reported that total C emissions from prescribed fire are likely to be sequestered by tree and shrub growth within a period of time that is shorter than the historic mean fire return interval. If this is true, the wildfire risk reduction and ecological benefits of prescribed fire could offset treatment-associated C emissions to the atmosphere. Overall, the temporary reduction in forest C sequestration and storage that results from fuel treatment implementation is a small price to pay for avoiding stand-replacing wildfire and its disruption of long-term C stock stability (Hurteau and North, 2010; Hurteau et al., 2010).

In removing forest biomass for fire hazard reduction, fuel reduction treatments inevitably reduce forest capacity to provide numerous ecosystem services, including air pollution removal and C storage, leading to concerns over long-term ecosystem integrity. As a result, current C accounting methods penalize landowners and managers for any forest C loss, including losses incurred during implementation of fuel treatments (Hurteau et al., 2008). However, these losses are temporary and relatively minor (Hurteau and North, 2010), and furthermore, such treatments are critically important if significant C loss due to stand-replacing wildfire is to be avoided in Sierra Nevada mixed-conifer and similar dry forest types (North et al., 2009a; Stephens et al., 2009b). This is particularly true in light of the uncertainties associated with projected climatic trends of increased drought and wildfire occurrence (Millar et al., 2007; Moritz and Stephens, 2008; Hurteau et al., 2010).

VI. Relationship to Other Recent Findings

Relationships to other recent findings were discussed in both the Key Findings and Management Implications sections above. Based on lingering questions brought to light in this study, the researchers continue to explore additional elements of the management quandary of how to mitigate WUI fire hazard while simultaneously limiting impacts to vegetative ecosystem services. At present, the following areas are being explored.

- **Stand-level impacts to fuel dynamics, potential fire behavior, and carbon sequestration and storage are being explored through time.**

The researchers are utilizing data collected in the present study and the Fire & Fuels Extension of the Forest Vegetation Simulator (FFE-FVS) to model surface and canopy fuels, potential fire behavior, and carbon dynamics at the Klamath and Sierra Nevada sites. Additionally, the technique is being employed in a subalpine forest in the Wasatch Mountains of northern Utah.

Initial results indicate that the impacts to potential fire behavior are longer lasting than are impacts to carbon sequestration and storage.

- **Landscape-level impacts to fuel dynamics, potential fire behavior, and carbon sequestration and storage are being explored through time.**

Dicus et al. (2009) found that totally denuding vegetation around structures had minimal impact on landscape-level air pollution removal and carbon sequestration and storage in a WUI community in the eastern Sierra Nevada. They warned, though, that this was the likely result of a currently low population, and that as population continued to increase, the cumulative impacts of development and defensible-space could impact ecosystem services in the community.

In the Klamath Mountains, the researchers are also currently investigating how multiple landscape-level treatment alternatives that vary by treatment type, percentage of the landscape treated, and configuration of treatment locations impact fire probability, fireline intensity, carbon emissions, carbon storage, and carbon sequestration over time. Preliminary results are reported in Osborne et al. (2011) and multiple manuscripts are currently in review.

VII. Future Work Needed

- **Shrub fuel quantification**: Our work here (and elsewhere) is complicated in that there is no standard methodology to quantify shrubland fuels as there is in forest fuels (e.g., Brown et al. 1982). Currently methodologies are extremely labor and time intensive. Lack of said basic science in this ecotype could discourage work in future work in shrublands, which are expansive in California and elsewhere.

- **Shrub ecosystem services**: Like fuels above, little work has been done to quantify ecosystem services provided by shrubland ecosystems. The i-Tree Eco software used in this project quantifies shrub air pollution removal, but not carbon dynamics. We are not aware of any methodology to quantify ecosystem services in grasslands. The inability to predict non-tree ecosystem services is problematic in much of California and other locales where large populations live in non-forested landscapes.

- **Interaction of fuel treatments with other pre-fire mitigation activities (construction materials and assembly, fire-response infrastructure, etc.)**: Fuel treatments are only one way to mitigate fire risk in WUI communities. Communities need to take a holistic approach to WUI fire management to ameliorate risk. Unfortunately, the cumulative effects of various strategies are currently anecdotal at best. Residents and community leaders are commonly asked "What should I do to reduce my risk?". At present, recommendations for specific communities seem to be based on a best-guess basis.

- **Cost effectiveness of fuel treatments:** Fuel treatments and other WUI mitigation activities are often implemented with little knowledge of their cost-effectiveness. With limited budgets, managers need to know how best to create and maintain WUI mitigation activities that are both effective and economically sustainable. Put another way, managers should know where they can get the biggest bang for their buck.

- **Social ways to effect change in the WUI:** Much work has been invested in investigating the effectiveness of individual WUI mitigation activities. Unfortunately, even if we discovered all there is to know in the biophysical realm on how to reduce fire risk, unless these mitigation activities are actually implemented by agencies and residents, the cycle of continued fire costs and losses will proceed unabated.

VIII.a. Deliverables Crosswalk

Proposed	Delivered	Status
Project website	1. http://nres.calpoly.edu/research/firelab/FireVsBenefits/index.ldml	1. Updated as needed
Poster	1. 5 posters (see citation database that follows)	1. Completed
Invited paper	1. 17 invited papers (see citation database that follows)	1. In progress
Non-refereed publication	1. 1 non-refereed publication (see citation database that follows)	1. Completed
Refereed publication	1. 1 published manuscript 2. 2 manuscripts in review 3. 4 manuscripts in preparation (see citation database that follows)	1. Completed 2. In progress 3. In progress
Conference Workshop	1. 1 Conference Workshop 2. 6 presentations in federal Training Sessions (see citation database that follows)	1. Completed 2. Completed
Field Tour	1. 1 Field Tour	1. Completed
Training Session (2)	1. Changed to two 1.5 hour seminars at request of sponsors (1 in Sierra Nevada, 1 in S. California)	1. Completed
Master's Thesis (2)	1. 3 Master's Thesis (see citation database that follows)	1. Two completed, one in progress
Final Report	1. Final Report	1. Completed

VIII.b. Citation Database

Posters

1. C.A. Dicus, C. Hamma, C. Isbell, A. Kirkpatrick, J. Large, D. Weise. 2008. Evaluating Fire Hazard Gains vs. Environmental Losses after Fuel Treatments in the Wildland-urban Interface. Presented at Association for Fire Ecology Pacific Coast Fire Conference: Changing Fire Regimes, Goals, and Ecosystems. 1-4 December, 2008. San Diego, California.

2. C.A. Dicus, C. Hamma, C. Isbell, A. Kirkpatrick, J. Large, D. Weise. 2008. Evaluating Fire Hazard Gains vs. Environmental Losses after Fuel Treatments in the Wildland-urban Interface. Presented International Association of Wildland Fire Conference, "The '88 Fires: Yellowstone and Beyond". Jackson Hole, WY, September .

3. J. Large, C. Hamma, A. Kirkpatrick, C. Dicus, D. Weise, and C. Isbell. 2009. "Impacts to Fire Behavior and Ecosystem Services Following Fuel Treatments in the Wildland-Urban Interface. 4th International Fire Ecology and Management Congress: Fire as a Global Process. November 30 – December 4, 2009. Savannah, Georgia.

4. Osborne, K., C. Dicus, C. Isbell, and D. Weise. 2009. "Effects of Landscape-Level Fuel Treatments on Burn Probability and Fire Severity in the Klamath Mtns." Association for Fire Ecology International Fire Ecology & Management Congress. Savannah, GA, December 1-4, 2009.

5. Osborne, K., C. Dicus, C. Isbell, and D. Weise. 2010. "Effects of landscape-level fuel treatments on carbon emissions and storage over a 50 yr time cycle" . International Association of Wildland Fire Behavior and Fuels Conference. Spokane, WA. October 25-29.

Invited Papers

1. C.A. Dicus and K. Delfino. 2008. "The Paradox of Vegetative Fire Risk vs. Societal Benefits in a SW Wildland-Urban Interface Community". Association for Fire Ecology Fire in the Southwest Conference: Integrating Fire into Management of Changing Ecosystems. January28-31, 2008.
Tucson, Arizona.

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3. C.A. Dicus, C. Hamma, A. Kirkpatrick, J. Large, D. Weise, C. Isbell. 2008. "A Methodology to Evaluate Fire Hazard Gains vs. Environmental Losses after Fuel Treatments in the Wildland-

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6. C.A. Dicus. 2009. “Fire Hazard Gains Vs. Environmental Losses After Fuel Treatments in The Wildland-Urban Interface”. Presented to the University of Tasmania. May 14, 2009. Hobart, Tasmania, Australia.

7. Dicus, C.A. 2009. “Fire Down Under: The good, the bad, and the downright tragic”. Keynote Address: Department of Homeland Security Wildland-urban Interface Fire Research Colloquium, June 16-17.

8. C.A. Dicus, C. Hamma, A. Kirkpatrick, J. Large, K. Osborne. 2009. “A Methodology to Evaluate Fire Hazard Gains vs. Environmental Losses after Fuel Treatments in the Wildland-urban Interface”. ½ day workshop at the 4th International Fire Ecology and Management Congress: Fire as a Global Process. November 30 – December 4, 2009. Savannah, Georgia.

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12. Dicus, C.A., J. Large, C. Isbell, and D. Weise. 2010. Long-term Simulated Wildfire Behavior and C Emissions Following Fuel Treatments in the Klamath Mountains, USA. International Association of Wildland Fire Behavior and Fuels Conference. Spokane, WA. October 25-29.

13. Dicus, C.A. 2011. Wildland Fire: Winners and Losers. Wildfire Litigation Conference. San Diego, CA. April 15-17.

14. Dicus, C.A. 2011. Lessons learned down under: Applying the Australian Fire Experience to California. SoCal Society of American Foresters. La Canada Flintridge, CA. April 28.

15. C.A. Dicus, J. Large, C. Isbell, and D.R. Weise. 2011 (invited). Long-term carbon storage/emissions following fuel treatments in the Klamath Mountains. Society of American Foresters National Convention, Honolulu, HI, November 2011.

16. C.A. Dicus. 2011 (invited). Simulated carbon dynamics in post-fire successional pathways of the Wasatch Mountains, Utah. Association for Fire Ecology Interior West Conference, Snowbird, UT, November 2011.

17. Osborne, K., C. Dicus, and A. Ager. 2011 (invited). Impacts of Alternative landscape-level fuel management strategies on short-term carbon emissions and long-term carbon storage. Association for Fire Ecology Interior West Conference, Snowbird, UT, November 2011.

<u>Non-refereed Papers</u>

1. Osborne, K., **C. Dicus**, C. Isbell, D. Weise, A. Ager, and M. Landram. 2011. Effects of landscape-level fuel treatments on carbon emissions and storage over a 50yr cycle. Proceedings of the 3rd Fire Behavior and Fuels Conference, October 25-29, 2010, Spokane, Washington.

<u>Refereed Papers</u>

1. Dicus, C.A., K. Delfino, and D.R. Weise. 2009. Predicted fire behavior and societal benefits in three eastern Sierra Nevada vegetation communities. Fire Ecology 5(1):61-58.

2. *In review.* Large, J., C.A. Dicus, C. Isbell, and D.R. Weise. Effects of Wildland Urban Interface Fuel Treatments on Fuels and Fire Behavior in the Klamath Mountains, California.

3. *In review*. Osborne, K., C.A. Dicus, A. Ager. Impacts on carbon loss and storage from varied landscape-scale fuel treatment strategies.

4. *In preparation*. Large, J., C.A. Dicus, and D.R. Weise. Effects of fuel treatments on carbon sequestration and air pollution removal in the Klamath Mountains, USA. Climate Change.

5. *In preparation*. Hamma, C., C.A. Dicus, and D.R. Weise. A Comparison of Fuel Reduction Treatment Effects on Simulated Fire Behavior in Mixed-Conifer Forests of the Central Sierra Nevada Mountains.

6. *In preparation*. Hamma, C., C.A. Dicus, and D.R. Weise.A Comparison of Fuel Reduction Treatment Effects on Ecosystem Services in Mixed-Conifer Forests of the Central Sierra Nevada Mountains

Conference Workshops

1. Dicus, C. J. Large, C. Hamma, A. Kirkpatrick, K. Osborne, and D. Weise. 2009. "A Methodology to Evaluate Fire Hazard Gains vs. Environmental Losses after Fuel Treatments in the Wildland-urban Interface." Association for Fire Ecology International Fire Ecology & Management Congress. Savannah, GA, December 1-4, 2009.

2. Research findings incorporated into lectures presented at Continuing Education in Fuels Management course. 2008, 2010, 2011

3. Research findings incorporated into lectures presented at the National Advanced Silviculture Program. 2008, 2010, 2011

Master's Thesis

1. Large, J. 2010. Effects of Wildland Urban Interface Fuel Treatments on Fire Behavior and Ecosystem Services in the Klamath Mountains of California. M.S. Thesis, California Polytechnic State University, San Luis Obispo, CA.

2. Hamma, C. 2011. Effects of Wildland-Urban Interface Fuel Treatments on Potential Fire Behavior and Ecosystem Services in the central Sierra Nevada Mountains of California. M.S. Thesis, California Polytechnic State University, San Luis Obispo, CA.

3. *In preparation*. Osborne, K. Impacts to fire risk, flame length, and fire size from varied landscape-scale fuel treatment strategies. M.S. Thesis, California Polytechnic State University, San Luis Obispo, CA.

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