Title: Sagehen Experimental Forest Past, Present, and Future: An Evaluation of the Fireshed Assessment Process

by

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Introduction

With the ever-present threat of wildland fire occurrence in the Sierra Nevada there is a need for fuel treatments to alter potential fire behavior and effects. The fireshed assessment process is a new method for planning and implementing landscape-level fuel treatments (Bahro et al. 2007). A fireshed is a large landscape that shares similar fire regimes, fire history or wildland fire risk (Bahro and Perot 2006, Bahro et al. 2007). The current treatment philosophy for firesheds is a system of strategically placed area treatments (SPLATs) (Finney 2001, Finney 2007). SPLATs are disconnected, overlapping, equal area, rectangular treatment units aligned perpendicular to the direction of the “problem” fire to slow the forward progression of the heading fire. The problem fire is a hypothetical wildland fire that is expected to burn with elevated intensity resulting in adverse effects (Bahro et al. 2007). The heading fire is one which is being pushed by winds and is the hardest to control. The primary objective of fuel treatments in the fireshed assessment process is to reduce potential fire behavior (i.e. fire type, flame length, and fireline intensity). However, SPLATs can also be used to improve forest health and to provide or protect wildlife habitat.

For land managers to properly complete a fireshed assessment they must understand the past, present and future fire conditions of the fireshed. Through my dissertational research, I will look at these three time periods for Sagehen Experimental Forest (Sagehen). Sagehen is an ecologically diverse 4594 ha watershed in the eastern Sierra Nevada. As part of the University of California Natural Reserve System, Sagehen has a long history of research including, but not limited to climate, wildlife, hydrology
and vegetation. From 2004 to 2005 an extensive grid of forest and fuel plots was installed and LiDAR (light detection and ranging) imagery taken in Sagehen. This data will be used to create a SPLAT design using the fireshed assessment process.

My dissertation consists of five chapters including this introduction and four main chapters. The four main chapters concentrate on the past, present and future fire conditions at Sagehen Experimental Forest. The first chapter investigates the past through a fire history reconstruction of lower elevation Jeffrey pine (*Pinus jeffreyi*) and Jeffrey pine – mixed conifer stands within Sagehen. Using fire perimeter maps and dendrochronology, the historic fire regime (frequency and seasonality) was determined. This chapter explores the influence of Native American land use practices, Comstock Era logging, fire suppression and climate indices (Pacific Decadal Oscillation and the Palmer Drought Severity Index) on the fire regime at Sagehen.

The second chapter focuses on the present comparing three geographic information system (GIS) data sets utilized in the fireshed assessment process available for Sagehen. Eight GIS data layers are required to model fire behavior in FlamMap (Finney 2006), a landscape-level fire behavior and propagation model. The eight layers required include: elevation, slope, aspect, canopy cover, canopy base height, canopy height, canopy bulk density and fuel model. The three GIS data sets being compared in this chapter included: 1) data created using LiDAR and plot information for Sagehen, 2) pre-existing Landscape Fire and Resource Management Planning Tools Project (Landfire) data (Ryan et al. 2006), and 3) pre-existing Tahoe National Forest Stewardship and Fireshed Assessment data (Bahro et al. 2007). The three GIS data sets were evaluated against the extensive grid of fuel and vegetation plots to test the correlation of
canopy cover, fuel model, canopy base height, canopy height and canopy bulk density to current conditions. Modeled fire behavior metrics (fire type, flame length and fireline intensity) were compared between the three GIS data sets to better understand the implications of different source data on management decisions made during the fireshed assessment process.

The third chapter will again concentrate on the present comparing six SPLAT treatment plans created for Sagehen. Four of the plans were created by the Tahoe National Forest in conjunction with University of California, Berkeley using the fireshed assessment process. These four plans take into account accessibility, cost, landownership and ecological objectives. The second two plans were theoretical. The first is based on the pattern outlined by the fundamental research on the SPLAT theory (Finney 2001). This plan does not consider any of the above limitations. The second was created using the treatment optimization model within FlamMap (Finney 2007). This SPLAT plan excludes areas not available for treatment including watercourse protection zones, archeological sites and locations protected for sensitive or endangered plant and animal species. Potential fire behavior metrics (fire type, flame length, fireline intensity and arrival time) were modeled in FlamMap to evaluate the effectiveness of the six SPLAT plans.

The fourth chapter assesses the longevity of treatment effectiveness to reduce potential fire behavior for one of the fireshed assessment SPLAT treatments into the future. A forest vegetation growth simulator was utilized to model natural regeneration and growth of trees in Sagehen from 2005 through 2055 for the untreated and treated landscapes. Modeled fire behavior (fire type, flame length and fireline intensity) was
used to assess the effectiveness of the treated landscape compared to the untreated landscape from 2005 to 2055.

There is much to be gained by integrating the past, present and future of Sagehen Experimental Forest into a spatial and temporal evaluation of the fireshed assessment and SPLATs. To my knowledge, no other watershed has the amount of information available for such a detailed analysis. Nor has there been a detailed evaluation of proposed SPLAT treatments created through the fireshed process. This study would be a first for both SPLAT placement and fireshed analysis, and should be of great value to land managers.

Literature Cited


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Abstract

Title: Sagehen Experimental Forest Past, Present, and Future: An Evaluation of the Fireshed Assessment Process

by

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Doctor of Philosophy

University of California, Berkeley

Associate Professor Scott Stephens, Chair

This research investigates the fireshed assessment process with a thorough evaluation of past, present and future fire characteristics at Sagehen Experimental Forest (Sagehen). The past fire regime was determined through a dendrochronological fire scar reconstruction of lower elevation Jeffrey pine-mixed conifer stands within Sagehen. Mean composite fire return interval for the study area was 2.2 years from 1700 to 2006. The mean composite fire return interval was significantly longer during the suppression period (1924 to 2006) than during the pre-settlement (1700 to 1859) and settlement (1860 to 1923) periods. A superposed epoch analysis found significant correlation to warmer and wetter conditions three years prior to fire events pre-settlement.

Present fire hazard and potential fire behavior was modeled to better understand the complexity of available data and resulting fire behavior metrics to assess potential SPLAT treatment scenarios for Sagehen. The ability of the input data to represent current vegetation and fuel characteristics does impact potential fire behavior (fire type,
flame length and fireline intensity) and probable fuel treatments on the landscape. The effectiveness of six SPLAT designs was compared to assess the outcome of the fireshed process. All six treatment plans effectively reduced potential fire behavior. Two of the treatments preformed better than the remaining four.

Finally, future forest growth was modeled from 2005 to 2055 to assess long term effectiveness of one of the SPLAT designs. Fuel treatment effectiveness is expected to last at least 25 years and up to 50 years based on maximum and mean flame length and fireline intensity. The xeric conditions at Sagehen may partially explain the longevity of fuel treatment effectiveness. The complexity of the landscape at Sagehen provided a unique experience to assess the effectiveness of both the fireshed process and SPLATs. Findings from this research should be of interest to forest managers and scientists working to reduce fire severity at the landscape-scale.
Chapter 1: Fire history of a lower elevation Jeffrey pine-mixed conifer forest in the eastern Sierra Nevada, California

Abstract

For thousands of years fire has shaped coniferous forests of the western United States. In more recent time, land use practices have altered the role fire plays in the Sierra Nevada Mountains. By understanding the past, land managers can design better fuel treatments today. This research explores the fire regime(s) of Sagehen Experimental Forest in the eastern Sierra Nevada, California through a fire scar reconstruction of lower elevation Jeffrey pine (Pinus jeffreyi) and Jeffrey pine – mixed conifer stands.

Prehistoric and historic land use practices, fuel accumulation and climate influence fire regime over three periods of time: pre-settlement (1700 to 1859), settlement (1860 to 1925) and suppression (1925 to 2006). Over the period of analysis (1700 to 2006) 293 fire scars were assigned a calendar year. The mean composite fire return interval for all samples in the study area was 2.17 years from 1700 to 2006. The mean composite fire return interval was significantly longer for the suppression period than both the pre-settlement and settlement periods. The lack of sufficient fire intervals for analysis at the C25 filter (scarring at least three or more trees and 25% of the total sample) indicate fires in the study area are small in spatial extent. The proportion of dormant season fires increased from pre-settlement through suppression. Middle and early earlywood fires no longer occurred during suppression. A superposed epoch analysis found significant correlation to warmer (Pacific Decadal Oscillation) and wetter (Palmer Drought Severity Index) conditions three years prior to fire events pre-settlement. These findings suggest
that small frequent prescribed burns would best mimic the pre-settlement fire regime if fire is reintroduced into the ecosystem.

**Introduction**

For thousands of years fire shaped coniferous forests of the Sierra Nevada Mountains. In more recent time, land use practices have altered the role fire plays in this system. With the birth of the United States Forest Service (USFS) over a century ago, fire suppression has been the universal practice on Federally owned land in the western United States (Pyne 1982, Stephens and Ruth 2005). In order to reintroduce fire into the ecosystem today, one needs to understand the role it played in the past. Fire atlases and fire scarred trees both aid in understanding past fire regimes (frequency and seasonality). When available, fire history data from fire scarred trees contain information about the fire frequency and seasonality of fire events that occurred before fire atlas records existed. Factors such as land use history and climatic variability can influence forest structure and fire regimes.

The Washoe Indians and their prehistoric ancestors have been a part of the Truckee River Basin in the northern Sierra Nevada for the past 8000 to 9000 years (Lindstom 2000). Although the Washoe have been present for over 8000 years, the intensity of land use was minimal until between 5000 and 1500 years before present (Lindstom 2000). The Washoe were known to use fire to clear brush, improve browse for wildlife, select for desirable plants and hunt game (Anderson and Moratto 1996, Lindstom 2000). During the settlement period, native populations started to dwindle because of disease and warfare (Johnston 1990, Anderson and Moratto 1996).
Throughout the settlement period (1860 to 1923) logging to support the extraction of silver for the Comstock Lode was the focus in the Truckee River Basin. This era was a time of extensive timber harvesting to supply lumber to support silver mining, railroad construction and building of cities in the eastern Sierra Nevada and the Great Basin (Johnston 1990, Wilson 1992). Anthropogenic fires still occurred in this time; however, due to the dwindling Native American population most of the fires were likely the result of settlement and lightning. Fires were common at mills and along railroads built for moving timber (Wilson 1992). In addition to timber driven fires, sheep herders were known to set fires to improve browse (Sudworth 1900, Leiberg 1902).

The USFS was initiated in 1891 with the creation of the forest reserves system (Pyne 1982). From the beginning, one of the primary objectives of the USFS was timber production, and therefore, a policy of complete fire suppression was adopted (Pyne 1982, Stephens and Ruth 2005). It was not until 1924 when the federal Clarke-McNary Act was created that national fire suppression became law (Stephens and Ruth 2005). With the onset of fire suppression and aggressive land use methods forests started to change into what they are today. The absence of regular fire has led to higher tree densities (Biswell 1959), changes in species composition (Weaver 1943) and higher fuel loads (Dodge 1972) in many coniferous forests. This change has altered fire regimes (Taylor 2000, Beaty and Taylor 2001, Stephens and Collins 2004, Fry and Stephens 2006, Moody et al. 2006).

In addition to human influences and land use policies, climatic variation may play a role in defining the fire regime of the Truckee River Basin. A common practice with dendrochronological based fire history research is to complete a superposed epoch
analysis (SEA) to explore fire-climate interactions (Taylor 2000, Stephens and Collins 2004, Taylor and Beaty 2005, Fry and Stephens 2006, Moody et al. 2006). A Monte Carlo simulation of 1000 runs creates bootstrapped confidence intervals to test the statistical significance of climate conditions surrounding fire years (Grissino-Mayer and Swetnam 2000). Through the use of a SEA the temporal relationship between fire occurrence, drought, and large-scale climate anomalies can be better understood (Westerling et al. 2003, Schoennagel et al. 2005). The Palmer Drought Severity Index (PDSI) is an index of drought severity during the summer months (June, July, and August) and can be used to capture seasonal moisture availability (Palmer 1965, Cook et al. 1999). The Pacific Decadal Oscillation index (PDO) (Mantua et al. 1997) is related to the El Niño-Southern Oscillation index (ENSO) (Glantz 1996) which affects precipitation due to variation in atmospheric processes. PDO is thought to be a driver in climate variation (Dettinger et al. 1998, Biondi et al. 2001). It has been found that the northern Sierra Nevada can exhibit fire-climate interactions similar to both the Pacific Northwest and Southwest because of its geographic location (Dettinger et al. 1998).

To date there are few fire history studies in the Sierra Nevada. In the literature even fewer exist from the eastern Sierra Nevada with Jeffrey pine (*Pinus Jeffreyi*) trees for the fire scar specimens. Two fire history studies that use Jeffrey pine occurred south of the Truckee River Basin near Mammoth Lakes at the University of California Valentine Camp Natural Reserve (Stephens 2001) and in Yosemite National Park (Collins and Stephens 2007). Although these are useful studies for reference, impacts of pre-settlement and settlement land use vary from that of the Truckee River Basin. An additional three studies occurred closer to this research site. One was on the Plumas
National Forest and incorporated both eastern and western Sierra Nevada forest types (Moody et al. 2006). The final two studies took place in the Lake Tahoe Basin and are most relevant to this work (Taylor and Beaty 2005, Beaty and Taylor 2007).

The goal of this study was to describe the fire history of a Jeffrey pine mixed-conifer forest in the Truckee River Basin using dendrochronology. Specifically the objectives were to: 1) describe the fire regime (fire return interval and seasonality) for three periods, pre-settlement (1700 to 1859), settlement (1860 to 1923) and suppression (1924 to 2006); 2) complete a superposed epoch analysis to determine fire-climate interactions for two time periods, pre-settlement (1700 to 1859) and post-settlement (1860 to 2006); and 3) consider management implications for Sagehen Experimental Forest today.

**Methods**

Sagehen Experimental Forest (Sagehen) is a 4594 ha watershed on the eastern slope of the Sierra Nevada 32 km north of Lake Tahoe. The watershed extends east from the crest of the Sierra Nevada at 2670 m to Highway 89 at 1862 m. Slopes are typically mild, averaging 18% but can reach 70% in parts of the watershed. Soils are generally Andic and Ultic Haploxeralfs derived from volcanic parent material (Pacific Southwest Research Station 2008).

Sagehen has a Mediterranean climate with warm, dry summers and cold, wet winters. Average low and high winter (January) temperatures measured at 1943 m from 1953 to present are -10 and 4°C; average summer (July) temperatures are 3 and 26°C. Average annual precipitation is 85 cm with snowfall accounting for about 80% of annual
precipitation (515 cm average snowfall per year) (climate data available at http://www.wrcc.dri.edu/).

A reconnaissance of Sagehen Experimental Forest was conducted to determine where clusters of trees and stumps with visible fire scars existed. Only clusters with a minimum of five samples (fire scarred trees and/or stumps) within a five hectare area were considered for sampling. Fire scar sampling was limited to lower elevation Jeffrey pine and Jeffrey pine-mixed conifer stands within Sagehen, which was where clusters were found. The study area occupied about 360 ha of the entire watershed and was located north of Sagehen Creek. An attempt was made to select clusters with diversity (i.e. aspect, slope and vegetation) to better assess the study area as a whole.

Tree species present in the study area include Jeffrey pine, lodgepole pine (P. contorta), sugar pine (P. lambertiana), white fir (Abies concolor) and red fir (A. magnifica). Shrub cover type is dominated by tobacco brush (Ceanothus velutinus), mahala mat (C. prostratus), greenleaf manzanita (Arctostaphylos patula), wax currant (Ribes cereum) and woolly mule-ears (Wyethis mollis).

Each sample was progressively sanded up to 400 grit sandpaper to distinguish tree rings and fire scars. Fire scars were identified by the disruption and healing pattern of tree ring growth associated with the injury (McBride 1983). Calendar years were assigned to each fire scar by cross-dating rings using common dendrochronological techniques (Dieterich 1980, Swetnam and Thompson 1985). Patterns of tree ring widths were compared to each other and to a nearby published master tree chronology from Lemon Canyon (Holmes 1980). When possible the season of each fire scar was identified from the location of the scar within the growth ring (Caprio and Swetnam
1995). The position was noted as early earlywood (EE), middle earlywood (ME), late earlywood (LE), latewood (L), dormant (D) or undetermined (U) (Ahlstrand 1980, Dieterich and Swetnam 1984, Caprio and Swetnam 1995).

**Evidence of Past Management at Sagehen Experimental Forest**

Pre-settlement is defined as prior to 1860 for this study. The Washoe were a nomadic tribe who lived on the eastern slopes of the Sierra Nevada and in the Great Basin from Honey Lake to the headwaters of the Stanislaus River (Downs 1966, Rawls and Bean 1998, Lindstom 2000). The Washoe moved into the mountain highlands to fish in creeks, hunt wild game and gather plants and berries for food in the summer. Archeological evidence of the Washoe exists at Sagehen (West 1982).

The first successful wagon over the Sierra Nevada happened in 1844 (Rawls and Bean 1998), but settlement did not start until the late 1850s. The discovery of silver in Virginia City, Nevada, was the start of the Comstock Era and subsequent railroad construction. This marked the beginning of Euro-American settlement in the eastern Sierra Nevada in the late 1850s and was the start of a timber harvest of historic proportions (Downs 1966). Timber was needed to line mines, run and fuel mills, construct the Central Pacific Railroad and build homes (Wilson 1992). Three sawmills existed in or along Sagehen Creek from the 1870s until at least 1915 (Wilson 1992). Remnants from the narrow gauge railroad that ran from Sagehen to the Hobart Mills and other artifacts from logging have been found in Sagehen (West 1982). The remains of old cabins were discovered supporting a history of sheep grazing and fur trapping in addition to logging in Sagehen Experimental Forest (Wilson 1992).
In 1924 the USFS mandated a policy of active fire suppression on all public lands (Stephens and Ruth 2005). However, Sagehen did not become a part of the Tahoe National Forest until 1936. By this time much of the merchantable timber had been culled from the basin (Leiberg 1902). In 1952 Sagehen became a field station for the University of California, Berkeley, for studying freshwater ecology. The first notable timber harvest conducted by the USFS occurred in 1967; since then Sagehen has experienced more silvicultural treatments, including harvesting, mechanical thinning for fuel treatments and prescribed burns. In addition, the research station has grown to include more fields of study than freshwater ecology. Finally in 2005, the research station and the surrounding watershed officially became an Experimental Forest under the direction of the United States Forest Service’s Pacific Southwest Research Station.

**Data Analysis**

Forest structure was derived from existing georeferenced plots (0.05 ha) installed in 2004 and 2005 to assess vegetation and fuel characteristics within Sagehen Experimental Forest. Plots closest to the fire scar clusters were used to further describe (i.e. tree species, basal area and density) the sampled area (Figure 1).

The FHX2 software package was used to analyze fire return intervals (mean, median and range), seasonality and fire-climate interactions (Grissino-Mayer 2001). Fire return intervals were determined for individual points on the landscape (PFI) (Taylor 2000) and composites of fire scars by cluster and for the entire study area (CFI). Seasonality of fire scars was determined using the whole study area for three time periods: pre-settlement (1700 to 1859), settlement (1860 to 1923) and suppression (1924 to 2006).
Three different composite scales, or filters, were utilized in this study for each of the five clusters and the study area as a whole. The broadest composite (C01) included all samples experiencing a fire scar. The intermediate composite (C10) included fires that scarred a minimum of two trees and at least 10% of the samples. The final composite (C25), included fires that scarred a minimum of three trees and at least 25% of the sample. Composites of multiple trees will often provide a more comprehensive record of fire events (Dieterich 1980, Agee 1993). Using filters (C10 and C25) removes relatively small fires (Swetnam and Baisan 1996). A Kruskal-Wallis test was used to determine if significant differences existed (p<0.05) between mean CFIs for the clusters at each composite (C01, C10 and C25) (Zar 1999). In addition, the Kruskal-Wallis test was used to determine if a significant difference existed between mean CFIs for the three time periods (1700 to 1859, 1860 to 1923 and 1924 to 2006) at each composite (C01, C10 and C25) for the study area (Zar 1999). If a significant difference was found in mean CFIs a Nemenyi test was used to determine where the significant differences exist (p<0.05) (Zar 1999).

A superposed epoch analysis was used to investigate fire-climate interactions (Baisan and Swetnam 1995, Swetnam and Betancourt 1998). Fire years from the C10 composite for the study area were compared to two climate indices to determine if climate was significantly correlated to climatic conditions five years before, the year of and/or four years after fire events (p<0.05). Two time periods were used for this analysis, pre-settlement (1700 to 1859) and post-settlement (1860 to 2006). The two climate indices include the Palmer Drought Severity Index (PDSI) (Palmer 1965, Cook et al. 1999) and Pacific Decadal Oscillation (PDO) (Mantua et al. 1997).
Results

Five clusters of fire scars were located and sampled in Sagehen (Figure 1). A total of 42 samples were collected and sanded; however, only 37 samples were used for the analysis because five samples were excessively rotten or not datable. Of the 37 samples used 13 (35%) were live samples with the remainder from stumps, snags, and downed trees. The duration of recordable years was from 1575 to 2006, with 300 fire scars assigned a calendar year. The average length of samples was 224.4 years (standard deviation 77.2 years, range 76-344 years). The earliest fire scar recorded was 1605 and the most recent 2001. The average number of scars per sample was 8.1 scars (standard deviation 3.8 scars, range 2-16 scars). The chronology is depicted in Figure 2, and the data for the individual samples can be found in Appendix A.

Stand structure was assessed using 31 reference plots in and around the fire scar clusters (Figure 1, Table 1). All calculations were completed using live overstory trees (defined as trees greater than 19.4 cm diameter at breast height, DBH). The average tree density ranged from 190 to 348 trees per hectare. The average basal area was between 13.6 and 41.6 m²/ha. Overstory tree species present included white fir, red fir, lodgepole pine, and Jeffrey pine. Jeffrey pine had the highest percentage of basal area in all clusters except number two where white fir represented the highest percentage (Table 1).

Fire Regime

The initial date for analysis of fire return intervals was chosen as 1700. This was due to a limited number of samples prior to 1700 based on visual inspection of the composite scar chronology (Figure 2). The overall point fire return interval mean was 22.3 years (median 17.3 years, range of means 6-110 years).
The mean composite fire return interval for the entire study area for C01 was 2.17 years (median 2 years, range 1-10 years) with 293 fire scars recorded and 137 fire intervals from 1700-2006 (Table 2). The C10 CFI for the study area was 12.09 years (median 7 years, range 1-41 years). There was insufficient data to complete the analysis for C25.

Mean composite fire return intervals were also compared between the five clusters for three composite levels (C01, C10 and C25) when enough data existed. A significant difference (p<0.05) between mean CFIs was found for C01 and C10 with the Kruskal-Wallis test (p<0.05). For C01 Clusters 1 and 5, Clusters 2 and 3 and Clusters 3 and 5 mean CFIs remained significantly different using the Nemenyi test (p<0.05). Clusters 1 and 5 had significantly different CFIs for C10. Only Clusters 1 and 3 had enough data to complete the analysis for C25 and the means were not significantly different (Table 2).

For the study area as a whole an analysis was completed to determine if differences existed between mean CFIs for three time periods: pre-settlement (1700 to 1859), settlement (1860 to 1923) and suppression (1924 to 2006). The Kruskal-Wallis test found a significant difference between mean CFI for the three time periods for C01. Mean composite fire return interval for the suppression period was significantly longer than both the pre-settlement and settlement periods with the Nemenyi tests (p<0.05) (Table 3).

It was possible to determine fire season for 78.4% of the scars. The proportion of fires occurring during the dormant period increased from pre-settlement to settlement, and again from settlement to suppression (Figure 3). Early earlywood fires do not occur
after settlement (1860 to 2006). Middle earlywood fires no longer exist during suppression (1924 to 2006).

**Fire-Climate Interactions**

A superposed epoch analysis was conducted using fires scarring more than 10% with a minimum of two trees scarred by fire (C10). Using this filter selects only those fires which were larger in the study area (Swetnam and Baisan 1996). Pre-settlement (1700 to 1859) fire years were significantly associated with wetter (PDSI) and warmer conditions (PDO) three years prior to fire events (p<0.05, Figure 4). Fire years were not associated with PDSI and PDO post-settlement (1860 to 2006).

**Discussion**

The mean composite fire return interval at Sagehen is similar to other studies of mixed conifer forests in the Sierra Nevada, Cascades and northern Baja Mexico (Stephens 2001, Stephens et al. 2003, Stephens and Collins 2004, Taylor and Beaty 2005, Fry and Stephens 2006, Moody et al. 2006, Beaty and Taylor 2007, Collins and Stephens 2007). As filtering increased the composite fire return interval became longer (median C01 3-9.5 years, C10 8-56 years). The lack of fire intervals for the C25 filter was also seen by Moody et al. (2006) in the eastern Sierra Nevada. The lack of fire intervals for this filter level is due to the nature of fire spread in this ecosystem. From 1910 to 2006 fires tended to be small in extent for the land surrounding Sagehen (Figure 5). Those which grew larger were due to extreme wind which can be seen by the fire perimeters in the fire atlas. Beaty and Taylor (2007) found fire propagation and spread is dictated by the spatial pattern of fuels (abundance, pattern and continuity) rather than strictly the
forest structure. Fires are known to burn with equal frequency between stands in the Lake Tahoe Basin, but do not burn all stands in a given fire event (Beaty and Taylor 2007).

The mean composite fire return interval was the longest for Cluster 5 (C01 13.23 years). The low fire frequency may be attributed to stand structure. This cluster has the lowest tree density (190 trees per hectare) and highest proportion of Jeffrey pine (94% based on average basal area) of the five clusters (Table 1). Typically the CFI decreases with an increased proportion of Jeffrey pine (Taylor 2000, Moody et al. 2006, Beaty and Taylor 2007). However, with the low stand density fuels might not be able to accumulate as quickly as in other stands of this study lengthening the interval. Also the sample size was small for this cluster (28 fires) possibly attributing to the longer CFI (Table 2).

The mean composite fire return interval for the study area was significantly shorter for both the pre-settlement period (1700 to 1859) and settlement period (1860 to 1923) than for the suppression period (1924 to 2006) for C01. Pre-settlement fires can be attributed to lightning and possibly Native American burning. Settlement fires were likely due to lightning, timber harvesting and sheep herding. The occurrence of fires in Sagehen after 1900 is different than other fire history work in the Sierra Nevada (Stephens 2001, Stephens and Collins 2004, Moody et al. 2006, Beaty and Taylor 2007, Collins and Stephens 2007). Five fires occurred at a larger spatial scale (C10) in Sagehen after 1900 (Figure 2). Two of these fires are known to be human-caused; the Donner Ridge Fire of 1960 was started during the construction of Interstate 80 and burned over 16,000 ha (39,550 ac) and the fire in 2001 was from a prescribed burn. With active
logging in Sagehen until 1936 and lightning-caused fires still possible it is not surprising that fires still occurred even with a policy of suppression intact.

In the study area the majority of fires occurred during the latewood and dormant portions of the growth ring (67.7%) as compared to the earlywood (32.3%) for the duration of the study period (Figure 3). The proportion of fires occurring during the earlywood section of the tree ring is higher than other studies in the eastern Sierra Nevada during the pre-settlement and settlement periods (Taylor and Beaty 2005, Moody et al. 2006, Beaty and Taylor 2007). The higher proportion of growing season fires could have been caused by Native American burning, logging accidents or opportunistic burning by sheep herders. Although latewood and dormant season fire occurrence is dominant through the pre-settlement (66.0%) and settlement (67.2%) periods, suppression period fires mainly occurred during this time (91.7%) (Figure 3). The loss of early earlywood fires during both the settlement and suppression periods is possibly due to a lack of Native American burning in Sagehen. The effectiveness of suppression likely eliminated middle earlywood fires after 1923. Fires are easier to extinguish earlier in the fire season when weather and fuel conditions make suppression less difficult.

Fire-climate interactions were analyzed using a superposed epoch analysis. Fire scar samples were filtered at the C10 level (10% of the sample scarring at least two trees) to determine fire years. Two time periods, pre-settlement (1700 to 1859) and post-settlement (1860 to 2006) were used for the analysis. Fire years were compared to two climate indices (PDSI – grid point 13 and PDO) to determine if correlations exist. The northern Sierra Nevada occurs at a pivot point for the ENSO-PDO precipitation zones and can exhibit fire-climate relationships similar to both the Southwest and Pacific
Northwest (Dettinger et al. 1998). The results of this study can be most closely compared to one study in the Lake Tahoe Basin (Taylor and Beaty 2005) and one in the eastern portion of the Plumas National Forest (Moody et al. 2006). Although informative it must be stated that this study is much smaller in spatial scale than those mentioned above. The study in the Lake Tahoe Basin was comprised of 93 samples in a 6000 ha study area (Taylor and Beaty 2005). The study on the Plumas National Forest included 23 samples from five clusters across the forest (Moody et al. 2006).

Pre-settlement fire years were associated with drought (PDSI) and El Niño conditions (PDO) (Figure 4). Fires occurred at phase shifts during the pre-settlement period. Phase shifts are changes from wet to dry (PDSI) or El Niño to La Niña (PDO) conditions or visa versa. The occurrence of fire years with phase shifts is common for studies in the northern Sierra Nevada (Westerling et al. 2003, Taylor and Beaty 2005, Moody et al. 2006). Pre-settlement fire events were significantly correlated (p<0.05) to wet (PDSI) and warm (PDO) conditions three years prior to fire events. The finding for PDSI is similar to that found by Taylor and Beaty (2005) for the period from 1650 to 1850. Post-settlement fire years were not statistically correlated to PDSI or PDO. However, during the post-settlement period all three years prior to and the year of fire events occurred during wet years in Sagehen (Figure 4). If fire propagation and spread is dictated more by the spatial pattern and abundance of fuels in the eastern Sierra Nevada (Stephens 2001, Beaty and Taylor 2007), the significant correlation to a wetter climate before fire years is logical. This allows for the accumulation of fine fuels (herbs and forbs) increasing the likelihood of fire occurrence and spread, which remains consistent with the pre-settlement findings.
Different fire-climate interactions over the two time periods show these relationships to be unstable. It has been found that the 1900s signify a time of more frequent climate swings (between El Niño and La Niña periods) as compared to the 1600s through the 1800s (Biondi et al. 2001). This fluctuation in climate might account for the differing fire-climate interactions during the two time periods. In addition, the location of Sagehen plays a role in the fire-climate interactions. The northern Sierra Nevada is located at the ENSO-PDO dipole, where El Niño/La Niña influences are not clearly defined like in the Pacific Northwest and Southwest (Trouet et al. 2006). The pivot point shifts north and south on decadal time scales, shifting the associated fire-climate interactions to mimic those of the Pacific Northwest or Southwest depending on the time period in question (Westerling and Swetnam 2003). More research needs to be completed to fully understand the relationship between fire and climate in this region of California and Nevada.

With fire regimes changing in many conifer forests in the west an understanding of historic fire regimes is important to land managers today. Fuel treatments can be used to do more than alter fire behavior and effects. Prescribed fire can be used to reintroduce fire into the ecosystem. Fire history research can determine the frequency and seasonality of past fires. This information can be used to plan future prescribed burns. Although the study area was located in less than 10% of Sagehen Experimental Forest it can be utilized for other stands with similar forest composition. It would not be safe to assume all vegetation types within Sagehen experienced similar fire regimes. These findings suggest that small frequent prescribed burns would best mimic the pre-settlement fire regime if fire is reintroduced into the ecosystem. Although the majority of
fire occurred during the dormant and latewood seasons, growing season fires can be implemented.

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pp. 600.

and PDO variability affect drought-induced fire occurrence in Rocky Mountain 


### Tables

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<th>Cluster</th>
<th>No. Plots</th>
<th>Average Density (trees/ha)</th>
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Table 1: Average (standard error) stand characteristics of the vegetation plots in and around the fire scar clusters at Sagehen Experimental Forest. Calculations include live trees with diameter at breast height greater than 19.4 cm.
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Table 2: Fire return interval data (1700 to 2006) from a fire history study within Sagehen Experimental Forest.

C01-composite of all fire scars, C10-composite of fires scarring two or more trees and at least 10% of the sample, C25-composite of fire scarring at least three or more trees and 25% of the sample

--not enough data to complete analysis.

Means followed by the same letter in a column are significantly different (p <0.05)
Table 3: Fire return interval data by time period, pre-settlement (1700 to 1859), settlement (1860 to 1923), and suppression (1924 to 2006) for the fire scar study area within Sagehen Experimental Forest.

C01-composite of all fire scars, C10-composite of fires scarring two or more trees and at least 10% of the sample, C25-composite of fire scarring at least three or more trees and 25% of the sample, --not enough data to complete analysis.

Means followed by the same letter in a column are significantly different (p <0.05).
**Figures**

Figure 1: Fire scar samples (with cluster numbers) and vegetation plots for a fire history study in the eastern Sierra Nevada, California. The background depicts a hillshade of the study area.

Figure 2: Composite fire activity of five fire scar clusters in Sagehen Experimental Forest. Each horizontal line represents a fire scar sample, with the vertical lines representing fire events. The collection of years at the bottom represents the C10 composite (scarring more than 10% and at least two trees) for all samples.
Figure 3: Seasonality of fire scars (proportion with standard error bars) for pre-settlement (1700 to 1859), settlement (1860 to 1923) and suppression (1924 to 2006) for a fire history study within Sagehen Experimental Forest. D-dormant; L-latewood; EE-early earlywood; ME-middle earlywood; LE-late earlywood

Figure 4: Superposed epoch analysis of fires scarring more than 10% with a minimum of two trees scarred by fire compared to two climate indices. The left column represents pre-settlement (1700 to 1859) and the right post-settlement (1860 to 2006). Dark gray bars denote statistical significance and the dashed lines represent the 95% confidence interval.
Figure 5: Fire atlas for the area around the Sagehen Experimental Forest representing 1910 to 2006. The red outline depicts the boundary of Sagehen Experimental Forest and the red triangles are individual fire scar samples. Fire perimeter data was obtained from Fire and Resource Assessment Program (FRAP 2006).
Chapter 2: Assessment of fireshed data, affects on modeled fire behavior and implications for management decisions at Sagehen Experimental Forest

Abstract

Since 2000 the National Fire Plan, 10-Year Comprehensive Strategy and Healthy Forests Restoration Act have been enacted to bring together public and private land owners to address the problem of elevated fuel loading and facilitate the reduction of wildland fire risk. For land managers to assess areas for treatment they need continuous geographic information system (GIS) data for elevation, slope, aspect, canopy cover, canopy base height, canopy height, canopy bulk density and fuel model characteristics of the landscape. Currently the Stewardship and Fireshed Assessment (SFA) and Fire and Resource Management Planning Tools Project (Landfire) supply this GIS data for California. A third data set was created for this study and is comprised of high-resolution data derived from light detection and ranging (LiDAR), vegetation and fuel plot data and aerial photographs for Sagehen Experimental Forest (Sagehen) in the eastern Sierra Nevada. The goal of this research was to assess the accuracy of the three GIS data sets to current vegetation and fuel conditions at Sagehen and compare the resulting modeled fire behavior metrics. Both the Landfire and Sagehen data sets were significantly correlated to the field plot values; the SFA data was not correlated. Although significantly correlated the relationship to current fuel conditions was weak for the Landfire data. A sensitivity analysis found modeled fire behavior values for all three data sets to be most influenced by changes in the canopy base height and canopy cover layers. Resulting modeled fire behavior metrics varied between the three GIS data sets. These differences...
can result not only in treating an incorrect proportion of Sagehen but also treating vastly different areas of the basin.

**Introduction**

A recent analysis of fire extent on United States Forest Service (USFS) lands (Stephens 2005) demonstrates that from 1940 to 2000, California experienced a significant increase in the total number of fires and had the most area burned relative to other regions in the United States. California has continued along this trend since 2000. The October Fire Siege of 2003 burned over 303,500 ha, consumed 3710 homes and took 24 lives (including one firefighter) in southern California. The 2007 fire season was also devastating. In northern California, the Angora Fire destroyed 254 homes and burned 1250 ha near Lake Tahoe and the Moonlight Fire consumed 26,300 ha on the Plumas National Forest. In southern California, the Zaca Fire burned over 97,125 ha and the 2007 Southern California Firestorm burned 183,300 ha, consumed 2813 structures and claimed seven lives. As California’s lands continue to burn, suppression will remain necessary to attempt to protect life and property.

Unfortunately, fire suppression itself can lead to a fire regime with larger, more frequent and more severe fires. Suppression over the past century has created higher tree densities (Biswell 1959) and increased fuel loads (Dodge 1972), which have altered fire regimes (Taylor 2000, Beaty and Taylor 2001, Stephens and Collins 2004, Moody et al. 2006) in many of California’s coniferous forests. However, fire suppression alone is not to blame for the changes seen in fire frequency, size and severity; climate also plays a role (Swetnam and Betancourt 1990, Millar and Woolfenden 1999, Mayer et al. 2000,
Westerling et al. 2003, Falk et al. 2007). This alteration in fire regime can partially explain why fires burning in California are much larger today than in the past.

Since 2000 the National Fire Plan, 10-Year Comprehensive Strategy and Healthy Forests Restoration Act were enacted to bring together public and private land owners to address the problem of elevated fuel loads and facilitate the reduction of wildland fire risk (Stephens and Ruth 2005). Specifically in California, the Sierra Nevada Forest Plan Amendment (SNFPA) was initiated to review the 2001 Sierra Nevada Ecosystem Plan. One of the primary goals of the SNFPA was to pursue more aggressive fuels reduction treatments (USDA Forest Service 2004). In order to facilitate the decision making process of where to implement these fuel treatments, land managers need a way to assess the area being discussed.

A fireshed assessment is a collaborative landscape-scale fuels management process (Bahro and Perrot 2006, Husari et al. 2006). A fireshed is a large landscape that shares similar fire regimes, fire history or wildland fire risk (Bahro and Perot 2006, Bahro et al. 2007). The idea of the fireshed assessment is to implement strategically placed fuel and vegetation treatments to reduce the potential fire behavior across a landscape (Finney 2001). Ideally by employing these treatments on a fraction of the landscape the overall impacts of a wildland fire event will be moderated because fire intensity and spread will be dampened (Finney 2001). In order to complete the fireshed assessment process, managers need accurate vegetation and fuels data for the area in question.

The Stewardship and Fireshed Assessment (SFA) (Bahro et al. 2007) process and the Landscape Fire and Resource Management Planning Tools Project (Landfire) (Ryan et al. 2006) are two existing resources for the data needed to assess potential wildland fire
risk and model potential fuel treatments. The SFA process is a rapid process which evaluates performance of hazardous fuel treatments in the National Forests in California (Bahro et al. 2007). One of the by-products of this assessment was the creation of canopy and surface fuel data layers for geographic information system (GIS) and ultimately fire behavior modeling purposes. Landfire is a mapping project that will generate comprehensive GIS maps of the United States describing vegetation, fire and fuel characteristics (Ryan et al. 2006). Both of these data sources have been produced to aid the decision making process for landscape fuel treatments or fireshed assessments.

An additional assessment of Sagehen Experimental Forest (Sagehen), on the Tahoe National Forest in California, was completed in 2007. This high resolution GIS data set was derived from light detection and ranging (LiDAR) data, plot data and aerial photographs. The goal of this research was to: 1) evaluate the accuracy of the Landfire, SFA and Sagehen specific data sets to current canopy and surface fuels conditions; 2) attempt to understand how the various inputs affect modeled fire behavior (fire type, flame length and fireline intensity); and 3) explore how potentially different fire behavior outputs can alter treatment plans under the fireshed process.

**Methods**

**Study Area**

Sagehen Experimental Forest (Sagehen) is a 4594 ha watershed on the eastern slope of the Sierra Nevada about 32 km north of Lake Tahoe (Figure 1). The watershed extends east from the crest of the Sierra Nevada at 2670 m to Highway 89 at 1862 m. Slopes are typically mild, averaging 18% but can reach 70% in parts of the watershed.
Soils are generally Andic and Ultic Haploxeralfs derived from volcanic parent material (Pacific Southwest Research Station 2008).

Sagehen is in both the montane and subalpine vegetation ranges of the Sierra floristic province (Barbour et al. 2007). Sagehen is a diverse watershed with the majority of the landscape occupied by conifer forests (Figure 1). Tree species present include lodgepole pine (*P. contorta*), Jeffrey pine (*P. jeffreyi*), sugar pine (*P. lambertiana*), western white pine (*P. monticola*), white fir (*Abies concolor*), red fir (*A. magnifica*), mountain hemlock (*Tsuga mertensiana*) and quaking aspen (*Populus tremuloides*). The non-forested areas include fens, wet and dry montane meadows and shrub fields. The shrub cover type is dominated by tobacco brush (*Ceanothus velutinus*), mahala mat (*C. prostratus*), greenleaf manzanita (*Arctostaphylos patula*), wax currant (*Ribes cereum*) and woolly mule-ears (*Wyethis mollis*). Sagehen is divided into 47 stands which were delineated using an aerial photograph grouping similar vegetation types or densities into individual units (Appendix C: Figure 1 and Tables 1 and 2).

Sagehen has a Mediterranean climate with warm, dry summers and cold, wet winters. Average low and high winter (January) temperatures measured at 1943 m from 1953 to present are -10 and 4 °C; average summer (July) temperatures are 3 and 26 °C. Average annual precipitation is 85 cm with snowfall accounting for about 80% of annual precipitation (515 cm on average in snowfall per year) (climate data available at http://www.wrcc.dri.edu/).
Field Data Collection

Plot Selection

A systematic grid of 522 permanent, georeferenced 0.05 ha circular plots was installed, based on a random starting point within Sagehen. The grid consists of three different densities, 500 m, 250 m, and 125 m spacing (Figure 2). The entire watershed is sampled by plots spaced on a 500 m interval. Areas not occupied by Jeffrey pine plantations were sampled at 250 m spacing. The 125 m spacing was used in 10 unique forest types to conduct high density sampling. At each plot, plot center and elevation were recorded using a hand held global positioning system (GPS) unit. In addition, aspect and slope were noted using a compass and clinometer.

Vegetation Measurements

Tree measurements (species, diameter at breast height (DBH), height, canopy base height and tree crown position (dominant, codominant, intermediate or suppressed)) were recorded for all live trees greater than 5 cm DBH. Overstory trees (≥19.5 cm DBH) were tagged and measured in the whole plot (0.05 ha); pole-sized trees (≥5 cm DBH to <19.5 cm DBH) were measured in a randomly selected third of the plot (0.017 ha). Saplings, trees <5 cm DBH, were tallied by species and diameter class (1 cm increments) along a two meter belt encompassing three 12.62 m transects (0.0072 ha). In addition, snags greater than 5 cm DBH had species, DBH and height recorded. Canopy cover (CC) was measured at 25 points in a five-by-five grid with five meter spacing using a canopy sight tube (Gill et al. 2000) in all the plots for the 125 m spaced grid and any plots initiated after these were installed (113 plots).
Tree measurements (live trees ≥ 5 cm) were used to calculate average canopy base height (CBH), canopy height (CH) and canopy bulk density (CBD) using Fuels Management Analyst (FMA) at the plot level (Carlton 2005). FMA incorporates established published methodologies for computing canopy bulk density, canopy base height, fire behavior, and predicted scorch and mortality by species (Stephens and Moghaddas 2005a, Stephens and Moghaddas 2005b). FMA uses information from field measurements (i.e. tree species, DBH, tree crown ratio, tree crown position and tree height) to estimate average canopy base height and canopy bulk density for a stand or plot (Reinhardt et al. 2000). Canopy bulk density for each plot is calculated using a running mean along the height of the canopy. Canopy base height for each plot is determined as the height above the ground where the first canopy layer has a high enough density to support the vertical movement of fire (Carlton 2005). The running mean window was set to the defaults in FMA for CBH, CH (both 0.91 m) and CBD (4.57 m); the critical CBD is also set to the default, 0.011 kg/m³. Defaults were used in FMA because they are the same as is used in the Forest Vegetation Simulator (Crookston and Stage 1991) with the Fire and Fuels Extension (Reinhardt and Crookston 2003).

Shrub measurements were taken along the same three 12.62 m transects used to measure seedlings. Species, average height, and length along the transect were recorded for all shrubs present. In addition, an ocular estimate of percent cover classes (in 5% increments) of grasses, herbaceous species, and shrubs were noted for each whole plot.

**Fuel Measurements**

Surface and ground fuels were measured along the shrub transects in each of the plots using the line-intercept method (Van Wagner 1968, Brown 1974). Tallies of 1-hr
(diameter less than 0.64 cm) and 10-hr (diameter from 0.64 to 2.54 cm) time lag fuels were recorded from 0 to 2 m, and 100 hr (greater than 2.54 to 7.62 cm diameter) from 0 to 3 m. Species, diameter and decay status (rotten or sound) were recorded for all 1000-hr fuels (diameter greater than 7.62 cm) along the whole transect (12.62 m). Litter, duff, and fuel bed depth measurements were taken at two points along each transect (at 5 m and 10 m).

Surface and ground fuel loads were calculated using coefficients arithmetically weighted specific to the average basal area fraction of the tree species at each plot (van Wagtendonk 1996, van Wagtendonk et al. 1996, Stephens 2001, Vaillant et al. 2006). Fuel models (FM) were then assigned to plots based on the calculated surface fuel loads, vegetation type, and the presumed carrier of fire (Scott and Burgan 2005).

**Geographic Information System Data**

The geographic information system (GIS) data consist of three unique sets of eight raster layers needed to model potential fire behavior using FlamMap (Finney 2006), a landscape level fire behavior and propagation model. The eight layers include topographical information (elevation, slope and aspect), canopy characteristics (canopy cover, canopy base height, canopy height and canopy bulk density) and surface fuels information (fuel model). The three different sources of GIS data are: 1) data developed for Sagehen Experimental Forest (SEF), 2) Landfire (LF) (Ryan et al. 2006), and 3) Tahoe National Forest SFA data (TNF) (Bahro et al. 2007).

**Sagehen Experimental Forest Geographic Information System (GIS) Layers**

The GIS layers created for Sagehen (SEF) consists of five meter resolution raster data derived from LiDAR, field plots an aerial photograph. Topographical information
(elevation, slope and aspect) was derived directly from LiDAR data (dual pulse LiDAR flights took place in the summer of 2005). The LiDAR data was initially sampled at 0.25 m resolution and was aggregated up to one meter resolution. A five-by-five grid of one meter cells was next averaged to create the five meter resolution cells used to make the digital elevation model (DEM). Slope and aspect were derived from the DEM.

Data layers for canopy characteristics were created using both LiDAR and field data. The canopy height (CH) layer was created the same way as the DEM with an additional step to check the accuracy against the field data. The canopy cover (CC) layer was derived from canopy height data and compared to the field data. A binary grid of five-by-five one meter cells was created to denote a “hit or miss,” much like is done with a canopy tube in the field, to calculate percent canopy cover for each five meter cell. Finally, the data was filtered to only include canopy cover where trees taller than five meters were present.

The canopy base height (CBH) layer was created using a Kriging interpolation. A Kriging interpolation determines the value of an unknown field based on value of nearby fields using a linear least squares estimation (Goovaerts 1997). The interpolation for the canopy base height layer was based on a combination of the calculated CBH at each plot and the canopy height GIS layer. The canopy bulk density layer was also created using the values calculated in FMA (Carlton 2005). A global multiple-regression equation was used to calculate the CBD and create the raster layer in GIS. The regression equation used to create the CBD layer was:

$$\text{CBD (kg/m}^3\text{)} = \{0.03867 + [\text{canopy height (m)} \times (-0.0022)] + [\text{canopy base height (m)} \times 0.0018] + [\text{canopy cover (\%)} \times 0.0023]\}.$$
The fuel model layer was created using field data and aerial photography. An object-based image analysis (Jain 1988) was performed using a current aerial photograph to determine unique clusters and create the associated polygons based on vegetation characteristics in GIS. The fire carrying fuel type (litter, shrub, grass or a combination), average calculated fuel load and stand characteristics (i.e. basal area by tree species and shrub cover) at each plot was used to select appropriate fuel models from the extended set (Scott and Burgan 2005). A nearest-neighbor interpolation was used to populate polygons in GIS with fuel models. A nearest-neighbor interpolation is a technique for assigning data to non-valued cells in GIS by using the value of the nearest point (ESRI 2008). Finally, local expert opinion from the Tahoe National Forest was used to validate the fuel model selections. Experts were the Fuels Manager, Fuels Officer, Silviculturist and Timber Operation Manager from the Truckee Ranger District on the Tahoe National Forest. See Figure 3 for examples of the canopy bulk density and fuel model layers for SEF.

*Landfire GIS Layers*

Landfire GIS data consists of 30 m resolution raster data created from relational databases, georeferenced field plots, remote sensing, systems ecology, gradient modeling, predictive landscape modeling, vegetation disturbance dynamics and peer-reviewed fire science (Ryan et al. 2006). Available data for the western United States include layers needed for fire modeling, existing vegetation and fire regime conditioning class. Only the eight data layers needed for fire behavior modeling using FlamMap are utilized for this study. These layers include: elevation, slope, aspect, canopy cover, canopy base height, canopy bulk density, canopy height and fuel model.
The three topographical layers (elevation, slope and aspect) for Landfire are derived directly from the USGS (United Stated Geological Survey) digital elevation models (Rollins and Frame 2006). Data layers for canopy characteristics (canopy bulk density, canopy base height, canopy cover and canopy height) were derived in two different ways. CBD and CBH values were calculated using FUELCALC program which computes the vertical canopy distribution using allometric equations based on tree metrics (Reinhardt and Crookston 2003). The tree metrics are from plots included in the United States Forest Service (USFS) Forest Inventory and Analysis (FIA) program. The methodology used in FUELCALC is similar as is used in FMA. Data layers for canopy height and canopy cover were created using field referenced data, satellite imagery and statistical modeling (Rollins and Frame 2006). A classification or rule based approach was used to determine the surface fuel models using information from other data layers within the Landfire data set (including but not limited to potential vegetation type, structural stage and cover type) (Rollins and Frame 2006). The most current layers were downloaded (May 31, 2007 version) for the analysis (LANDFIRE 2007). In addition, the Landfire data was re-sampled to five meter resolution using a nearest-neighbor interpolation to compare fire model outputs with the five meter resolution SEF data. The Landfire GIS data set will be called LF for the duration of this study. See Figure 3 for examples of the canopy bulk density and fuel model layers for LF.

**Tahoe National Forest Fireshed Assessment GIS Layers**

The Tahoe National Forest fireshed assessment GIS (TNF) data is also comprised of 30 m resolution raster data. The Stewardship and Fireshed Assessment process uses existing data, robust assumptions and data models to create the information required to
run fire models (Bahro et al. 2007). The baseline data depends on USFS Forest Inventory and Analysis (FIA) plot data, along with the Forest Vegetation Simulator to characterize vegetation characteristics (canopy cover, canopy base height, canopy bulk density and canopy height) across the landscape (Bahro et al. 2007). The fuel model data is created using vegetation data to assign fuel models in GIS. All of the SFA data is managed in GIS using both vector and grid data sets along with databases and spreadsheets for ease in updating the data as needed (Bahro et al. 2007). Currently, data is available for most of the United States National Forests in California. In addition, the TNF data was re-sampled to five meter resolution in GIS using a nearest-neighbor interpolation to compare fire model outputs with the SEF data. See Figure 3 for examples of the canopy bulk density and fuel model layers for TNF.

Fire Modeling

FlamMap Inputs

In order to run FlamMap, a landscape file (LCP) and a fuel moisture file (FMS) are required. Wind (WND) and weather (WTR) files are used for these simulations to condition fuel moistures. When custom fuel models are used a custom fuel model file (FMD) is required. The FMD describes the characteristics (i.e. fuel load, fuel bed depth, surface area to volume ratio and heat content) of the custom fuel model(s). For this study one low-load slash custom fuel model was used in the TNF data. The parameters for the LCP, FMS, WND, and WTR files are described below.

The LCP is created by converting the eight GIS raster files (elevation, slope, aspect, canopy cover, canopy base height, canopy height, canopy bulk density and fuel model) into ASCII grid files, and importing them into FlamMap. These files need to be
coregistered, have equivalent extent, and have identical resolution to work within FlamMap. For the analysis 23 unique landscape files were created. One for the baseline SEF data, two each for the baseline LF and TNF data for the 30 m and five meter resolutions. Finally, an additional six LCP files for each of the SEF, LF and TNF GIS data sets (for a total of 18) were created for the sensitivity analysis.

In addition to the landscape file, FlamMap requires non-spatial and non-temporal weather and fuel moisture information to simulate fire behavior. The FMS file defines the initial fuel moisture for dead and down as well as live fuel components. Fire Family Plus (Main et al. 1990) was used to determine the values for the 90\textsuperscript{th} (high) and 97.5\textsuperscript{th} (extreme) percentile fire weather conditions (Appendix B: Table 1). Forty-five years (1961 to 2006) of weather data from the Stampede Remote Access Weather Station (less than 10 km east of Sagehen) from June 1 to October 31 were analyzed to determine percentile weather conditions.

Fire Family Plus was also used to create WND and WTR files with hourly weather data for the days leading up to the Cottonwood Fire. The Cottonwood Fire was a large fire (19,000 ha) that occurred just north of Sagehen in 1994. The 10 day period (August 6 to 15, 1994) prior to the fire was used to condition the initial fuel moistures from the FMS file. Conditioning fuel moistures creates more realistic fuel conditions for FlamMap simulations.

**Fire Behavior Outputs**

FlamMap is designed to help plan fuel treatments (Finney 2002, Stratton 2004, Finney 2006, Husari et al. 2006). FlamMap calculates fire behavior independently for each pixel across the landscape and holds the key fire weather variables (i.e. windspeed,
Therefore, the outputs capture the spatial variability in fire behavior due to differences in fuel conditions (Finney 2006). A total of 28 simulations were run to model potential fire behavior. Six simulations were completed with the baseline data for SEF, LF and TNF under both the 90th and 97.5th percentile fire weather scenarios. Four more simulations were run under the two weather scenarios for LF and TNF with the five meter resolution data sets. An additional 18 simulations were run to look at the sensitivity of modeled fire behavior outputs to changes in canopy cover (increasing (+) and decreasing (-) the GIS data layer by 50%), canopy bulk density (+/- 50%), and canopy base height (+/- 50%) for each data set. Each of the 18 simulations was run with one of the above variables (CC, CBD or CBH) being changed with the remaining seven layers representing the baseline data for the data set in question (SEF, LF or TNF). These simulations were only run under the 90th percentile weather scenario.

**Data Analysis**

A correlation analysis was completed to compare five of the eight data layers (canopy cover, canopy base height, canopy height, canopy bulk density and fuel model) from the three GIS data sets (SEF, LF and TNF) to the field plot data at the field plot points. The Pearson product-moment correlation coefficient, r, was used to test significance ($\alpha=0.02$) and determine the relative strength of the correlation between data sets (Zar 1999). In order to convert the fuel model data to a continuous data set the fine fuel load (dead 1-hr load plus the live herbaceous and live woody loads, ton/ac) values associated with each fuel model were used (Scott and Burgan 2005). All correlations were conducted using the Jmp Statistical Software package (Sall et al. 2005).
Percent of total landscape and hectares were presented for comparisons between the SEF data and LF and TNF data sets for the fire behavior outputs (fire type, flame length, and fireline intensity). A sensitivity analysis was completed to compare the difference in fire behavior outputs between the five meter and 30 meter resolution LF and TNF data sets. An additional sensitivity assessment was completed compare fire behavior outputs where +/-50% change in CC, CBD and CBH were tested for all three data sets. Due to the number of assumptions associated with fire behavior models, outputs were not statistically analyzed (Stephens and Moghaddas 2005, Vaillant et al. 2006).

**Results**

*Data Layer Comparisons: Fire Model Inputs*

Summary statistics (average, standard deviation and range) for CC, CBH, CH and CBD for the three GIS data sets and the field data plots are presented in Table 1. For the three GIS data sets, sample size depicts the number of cells in the raster data set. When comparing the field plot data to the SEF, LF and TNF GIS layers, all (CC, CBH, CH, CBD and FM) were significantly correlated for both SEF and LF, and none were for TNF (Table 2). The strength of the correlation is weak for the LF data (Table 2).

*Modeled Fire Behavior Outputs – Baseline Data*

Less than a 1.5% difference appeared between the modeled fire behavior outputs (fire type, flame length and fireline intensity) for the five meter and 30 m resolution data sets for LF and TNF. The rest of the results will be comparing the five meter resolution SEF data with those of the 30 m resolution LF and TNF data. About 2% of the landscape
experienced no fire with SEF data, 1% with LF data, and less than 1% with the TNF data under both fire weather scenarios.

Modeled fire type is divided into four categories, no fire, surface fire, passive crown fire and active crown fire in FlamMap (Table 3 and Figure 3 part 1). Modeled flame length (FL) was divided into four bins, zero (0 m), low (>0 to <1.2 m), moderate (1.2 to <2.4 m) and high (≥2.4 m) (Table 3 and Figure 3 part 2) (Sugihara et al. 2006). Modeled fireline intensity (FLIN) was categorized similarly with zero (0 kW/m), low (>0 to <346 kW/m), moderate (346 to <1730 kW/m) and high (≥1730 kW/m) groups (Table 3) (Sugihara et al. 2006). The categories for flame length and fireline intensity were chosen because of their relation to suppression tactics. The low category corresponds to fire behavior where suppression by a person with a hand tool is possible at the head or flanks of the fire (NWCG 2006). Here handline should hold the fire. Moderate flame lengths and fireline intensity occur when the fire is too intense for direct attack on the head fire by a person with a hand tool. At this point heavier equipment such as dozers, engines or aircraft with fire retardant may be necessary (NWCG 2006). Handline can not be relied on to hold the fire. The high category represents fires that may present serious control problems. Attempts to control the head fire will probably be ineffective (NWCG 2006).

The majority of Sagehen would burn as surface fire under both scenarios for all three data sets, with the amount decreasing between the 90th and 97.5th percentiles (Table 3). Both LF and TNF experience more active crown fire than passive crown fire with extreme fire weather. However, the amount of land burned in passive crown fire decreases for LF and increases for TNF between the 90th and 97.5th percentile weather.
scenarios. SEF only experiences a small percentage of active crown fire under both fire
weather scenarios (4 and 8% or 174 and 368 ha).

All three data sets experienced the highest proportion of the landscape having low
flame lengths (SEF 54%, 2,503 ha; LF 38%, 2,332 ha; TNF 68%, 3,291 ha) for the 90th
percentile fire weather (Table 4, Figure 3). These values decrease under 97.5th percentile
fire weather. Under the 90th percentile the SEF data has 4% (174 ha) moderate and 40%
(1842 ha) high flame lengths; LF has 7% (318 ha) and 41% (1895 ha); and TNF 5% (242
ha) and 22% (1032 ha) respectively. Under the 97.5th percentile the percentage of the
landscape exhibiting moderate flame lengths decreases except for SEF which stays
constant. High flame lengths increase for all three data sets relative to the 90th percentile
fire weather scenario. Modeled low, moderate and high fireline intensity follow the same
trends as flame length, except for SEF where the percent of landscape experiencing
moderate fireline intensity increases for the 97.5th percentile.

**Modeled Fire Behavior Outputs – Sensitivity Analysis Data**

SEF experienced the least amount of change followed by LF and TNF
respectively when canopy cover, canopy base height and canopy bulk density were
altered. Reducing canopy cover increased crown fire occurrence for all three data sets
(Table 4). An increase in canopy cover had the opposite effect on fire type. Flame
length and fireline intensity follow the same general trends when canopy cover was
altered. An increase in canopy cover reduced the proportion of high FL and high FLIN.

Changes in CBD most affected the proportions of passive and active crown fire
for all three data sets (Table 4). Fire type for the LF data set was most affected by
changes in CBD; passive crown fire was increased by 25% and active crown fire was
reduced by 25% with a 50% decrease in CBD values. The +50% CBD did not affect flame length for LF and less than a 3% change was seen for both SEF and TNF.

The +/-50% canopy base height variations seemed to alter the modeled fire behavior outputs the most (Table 5). A reduction in CBH decreased the amount of surface fire, low FL and low FLIN. High FL and high FLIN increased the most for the LF (22 and 23% respectively) and TNF (15 and 16% respectively) data sets with a lower CBH.

**Discussion**

Topography, weather and fuels play a role in the hazard and ultimately severity of a wildland fire event. The most feasible and successful way to change potential fire behavior is to reduce surface fuels (typically with pile or broadcast burning), increase the canopy base height (through removal of ladder fuels and/or pruning of existing trees) and reduce canopy bulk density (removal of trees). In order to begin the progression of delineating fuel treatments under the fireshed assessment process baseline GIS data is required. Specifically, information is needed on current vegetation (CC, CBH, CH and CBD) and fuel (FM) conditions. This research strives to investigate three different GIS data sets to see how their differences alter modeled fire behavior and ultimately management decisions for Sagehen.

The accuracy of the Landfire (LF), Tahoe National Forest SFA (TNF) and Sagehen specific (SEF) data sets was compared to an extensive grid of vegetation and fuel plots in Sagehen Experimental Forest (Figure 2). A correlation analysis was completed for the canopy cover, canopy base height, canopy height, canopy bulk density
and fuel model data layers (Table 2). The SEF and LF GIS data layers were significantly correlated to the plot data for all of the above mentioned metrics. The TNF data was not. The relatively high correlation between the plot and SEF data for the canopy base height, canopy bulk density and fuel model layers is not too surprising. These three layers were partially (CBH and CBD) or fully (FM) derived from the plot data. Although significant, the relationship between the plot data and LF for CBD, CBH, CH and FM were weak (Table 2). The lack of and weak significant correlation for the TNF and LF data to current conditions was unexpected.

The low correlation coefficient values for LF may be due in part to how Landfire data is derived and presented. For example the canopy height layer is assigned very few values (0, 2.3, 7.5, 17.5, 37.5, and 50 m). The same is true for canopy base height and canopy bulk density layers. The GIS data created for SEF does not have these limitations. For example, the canopy cover layer is divided into one-percent increments and the canopy base height and canopy height layers are accurate to one one-hundredth of a meter. Although the SFA data is comprised of 30 m raster layers, it appears to have been tabulated from areas larger than the pixel level (Figure 3). The resulting lower resolution might partially explain the lack of correlation to current vegetation and fuel characteristics at Sagehen.

The SEF layers are the most detailed and data informed layers due to the combined use of LiDAR, extensive plot data and aerial photographs. In addition, by utilizing these sources of information it was possible to produce the SEF layers at a higher resolution (five meter) than the LF and TNF (both 30 m) data sets. However, it must be noted that the creation of the SEF data layers was time consuming and costly.
Landfire and SFA data sources already exist for USFS land in California and are readily available for use. Although the SEF data is the most informed of the three, land managers will typically not have access to such data and must rely on existing sources.

The differences between the three baseline data sets are apparent in modeled fire behavior outputs (fire type, flame length and fireline intensity). The proportion of the total landscape and resulting area burning as different fire types varied between the three data sets (Table 4). The Tahoe National Forest SFA data creates the highest proportion of the landscape burning as modeled surface fire, followed by the Sagehen Experimental Forest data and finally the Landfire data set. When compared to the SEF data, both LF and TNF overestimate probable active crown fire (Table 4). Modeled flame lengths follow the same general trends in all three data sets, the majority of the basin burns with either low (>0 to <1.2 m) or high (≥2.4 m) flame lengths. The SEF and LF data create similar proportions of modeled flame length. The TNF data predicts the majority of the landscape to burn with low flame lengths (Table 4). Modeled fireline intensity follows the same patterns seen with flame length. These patterns are possibly due to the fact that both TNF and LF have higher average canopy cover, canopy height and canopy bulk density than SEF (Table 2).

In order to better understand the impact canopy cover, canopy base height and canopy bulk density have on modeled fire behavior a sensitivity analysis was completed. Surface fire intensity coupled with crown characteristics (CBH, CH, CBD and foliar moisture content) determine fire type and resulting flame length and fireline intensity (van Wagner 1977, van Wagner 1993) in FlamMap. For each of the three GIS data sets CC, CBH and CBD were individually increased and decreased by 50% holding all else
constant. Decreasing canopy base height and canopy cover had the largest impact on modeled fire type, flame length and fireline intensity. Lowering canopy base height eases the transition from surface fire to crown fire. A reduction in canopy cover allows wind to travel through the canopy with less resistance. This reduced resistance results in higher rates of spread and possibly higher FL and FLIN and therefore an increase in crown fire occurrence. Changing canopy bulk density had relatively little effect on modeled fire behavior outputs. The LF data was most affected by changes in canopy metrics, followed by TNF and finally SEF (Table 5). The fact that the LF data was the most effected by changes in canopy metrics might again be explained by the creation and presentation of the data. Since the data is categorized into larger bins a 50% change is drastic. The TNF and SEF will not be similarly impacted. For the remained of this discussion baseline data for SEF, LF and TNF will be used.

FlamMap produces maps based on modeled fire behavior outputs which can be used as guides for managers to target hazardous areas across a landscape (Figure 4). These maps highlight the differences in the three data sets. Figures 3 and 4 illustrate the difference between the two resolutions for input and output data for the SEF (five meter), LF and TNF (both 30 m) GIS data sets. The input and output maps produced using the SEF data are more detailed than the other two. The TNF maps exhibit data in large blocks which is due to the creation of the input data layers. The LF data is more uniformly distributed across the landscape. Modeled fire behavior outputs follow the same patterns as the input data for all three data sets (Figure 4).

As mentioned above FlamMap can be used as a guide for land managers’ use in the fireshed assessment process. Often in the fireshed practice the overlapping
strategically placed area treatment (SPLAT) pattern (Figure 5) is projected on a white board as a template for an initial treatment pattern (Finney 2001, Bahro et al. 2007). However, recent research by Finney (2007) has found the pattern of treatments on more complex landscapes to be less systematic. Flame length and fire type maps are also projected to help guide the treatment locations (Bahro et al. 2007). Managers typically design fuel treatments to withstand high fire weather conditions (personal communication, Grace Newell, Tahoe National Forest). Under 90th percentile weather conditions managers try to minimize the amount of landscape burning under crown fire conditions and aim to maintain flame lengths of less than 1.2 m.

Discrepancies in modeled fire type, flame length and fireline intensity from the three data sets can lead to fuel treatment plans that might not be effective. If a manager only looks at modeled flame length to determine the total area of the landscape requiring treatment, SEF would require 44%, LF 48% and TNF 27% for the 90th percentile fire weather condition (Table 4). As with the proportion of landscape needing treatment, the location for potential treatments varies between the three data sets (Figure 4). The SEF and LF fire behavior maps are more similar to each other than to TNF. Based on potential fire type or flame length maps, a manager might not treat the middle portion of Sagehen with the TNF data (Figure 4). Treatment scenarios would be quite different with each of the three data sources based in resulting FlamMap maps.

In order for land managers to make the most informed decision on landscape-level fuel treatments, accurate canopy and surface fuels data is needed. Overall modeled fire behavior was more similar between SEF and LF as compared to SEF and TNF (Table 4, Figure 4). This might be attributed to the fact that SEF and LF were significantly
correlated to the field plots, whereas TNF was not. When comparing the differences in modeled fire behavior mangers might be inclined to treat the highest proportion of the landscape if they use the LF data followed next by the SEF data and finally the TNF data. The ability of the input data to represent current vegetation and fuel characteristics does impact potential fire behavior (fire type, flame length and fireline intensity) and probable fuel treatments on the landscape.

**Literature Cited**


Table 1: Summary statistics from three geographic information system (GIS) data sets for Sagehen Experimental Forest and the field plot data.

SEF = Sagehen Experimental Forest GIS data; LF = Landfire GIS data; TNF = Tahoe National Forest GIS data;

CC = canopy cover; CBH = canopy base height; CH = canopy height; CBD = canopy bulk density

<table>
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<th>LF n=51044</th>
<th>TNF n=51044</th>
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<td>Range</td>
<td>Avg. (SD)</td>
<td>Range</td>
</tr>
<tr>
<td>CC (%)</td>
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<td>0-100</td>
<td>57(19)</td>
<td>0-95</td>
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<td>0-10.5</td>
<td>1.7(0.7)</td>
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<td>0.146(0.06)</td>
<td>0-0.360</td>
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<td></td>
<td></td>
<td>0.096(0.066)</td>
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Table 2: Pearson product-moment correlation coefficient, r, values for comparing canopy cover (CC), canopy base height (CBH), canopy height (CH), canopy bulk density (CBD), and fuel model (FM) between the GIS layers and the 522 field plots at Sagehen Experimental Forest, note CC only compares the 113 plots where values were collected.

SEF = Sagehen Experimental Forest GIS data; LF = Landfire GIS data; TNF = Tahoe National Forest GIS data

* denotes statistically correlated to plot data (α=0.02)
Table 3: a) Percentage of total landscape and b) area (ha) occupied by modeled fire type, flame length and fireline for Sagehen Experimental Forest for the 90th and 97.5th percentile fire weather scenarios.

SEF = Sagehen Experimental Forest GIS data; LF = Landfire GIS data; TNF = Tahoe National Forest GIS data
PCF = passive crown fire; ACF = active crown fire

Flame length categories: Low = 0 to <1.2 m; moderate = 1.2 to <2.4 m; high >2.4 m
Fireline intensity categories: Low =0 to <346 kW/m; moderate = 346 to <1730 kW/m; high >1730 kW/m
Table 4: Percent difference between base level values and sensitivity analysis values at Sagehen Experimental Forest where either a) CC (canopy cover), b) CBD (canopy bulk density), or c) CBH (canopy base height) layers were decreased by 50% (-50%) or increased by 50% (+50%). A negative value denotes a decrease in the given metric as compared to the baseline data.

SEF = Sagehen Experimental Forest GIS data; LF = Landfire GIS data; TNF = Tahoe National Forest GIS data; SF = surface fire; PCF = passive crown fire; ACF = active crown fire

### a) CC

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<th>PCF</th>
<th>ACF</th>
<th>SEF - 50%</th>
<th>SEF + 50%</th>
<th>LF - 50%</th>
<th>LF + 50%</th>
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</tr>
<tr>
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<td>(kW/m)</td>
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### b) CBD

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<th>SEF + 50%</th>
<th>LF - 50%</th>
<th>LF + 50%</th>
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<td>(m)</td>
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### c) CBH

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<th>PCF</th>
<th>ACF</th>
<th>SEF - 50%</th>
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Figures

Figure 1: Location and dominant vegetation types for Sagehen Experimental Forest.

Figure 2: Georeferenced vegetation and fuel characteristic plots (note the three densities 500 m, 250 m and 125 m spacing) in Sagehen Experimental Forest.
Figure 3: Examples of input data maps created for Sagehen Experimental Forest for 1) canopy bulk density and 2) fuel model for the a) SEF, b) LF and c) TNF data sets. SEF = Sagehen Experimental Forest GIS data; LF = Landfire GIS data; TNF = Tahoe National Forest GIS data.
Figure 4: Examples of output fire behavior maps created in FlamMap created for Sagehen Experimental Forest for 1) fire type and 2) flame length for the a) SEF, b) LF and c) TNF data sets under the 90th percentile fire weather scenario.
SEF = Sagehen Experimental Forest GIS data; LF = Landfire GIS data; TNF = Tahoe National Forest GIS data.
Figure 5: Figure depicting the layout for strategically placed area treatment units (adapted from Finney 2001).
Chapter 3: Evaluation of the fireshed assessment process for delineating strategically placed area treatments in a complex landscape, Sagehen Experimental Forest

Abstract

The goal of a fuel treatment is to reduce potential intensity and severity of a wildland fire event. Much of the existing research explores stand-level fuel treatments; currently landscape-level treatments are not well understood. The fireshed assessment, an iterative process used to delineate landscape-level fuel treatments, was implemented for Sagehen Experimental Forest (Sagehen) on the Tahoe National Forest in California. Sagehen provided an opportunity for testing the effectiveness of strategically placed area treatments (SPLATs) in a complex landscape. The goal of this research is to assess the outcome of fireshed planning by comparing the effectiveness of six SPLAT plans created for Sagehen to reduce potential fire intensity. Four of the SPLAT designs were created using the fireshed assessment process (S1, S2, S3 and S4) and two were theoretically derived (Finney and TOM). The six SPLAT scenarios treated between 27 and 38% of the landscape. In addition to the various percentages of treated areas the location, size and shape of the treatment units varied between the six scenarios. All treated landscapes had reduced mean modeled flame lengths, fireline intensity and less intense fire types when compared to the untreated landscape. The S3 and S4 SPLATs experienced the greatest reduction in fire intensity. The TOM SPLAT design proved to be the most effective at slowing the forward progression of the problem fire. It might be worth considering additional treatment plans based on the TOM SPLAT design before selecting a treatment plan for Sagehen.
Introduction

Land managers have new-found interest in the effectiveness of fuel treatments with the large number of wildland fires in California in recent history (Stephens 2005). An effective fuel treatment reduces potential fire behavior (i.e. fireline intensity and flame length) and ultimately effects (i.e. tree mortality). Fuel treatments are implemented to target surface fuels, ladder fuels, canopy fuels or any combination of the three. Mechanical or manual thinnings of various intensities, mastication, whole tree removal and/or prescribed fire are some of the methods used to alter fuels. Treatments are completed in many shapes and sizes and are used reduce potential fire behavior at both stand and landscape-scales. Much of the decision making process for designing and implementing fuel treatments depends on the objectives. For example, treatment design will vary for the following objectives: protecting the wildland urban interface, reintroducing fire as a natural process, protecting wildlife habitat, increasing forest health, aiding in suppression efforts and reducing the risk of catastrophic wildland fire occurrence.

Fuel treatment effectiveness at reducing fire behavior and effects at the stand-level has been well studied in coniferous forests (i.e. Kauffman and Martin 1989, van Wagendonk 1996, Pollet and Omi 2002, Agee and Skinner 2005, Stephens and Moghaddas 2005a, Stephens and Moghaddas 2005b, Vaillant et al. 2006). Effectiveness of fuel treatments is often shown indirectly through fire behavior modeling or directly through monitoring wildland fire effects such as tree mortality. Stand-level treatments have been shown to effectively reduce fire severity, reduce fire size and aid in

As mentioned above, much of the current research explores the effectiveness of stand-level fuel treatments; currently the effectiveness of landscape-level treatments is not well understood. The concept of designing fuel treatments to reduce potential fire behavior at the landscape-level is new. Finney (2001) introduced the theory of strategically placed area treatments (SPLATs). SPLATs are disconnected, rectangular treatment units which overlap to slow the forward progression of a heading fire (Figure 1). A heading fire is the portion of a fire being pushed by wind and is often the fastest moving and most difficult to control. Simulations proved SPLAT treatments to reduce the heading fire spread rate by treating less than one-third of the landscape (Finney 2001). The reduced spread rate was seen both inside the treatment units and in the matrix between units (Finney 2001). To date, few studies further explored the idea of landscape treatments using fire behavior modeling (Stratton 2004, Finney 2007, Finney et al. 2007, Kerby et al. 2007, Parisien et al. 2007, Gonzalez et al. 2008, Schmidt et al. 2008).

The Stewardship and Fireshed Assessment (SFA) process was created to evaluate and design landscape-level fuel treatments for the National Forests in California (Bahro et al. 2007). A fireshed is a large landscape that shares similar fire regimes, fire history or wildland fire risk (Bahro and Perot 2006, Bahro et al. 2007). Often a fireshed is delineated by a watershed boundary. Once the fireshed is defined, the next step is to determine the “problem” fire. A problem fire is a hypothetical wildland fire that is expected to burn an area with elevated intensity resulting is adverse effects (Bahro et al. 2007). The problem fire is defined based on current fuel conditions, known hazardous
wind patterns, topographic features or a combination. Finally, a SPLAT plan is created to reduce potential fire behavior and effects taking into consideration current fuel conditions, treatment opportunities and resources for the fireshed (Bahro et al. 2007).

The typical progression of creating a SPLAT plan with the fireshed assessment starts with a template of overlapping treatments aligned to reduce the potential fire behavior of the problem fire (Figure 1). The template is projected onto a white board with current vegetation, fuels (canopy and surface) and topographic layers displayed. Next, the assessment team identifies areas available for treatment based on feasibility (cost and accessibility), environmental sensitivity and logistical restraints (Bahro et al. 2007). The more complex the fireshed, the farther treatment units might deviate from the initial projected template (Finney 2007). In FlamMap (Finney 2006), a fire behavior and growth model, fire behavior maps are created to highlight areas of greater concern (i.e. areas exhibiting crown fire or high flame lengths). Once treatment units are delineated the fireshed assessment team defines prescriptions for each unit creating a treatment plan. At this point the treatment scenario(s) can be modeled in FlamMap to test the effectiveness of the treatment(s) to alter potential fire behavior under potential weather conditions. The fireshed assessment is an iterative process to guide local interdisciplinary teams to design, test and schedule fuel treatments (Bahro et al. 2007).

The fireshed process was implemented for Sagehen Experimental Forest (Sagehen) on the Tahoe National Forest in California. Sagehen provided an opportunity for testing the effectiveness of SPLATs on a complex landscape. Sagehen is a diverse watershed comprised multiple vegetation types (Figure 2), across many different aspects along a large elevational gradient in the eastern Sierra Nevada. Six SPLAT treatment
plans were created for Sagehen. Four were created using the fireshed assessment process by the Tahoe National Forest in conjunction with University of California, Berkeley. The next two treatment plans were theoretical. The first was modeled after the original research completed by Finney (2001). The second was created using a treatment optimization model (Finney 2006). The goal of this research is to assess the outcome of fireshed planning by comparing the effectiveness of six SPLAT plans created for Sagehen to reduce potential fire intensity.

**Methods**

**Study Area**

Sagehen Experimental Forest (Sagehen) is a 4594 ha watershed on the eastern slope of the Sierra Nevada about 32 km north of Lake Tahoe (Figure 2). The watershed extends east from the crest of the Sierra Nevada at 2670 m to Highway 89 at 1862 m. Slopes are typically mild, averaging 18% but can reach 70% in parts of the watershed. Soils are generally Andic and Ultic Haploxeralfs derived from volcanic parent material (Pacific Southwest Research Station 2008).

Sagehen is in both the montane and subalpine vegetation ranges of the Sierra floristic province (Barbour et al. 2007). Sagehen is a diverse watershed with the majority of the landscape occupied by conifer forests (Figure 2). Tree species present include lodgepole pine (*P. contorta*), Jeffrey pine (*P. jeffreyi*), sugar pine (*P. lambertiana*), western white pine (*P. monticola*), white fir (*Abies concolor*), red fir (*A. magnifica*), mountain hemlock (*Tsuga mertensiana*) and quaking aspen (*Populus tremuloides*). The non-forested areas include fens, wet and dry montane meadows and shrub fields. The
shrub cover type is dominated by tobacco brush (Ceanothus velutinus), mahala mat (C. prostratus), greenleaf manzanita (Arctostaphylos patula), wax currant (Ribes cereum) and woolly mule-ears (Wyethia mollis). Sagehen is divided into 47 stands which were delineated using an aerial photograph grouping similar vegetation types or densities into individual units (Appendix C: Figure 1 and Tables 1 and 2).

Sagehen has a Mediterranean climate with warm, dry summers and cold, wet winters. Average low and high winter (January) temperatures measured at 1943 m from 1953 to present are -10 and 4 °C; average summer (July) temperatures are 3 and 26 °C. Average annual precipitation is 85 cm with snowfall accounting for about 80% of annual precipitation (515 cm on average in snowfall per year) (climate data available at [http://www.wrcc.dri.edu/](http://www.wrcc.dri.edu/)).

**Field Data Collection**

**Plot Selection**

A systematic grid of 522 permanent, georeferenced 0.05 ha circular plots was installed, based on a random starting point within Sagehen. The grid consists of three different densities, 500 m, 250 m, and 125 m spacing. The entire watershed is sampled by plots spaced on a 500 m interval. Areas not occupied by Jeffrey pine plantations were sampled at 250 m spacing. The 125 m spacing was used in 10 unique forest types to conduct high density sampling. At each plot, plot center and elevation were recorded using a hand held global positioning system (GPS) unit. In addition, aspect and slope were noted using a compass and clinometer.
Vegetation Measurements

Tree measurements (species, diameter at breast height (DBH), height, canopy base height and tree crown position (dominant, codominant, intermediate or suppressed)) were recorded for all live trees greater than 5 cm DBH. Overstory trees (≥19.5 cm DBH) were tagged and measured in the whole plot (0.05 ha); pole-sized trees (≥5 cm DBH to <19.5 cm DBH) were measured in a randomly selected third of the plot (0.017 ha). Saplings, trees <5 cm DBH, were tallied by species and diameter class (1 cm increments) along a two meter belt encompassing three 12.62 m transects (0.0072 ha). In addition, snags greater than 5 cm DBH had species, DBH and height recorded. Canopy cover (CC) was measured at 25 points in a five-by-five grid with five meter spacing using a canopy sight tube (Gill et al. 2000) in all the plots for the 125 m spaced grid and any plots initiated after these were installed (113 plots).

Tree measurements (live trees ≥5 cm) were used to calculate average canopy base height (CBH), canopy height (CH) and canopy bulk density (CBD) using Fuels Management Analyst (FMA) at the plot level (Carlton 2005). FMA incorporates established published methodologies for computing canopy bulk density, canopy base height, fire behavior, and predicted scorch and mortality by species (Stephens and Moghaddas 2005a, Stephens and Moghaddas 2005b). FMA uses information from field measurements (i.e. tree species, DBH, tree crown ratio, tree crown position and tree height) to estimate average canopy base height and canopy bulk density for a stand or plot (Reinhardt et al. 2000). Canopy bulk density for each plot is calculated using a running mean along the height of the canopy. Canopy base height for each plot is determined as the height above the ground where the first canopy layer has a high enough
density to support the vertical movement of fire (Carlton 2005). The running mean window was set to the defaults in FMA for CBH, CH (both 0.91 m), and CBD (4.57 m); the critical CBD is also set to the default, 0.011 kg/m³. Defaults were used in FMA because they are the same as is used in the Forest Vegetation Simulator (Crookston and Stage 1991) with the Fire and Fuels Extension (Reinhardt and Crookston 2003).

Shrub measurements were taken along the same three 12.62 m transects used to measure seedlings. Species, average height, and length along the transect were recorded for all shrubs present. In addition, an ocular estimate of percent cover classes (in 5% increments) of grasses, herbaceous species, and shrubs were noted for each whole plot.

**Fuel Measurements**

Surface and ground fuels were measured along the shrub transects in each of the plots using the line-intercept method (Van Wagner 1968, Brown 1974). Tallies of 1-hr (diameter less than 0.64 cm) and 10-hr (diameter from 0.64 to 2.54 cm) time lag fuels were recorded from 0 to 2 m, and 100 hr (greater than 2.54 to 7.62 cm diameter) from 0 to 3 m. Species, diameter and decay status (rotten or sound) were recorded for all 1000-hr fuels (diameter greater than 7.62 cm) along the whole transect (12.62 m). Litter, duff, and fuel bed depth measurements were taken at two points along each transect (at 5 m and 10 m).

Surface and ground fuel loads were calculated using coefficients arithmetically weighted specific to the average basal area fraction of the tree species at each plot (van Wagendonk 1996, van Wagendonk et al. 1996, Stephens 2001, Vaillant et al. 2006). Fuel models (FM) were then assigned to plots based on the calculated surface fuel loads, vegetation type, and the presumed carrier of fire (Scott and Burgan 2005).
Sagehen Experimental Forest Geographic Information System (GIS) Layers

The GIS layers created for Sagehen consists of five meter resolution raster data derived from LiDAR, field plots an aerial photograph. Topographical information (elevation, slope and aspect) was derived directly from LiDAR data (dual pulse LiDAR flights took place in the summer of 2005). The LiDAR data was initially sampled at 0.25 m resolution and was aggregated up to one meter resolution. A five-by-five grid of one meter cells was next averaged to create the five meter resolution cells used to make the digital elevation model (DEM). Slope and aspect were derived from the DEM.

Data layers for canopy characteristics were created using both LiDAR and field data. The canopy height (CH) layer was created the same way as the DEM with an additional step to check the accuracy against the field data. The canopy cover (CC) layer was derived from canopy height data and compared to the field data. A binary grid of five-by-five one meter cells was created to denote a “hit or miss,” much like is done with a canopy tube in the field, to calculate percent canopy cover for each five meter cell. Finally, the data was filtered to only include canopy cover where trees taller than five meters were present.

The canopy base height (CBH) layer was created using a Kriging interpolation. A Kriging interpolation determines the value of an unknown field based on value of nearby fields using a linear least squares estimation (Goovaerts 1997). The interpolation for the canopy base height layer was based on a combination of the calculated CBH at each plot and the canopy height GIS layer. The canopy bulk density layer was also created using the values calculated in FMA (Carlton 2005). A global multiple-regression equation was
used to calculate the CBD and create the raster layer in GIS. The regression equation used to create the CBD layer was:

\[
CBD (\text{kg/m}^3) = \{0.03867 + [\text{canopy height (m)} \times (-0.0022)] + [\text{canopy base height (m)} \times 0.0018] + [\text{canopy cover (\%)} \times 0.0023]\).
\]

The fuel model layer was created using field data and aerial photography. An object-based image analysis (Jain 1988) was performed using a current aerial photograph to determine unique clusters and create the associated polygons based on vegetation characteristics in GIS. The fire carrying fuel type (litter, shrub, grass or a combination), average calculated fuel load and stand characteristics (i.e. basal area by tree species and shrub cover) at each plot was used to select appropriate fuel models from the extended set (Scott and Burgan 2005). A nearest-neighbor interpolation was used to populate polygons in GIS with fuel models. A nearest-neighbor interpolation is a technique for assigning data to non-valued cells in GIS by using the value of the nearest point (ESRI 2008). Finally, local expert opinion from the Tahoe National Forest was used to validate the fuel model selections. Experts were the Fuels Manager, Fuels Officer, Silviculturist and Timber Operation Manager from the Truckee Ranger District on the Tahoe National Forest.

**Strategically Placed Area Treatments (SPLATs)**

**SPLAT Creation**

Six SPLAT designs were created for Sagehen Experimental Forest. The S1, S2, S3 and S4 SPLATs were created by an interdisciplinary (ID) team from the Tahoe
National Forest in conjunction with the University of California, Berkeley (UCB) (Figure 3). The ID team was comprised of at least one Fuels Specialist, Silviculturist, Hydrologist, Wildlife Biologist, District Ranger, Engineer and Archeologist. The UCB group primarily supplied technical support in the form of FlamMap (Finney 2006) and FARSITE (Finney 1998) fire behavior and spread modeling. All members were familiar with Sagehen and a few field trips were conducted to discuss possible scenarios. The S1, S2, S3 and S4 SPLATs take into account accessibility, cost, increased forest health, landownership and ecological objectives. The creation of these SPLATs was an ongoing process with several revisions. The S1 and S2 SPLATs only differ in the addition of a 25 ha treatment unit in the south-central region of Sagehen for the S2 SPLAT (Figure 3a and 3b). The S3 and S4 SPLATs included a larger treatment unit in the eastern part of the basin which was not present in the S1 and S2 SPLATs. The difference between the S3 SPLAT and the S4 SPLAT was the inclusion of the same 25 ha unit as the S2 SPLAT for the S4 SPLAT (Figure 3c and 3d). Once the four SPLAT designs were created, treatment prescriptions were assigned by the Tahoe National Forest ID team (Figure 3).

An additional two theoretical SPLAT plans were created for Sagehen for this research. The first SPLAT designs followed the theory put forth by Finney (2001) (Figure 4a). For the duration of this project this will be referred to as the Finney SPLAT. The Finney SPLAT did not take into account road access, land ownership, ecological objective, cost or protected areas. The equally sized rectangular units efficiently modify fire behavior with less than one-third of the landscape being treated (Finney 2001). The long axis of the treatment units is oriented perpendicularly to the most likely or worrisome direction of the problem fire. The orientation of the Finney SPLAT was
determined by the direction of a head fire starting along the southwest edge of Sagehen moving toward the northeast (Figure 4d), which is a main concern of the Tahoe National Forest. The treatment types within the Finney SPLAT units were based on the general proportion and location of treatments as outlined by the ID team Tahoe National Forest (Figure 4a).

The second theoretical SPLAT design was created using the treatment optimization model (TOM) in FlamMap (Figure 4b). TOM uses two landscapes, the baseline data and an “ideal landscape”. The ideal landscape represents the ideal post-treatment situation for the portions of the landscape available for treatment. For this study areas not available for treatment include a 22.9 m (75 ft) buffer around Sagehen Creek and it’s tributaries, areas with sensitive or threatened plant species, spotted owl and goshawk PACs (protected activity centers) and archeological sites (Figure 4c). The area not available represents about 15% of the entire landscape. TOM treatment areas are determined by using the minimum travel time (MTT) calculations in FlamMap (Finney 2002). MTT iterations propagate fire across the landscape to determine the major flow pattern pathways (the direction in which fire will move at the fastest rate) (Finney 2002). TOM will choose areas where treatments change fire behavior resulting in the greatest collective reduction in MTT fire spread rate (Finney 2006). For the treatment optimizing modeling a fire was initiated across the southwestern edge of Sagehen (Figure 4d); again this is the potential fire of highest concern for the Tahoe National Forest.

The treatment optimization model allows the user to input the resolution for calculations, weather conditions, maximum size of treatment and a proportion of the landscape to be treated. The 90th percentile weather scenario (derivation of the weather
conditions are described below) was utilized to remain consistent with the original SPLAT theory (Finney 2001). The proportion of the landscape available for treatment was set to 30%. Thirty percent of the landscape was treated to remain consistent with the Finney SPLAT. For the pattern of the resulting TOM SPLAT see Figure 4b. The TOM SPLAT will be treated based on the general proportion and location of the treatments created by UCB and the Tahoe National Forest much like the Finney SPLAT.

_SPLAT “Implementation”_

Implementation of the six SPLAT scenarios to the baseline GIS data for Sagehen followed a set of rules created through an iterative process of existing treatment data from many of the United States National Forests in northern California. Prescription target multiplication factors were determined for each treatment type for the canopy cover, canopy base height and canopy bulk density layers and applied within the SPLAT perimeters using GIS (Table 1). Multiplication factors are values used to manipulate the existing GIS data layers within the SPLAT perimeters to create post-treatment landscapes. In addition to the multiplication factors, prescription limits were applied so data remained realistic (Table 1). For example, canopy bulk density is not allowed to drop below 0.10 kg/m³ due to treatment. If CBD was already below 0.10 kg/m³ then CBD would maintain the original value. Canopy cover was not permitted to be below 45% or above 100%. Finally for the fuel model layer, new fuel models were assigned according to the starting point and treatment type within the SPLAT perimeters (Table 2). In general four types of treatments were chosen for Sagehen; 1) thin or thin with mastication; 2) heavy mechanical thin; 3) prescribed fire; and 4) a combination of thinning and burning. Elevation, slope, aspect and canopy height will remain constant no
matter the treatment. When multiple treatments occurred at a given point, treatments were completed successively with the mechanical treatment followed by the prescribed burn treatment.

**Fire Modeling**

**FlamMap Inputs**

In order to run FlamMap, a landscape file (LCP) and a fuel moisture file (FMS) are required. Wind (WND) and weather (WTR) files are used for these simulations to condition fuel moistures. When custom fuel models are used a custom fuel model file (FMD) is required. The FMD describes the characteristics (i.e. fuel load, fuel bed depth, surface area to volume ratio and heat content) of the custom fuel model(s). For this study one low-load slash custom fuel model was used inside the treatment units. The parameters for the LCP, FMS, WND, and WTR files are described below.

The LCP is created by converting the eight GIS raster files (elevation, slope, aspect, canopy cover, canopy base height, canopy height, canopy bulk density and fuel model) into ASCII grid files, and importing them into FlamMap. These files need to be coregistered, have equivalent extent, and have identical resolution to work within FlamMap. For the analysis eight unique landscape files were created. The first represented the baseline data for Sagehen. The next four the LCPs were for the SPLAT treatment plans determined by the Tahoe National Forest fireshed assessment. The six LCPs represented the landscape treated with the Finney SPLAT. And the final two landscape files were for the landscape treated with the TOM SPLAT (the ideal landscape used to create the TOM SPLAT and the resulting TOM SPLAT).
In addition to the landscape file, FlamMap requires non-spatial and non-temporal weather and fuel moisture information to simulate fire behavior. The FMS file defines the initial fuel moisture for dead and down as well as live fuel components. Fire Family Plus (Main et al. 1990) was used to determine the values for the 90\textsuperscript{th} (high) and 97.5\textsuperscript{th} (extreme) percentile fire weather conditions (Appendix B: Table 1). Forty-five years (1961 to 2006) of weather data from the Stampede Remote Access Weather Station (less than 10 km east of Sagehen) from June 1 to October 31 were analyzed to determine percentile weather conditions.

Fire Family Plus was also used to create WND and WTR files with hourly weather data for the days leading up to the Cottonwood Fire. The Cottonwood Fire was a large fire (19,000 ha) that occurred just north of Sagehen in 1994. The 10 day period (August 6 to 15, 1994) prior to the fire was used to condition the initial fuel moistures from the FMS file. Conditioning fuel moistures creates more realistic fuel conditions for FlamMap simulations.

\textit{Fire Behavior Outputs}

FlamMap is designed to help plan fuel treatments (Finney 2002, Stratton 2004, Finney 2006, Husari et al. 2006). FlamMap calculates fire behavior independently for each pixel across the landscape and holds the key fire weather variables (i.e. windspeed, wind direction and fuel moisture) constant. Therefore, the outputs capture the spatial variability in fire behavior due to differences in fuel conditions (Finney 2006). For this study both basic fire behavior outputs and MTT outputs will be utilized. Basic fire behavior outputs are used to create fire hazard maps based on current fuel conditions under the given weather scenario. The MTT outputs calculate fire growth from a
predetermined ignition point or line in the absence of time-varying winds and fuel moistures allowing analysis of the effects of spatial patterns of fuels and topography (Finney 2006). The ignition line was positioned along the southwest edge of Sagehen to mimic the potential problem fire for the watershed Figure 4d). For this study the MTT runs were allowed to burn indefinitely until the whole landscape experienced fire.

A total of 28 simulations were run to model potential fire behavior (fire type, flame length and fireline intensity) and MTT fire spread and MTT fireline intensity. Fourteen simulations were run for each of the seven landscape files for the 90th and 97.5th percentile fire weather scenarios. An additional 14 simulations were run for MTT fire spread and MTT fireline intensity using the 90th and 97.5th percentile fire weather scenarios to compare the baseline output to the six SPLAT scenarios.

**Data Analysis**

To compare treatments, normalized means were presented for flame length (FL) and fireline intensity (FLIN) for all seven treatment plans under both fire weather conditions. In addition, normalized difference between treated and untreated conditions for fire type (surface fire, passive crown fire and active crown fire), FL and FLIN were calculated for the 90th and 97.5th percentile weather conditions. The data was normalized by the proportion of the landscape treated. The Finney SPLAT was used to set the normalization ratios. The Finney SPLAT plan was chosen because it was the SPLAT which treated the smallest proportion of Sagehen.

Mean and standard deviation MTT fireline intensity (MTT FLIN) and MTT arrival time (MTT arrival) for all seven treatment scenarios for both fire weather conditions were presented. In addition, maps for the 90th percentile conditions showing
the difference in MTT FLIN and MTT arrival between the baseline data and each SPLAT scenario were created. Due to the number of assumptions associated with fire behavior models statistically testing is not possible (Stephens and Moghaddas 2005a, Vaillant et al. 2006).

**Results**

**SPLAT Descriptions**

Treated area ranged from 1227 to 1741 ha for the six SPLAT scenarios with the S4 SPLAT having the largest area treated and the Finney SPLAT the least (Table 3). The TOM SPLAT had the smallest average treatment unit size (4 ha) and the Finney SPLAT largest (45 ha). The S1, S2, S3 and S4 SPLATs all had the largest single treatment unit, 236 ha (Table 3).

**Modeled Basic Fire Behavior Outputs**

Modeled fire type is divided into four categories, no fire, surface fire, passive crown fire, and active crown fire in FlamMap (Table 4). Modeled flame length (FL) was divided into four bins, zero (0 m), low (>0 to <1.2 m), moderate (1.2 to <2.4 m) and high (≥2.4 m) (Table 4) (Sugihara et al. 2006). Modeled fireline intensity (FLIN) was categorized similarly with zero (0 kW/m), low (>0 to <346 kW/m), moderate (346 to <1730 kW/m), and high (≥1730 kW/m) groups (Table 4) (Sugihara et al. 2006). The categories for flame length and fireline intensity were chosen because of their relation to suppression tactics. The low category corresponds to fire behavior where the suppression by a person with a hand tool is possible at the head or flanks of the fire (NWCG 2006). Here handline should hold the fire. Moderate flame lengths and fireline intensity occur
when the fire is too intense for direct attack on the head fire by a person with a hand tool. At this point heavier equipment such as dozers, engines or aircraft with fire retardant may be necessary (NWCG 2006). Handline can not be relied on to hold the fire. The high category represents fires that may present serious control problems. Attempts to control the head fire will probably be ineffective (NWCG 2006).

The six treated landscapes experienced an increase in surface fire when compared to the baseline data for the 90th and 97.5th percentile weather situations (Table 4). Area (hectares) of low and moderate flame lengths increased for all six treatment scenarios when compared to the baseline data for 90th percentile weather (Table 4). Under the 97.5th percentile weather scenario, only land burning as moderate flame lengths increased as compared to the baseline data. Modeled fireline intensity followed the same basic trends as FL for both weather scenarios (Table 4).

Normalized mean values for both FL and FLIN were lower for all six of the treated landscapes (Finney, TOM, S1, S2, S3 and S4 SPLATs) when compared to the baseline data for both fire weather scenarios (Table 5). The S3 and S4 SPLATs experience the greatest reduction in normalized mean flame length and fireline intensity for the 90th and 97.5th percentile weather conditions (Table 5). The Finney SPLAT maintained the highest mean flame length of all the treated landscapes. For the 90th percentile weather scenario the TOM SPLAT had the highest mean FLIN of the treated landscapes (Table 5).

**Minimum Travel Time Outputs**

Minimum travel time outputs are based the problem fire propagating from the southwestern edge of Sagehen (Figure 4b). Mean minimum travel time fireline intensity
was reduced for all six SPLAT treatments under both weather conditions (Table 6). Mean MTT arrival was faster for all treatment scenarios under both weather conditions. The theoretical data sets had lower mean arrival times when compared to the designs created by the Tahoe National Forest. Figures 4 and 5 depict difference maps for MTT FLIN and MTT arrival. MTT FLIN both increases and decreases inside of treatment units as well as in the matrix between treatment units (Figure 5). As with MTT FLIN, MTT arrival both increases and decreases in speed occur inside and outside of the treatment units (Figure 6). However, the TOM SPLAT slows modeled fire spread more so than the other five treatments (Figure 6).

**Discussion**

The fireshed process is a tool for managers to devise a landscape-level fuel treatment plan. Finney (2001) showed strategically placed area treatments will reduce fireline intensity and spread rates both inside and outside of treated areas for a simplistic landscape. If treatments are opportunistically placed to impede the heading direction of a problem fire, only a fraction of the landscape will require alteration. In addition, Finney (2007) found the same to be true in a slightly more complex landscape with a test case landscape outside of Flagstaff, Arizona. This research attempted to follow the same fire behavior modeling protocol as the original work by Finney (2001) on a very diverse watershed, Sagehen Experimental Forest. Six SPLAT treatments designed for Sagehen were compared to assess the outcome of fireshed planning to reduce potential fire behavior.
At Sagehen, strategically placed area treatments did alter overall modeled fire behavior (fire type, flame length and fireline intensity) for all six SPLAT scenarios when compared to the untreated landscape. Four of the six SPLAT designs (S1, S2, S3 and S4) were created through the fireshed assessment process in conjunction with the Tahoe National Forest interdisciplinary team. All four of the variants treated at least one-third of the watershed with increased percentages from the S1 SPLAT to the S4 SPLAT (33, 35, 37 and 38% respectively). The S1 and S2 SPLATs vary in the inclusion of a smaller unit of heavy mechanical thinning followed by prescribed fire in the middle of the watershed for the S2 SPLAT (Figure 3b). The S3 and S4 SPLATs include a larger unit of thinning or thinning and mastication followed again by prescribed fire in the southeast end of the watershed which was not included in the S1 and S2 SPLATs (Figure 3). In addition, the S4 SPLAT includes the same extra unit as the S2 SPLAT, whereas the S3 SPLAT does not (Figure 3d).

The final two SPLAT plans were theoretically devised. One was modeled directly from the foundation of the theory (Finney SPLAT) and the other based on the treatment optimization model within FlamMap (TOM SPLAT) (Finney 2001, Finney 2006). Although both are of theoretical basis, the Finney and TOM SPLATs differed in their creation. The Finney SPLAT did not take into account areas unavailable for treatment where as the TOM SPLAT did. The TOM SPLAT was dominated by very small treatment units with an average treatment size of four hectares. The Finney SPLAT used replicated rectangular units aligned to impede the problem fire. Both of the theoretical SPLAT designs treated about 27% of the watershed.
The four SPLAT plans designed by the Tahoe National Forest with the fireshed process were created to do more than just modify potential fire behavior. Unlike the Finney SPLAT, the S1, S2, S3 and S4 SPLATs take into account accessibility, cost, forest health, landownership and ecological objectives. Like the TOM SPLAT, the S1, S2, S3 and S4 SPLATs are limited in the locations which treatments were allowable. Treatments could not occur in the stream course zone, archeological sites, goshawk and spotted owl PACs and in areas with sensitive and threatened plant species. The resulting SPLAT patterns greatly deviated from the theoretical (Finney SPLAT) framework once all exclusions and additional objectives were included.

The S3 and S4 SPLATs experienced the greatest change in potential modeled fire behavior for the 90th percentile fire weather condition (Table 4). The amount of land burning as surface fire increased and high flame lengths and fireline intensity decreases the most for the S3 and S4 SPLAT plans. Under the 97.5th percentile fire weather condition the S2, S3 and S4 SPLAT plans were the most changed for surface fire, flame length and fireline intensity respectively. The Finney SPLAT performed the worst out of the six SPLAT plans for both weather conditions.

The four fireshed assessment SPLAT scenarios experienced larger decreases in area burned as active crown fire, high flame lengths and high fireline intensity than the theoretical SPLATs under both high and extreme fire weather. However, the amount of land burning as low fireline intensity decreased. The decreased amount of land experiencing low FLIN is likely due to the implementation of the SPLATs and the post-treatment fuel model selection. In areas where the initial fuel model was either timber-litter or timber-understory, post-treatment became a slash-blowdown fuel model to better
depict reality for mechanical treatments (Scott and Burgan 2005, Table 2). Slash fuel models are characteristic of low flame lengths, moderate rates of spread and increased fireline intensity.

Minimum travel time (fireline intensity and arrival time) metrics were also altered by the six SPLAT treatments. MTT calculations are based on propagation of the problem fire initiated along the southwest edge of Sagehen (Figure 4d). Fire was allowed to burn indefinitely until the whole landscape burned. This was done to compare MTT arrival and MTT FLIN for the six SPLAT scenarios to the untreated baseline landscape. Mean MTT FLIN values were quite different than the basic mean fireline intensity values, but they followed the same trends (Tables 5 and 6).

The remainder of minimum travel time discussion will be based on difference maps for MTT fireline intensity (Figure 5) and MTT arrival time (Figure 6). As fire spreads the area inside of treatment units as well as the matrix between treatments will be affected. MTT FLIN changes not only inside the treatment units for each SPLAT scenario but also outside the treatment units. This is different than the original work that the theory of SPLATs was based on (Finney 2001). The difference might be associated with the increased complexity found at Sagehen. As with the basic fire behavior outputs changes in MTT FLIN may be partially attributed to the change in fuel model selection during the implementation of the SPLATs. Increasing and decreasing spread rates for the baseline landscape minus the treated landscapes can be seen in Figure 6. This shows that the TOM SPLAT slows fire more so than the other five SPLAT plans, even though the mean value is not higher than that of the baseline data (Table 6). Increasing rates of spread are not uncommon in fuel treatments in forested ecosystems (Martinson and Omi
By increasing canopy base height, and opening canopy closure winds are able to move more freely through the canopy and wind speeds will increase on the canopy floor.

All six SPLAT scenarios accomplished the goal of reducing basic fire behavior outputs and minimum travel time fireline intensity across the landscape. The four SPLAT treatments devised by the Tahoe National Forest fireshed assessment process reduced mean FL, FLIN and MTT FLIN more than the theoretical treatments. Of the four SPLAT treatments created through the fireshed process the S3 and S4 SPLATs preformed the best. However, the addition of the small 25 ha unit which differentiates the S3 SPLAT from the S4 SPLAT might not gain much as was seen in Tables 5 and 6 and Figures 5 and 6. The two theoretical treatments are not necessarily feasible given logistical, ecological and financial limitations. However, through the findings in this paper the TOM SPLAT design might be a better template for the fireshed process than the Finney SPLAT. The TOM SPLAT slowed fire progression more than any of the other treatment scenarios. This reduction in fire spread can lead to smaller fires and aid in the suppression process. In addition, the ability to exclude areas not available for treatment through the use of the ideal landscape, in the treatment optimization model in FlamMap, will result in more informed maps for land managers to base the fireshed assessment process (Finney 2007).

The fireshed assessment process for Sagehen Experimental Forest was based upon the Finney SPLAT design. The original fire behavior simulations were completed using FARSITE to visualize the differences in spread rates for the various SPLAT iterations under multiple weather conditions. The process started before the minimum travel time and treatment optimization models existed in FlamMap. With FlamMap gaining greater
acceptance in the management world (Finney 2002, Stratton 2004, Finney 2006, Husari et al. 2006) and with the addition of the MTT and TOM options within FlamMap (Finney 2006) it might be worth creating a new SPLAT template for the fireshed process at Sagehen based on the TOM SPLAT.

The TOM SPLAT and the S1, S2, S3 and S4 SPLATS are quite different in the spatial distribution of treatment units. The location of the S1, S2, S3 and S4 SPLATs seem to be counterintuitive to slowing the progression of the problem fire starting along the southwestern edge of Sagehen. The fireshed assessment SPLATs tend to be concentrated in the northern and eastern portions of Sagehen (Figure 3). On the other hand, the TOM SPLAT focused treatments in the western half of the basin (Figure 4b), concentrating efforts to slow the forward progression of the problem fire closer to the ignition source. The creation of new SPLAT designs using the TOM SPLAT as a template might be worth pursuing, and testing to see if a new alternative might be more effective at altering potential fire behavior from the problem fire.

**Literature Cited**


**Tables**

<table>
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<th>Prescription</th>
<th>Canopy Metric</th>
<th>Prescription Target Multiplication Factor</th>
<th>Prescription Limits</th>
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<td>Thin or Thin and Masticate</td>
<td>Canopy cover</td>
<td>0.75</td>
<td>45-100 %</td>
</tr>
<tr>
<td></td>
<td>Canopy base height</td>
<td>2.20</td>
<td>&gt;1.88 m</td>
</tr>
<tr>
<td></td>
<td>Canopy bulk density</td>
<td>0.63</td>
<td>&gt;0.10 kg/m³</td>
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<tr>
<td>Heavy Mechanical Thin</td>
<td>Canopy cover</td>
<td>0.55</td>
<td>45-100 %</td>
</tr>
<tr>
<td></td>
<td>Canopy base height</td>
<td>2.80</td>
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Table 1: Prescription target multiplication factors are the values the geographic information system (GIS) data was multiplied by to get post-treatment values. Prescription limits are the range in which GIS data layers were allowed to be altered.

<table>
<thead>
<tr>
<th>Initial FM</th>
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<tr>
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</tr>
<tr>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>102</td>
<td>102</td>
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Table 2: Fuel model rule set for selection fuel models post-treatment at Sagehen Experimental Forest. All fuel model numbers are associated with the expanded set of fuel models (Scott and Burgan 2005), except 212 which is a custom slash fuel model.
<table>
<thead>
<tr>
<th>SPLAT Treatment</th>
<th>Average Area (ha)</th>
<th>Range Area (ha)</th>
<th>Rx Fire Only (ha)</th>
<th>Thin or Thin and Masticate and Rx Fire (ha)</th>
<th>Heavy Mechanical Thin and Rx Fire (ha)</th>
<th>Total Area Treated (ha)</th>
<th>% of Landscape Treated</th>
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<tr>
<td>S1</td>
<td>55</td>
<td>2-236</td>
<td>134</td>
<td>818</td>
<td>561</td>
<td>1513</td>
<td>32.9</td>
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<td>S2</td>
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<td>2-236</td>
<td>134</td>
<td>818</td>
<td>586</td>
<td>1538</td>
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<td>S3</td>
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<td>2-255</td>
<td>134</td>
<td>1021</td>
<td>561</td>
<td>1716</td>
<td>37.3</td>
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<tr>
<td>S4</td>
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<td>2-255</td>
<td>134</td>
<td>1021</td>
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<td>1741</td>
<td>37.9</td>
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<td>5-60</td>
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<td>480</td>
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<td>26.7</td>
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<td>TOM</td>
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<td>&lt;1-207</td>
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<td>473</td>
<td>1240</td>
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Table 3: Description of six strategically placed area treatment plans designed for Sagehen Experimental Forest.
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<th>Fire Type</th>
<th>Untreated (ha)</th>
<th>a) 90th Percentile</th>
<th>Normalized Difference (ha) Between Treated and Untreated Landscapes</th>
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<tr>
<td></td>
<td></td>
<td>No Fire</td>
<td>SF</td>
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<td>Flame Length (m)</td>
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<tr>
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<td>Moderate</td>
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<td>351</td>
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<tr>
<td></td>
<td>High</td>
<td>1842</td>
<td>-408</td>
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<tr>
<td>Flame Length (m)</td>
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<td>2489</td>
<td>-61</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>250</td>
<td>476</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1781</td>
<td>-413</td>
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</table>

<table>
<thead>
<tr>
<th>Fire Type</th>
<th>Untreated (ha)</th>
<th>b) 97.5th Percentile</th>
<th>Normalized Difference (ha) Between Treated and Untreated Landscapes</th>
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<tr>
<td></td>
<td></td>
<td>No Fire</td>
<td>SF</td>
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<tr>
<td>Flame Length (m)</td>
<td>Low</td>
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<td>-67</td>
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<td></td>
<td>Moderate</td>
<td>173</td>
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<tr>
<td></td>
<td>Moderate</td>
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<td>444</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1903</td>
<td>-334</td>
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Table 4: Normalized difference between the treated and untreated landscapes for molded fire type, flame length and fireline intensity for the a) 90th and b) 97.5th percentile fire weather scenarios.
SF = surface fire; PCF = passive crown fire; ACF = active crown fire
Flame length categories: Low = 0 to <1.2 m; moderate = 1.2 to <2.4 m; high >2.4 m
Fireline intensity categories: Low = 0 to <346 kW/m; moderate = 346 to <1730 kW/m; high >1730 kW/m
S1, S2, S3, and S4 are the SPLAT treatments created using a fireshed assessment
Finney and TOM are the theoretical SPLAT treatments
Table 5: Mean flame length and fireline intensity for the base (untreated landscape) along with normalized mean flame length and fireline intensity for the six SPLAT treatments for Sagehen Experimental Forest for the 90th and 97.5th fire weather conditions. S1, S2, S3, and S4 are the SPLAT treatments created using a fireshed assessment. Finney and TOM are the theoretical SPLAT treatments.

<table>
<thead>
<tr>
<th>SPLAT</th>
<th>90th Percentile</th>
<th>97.5th Percentile</th>
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<tbody>
<tr>
<td></td>
<td>Mean Flame Length (m)</td>
<td>Mean Fireline Intensity (kW/m)</td>
</tr>
<tr>
<td>Base</td>
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<td>5430</td>
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<tr>
<td>S1</td>
<td>2.6</td>
<td>2813</td>
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<tr>
<td>S2</td>
<td>2.6</td>
<td>2765</td>
</tr>
<tr>
<td>S3</td>
<td>2.1</td>
<td>2167</td>
</tr>
<tr>
<td>S4</td>
<td>2.1</td>
<td>2134</td>
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<tr>
<td>Finney</td>
<td>3.9</td>
<td>4026</td>
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<tr>
<td>TOM</td>
<td>3.3</td>
<td>4189</td>
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<table>
<thead>
<tr>
<th>SPLAT</th>
<th>90th Percentile</th>
<th>97.5th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Arival Time (min)</td>
<td>Mean MTT FLIN (kW/m)</td>
</tr>
<tr>
<td>Base</td>
<td>2129</td>
<td>1757</td>
</tr>
<tr>
<td>S1</td>
<td>2070</td>
<td>1683</td>
</tr>
<tr>
<td>S2</td>
<td>2044</td>
<td>1660</td>
</tr>
<tr>
<td>S3</td>
<td>2054</td>
<td>1663</td>
</tr>
<tr>
<td>S4</td>
<td>2050</td>
<td>1660</td>
</tr>
<tr>
<td>Finney</td>
<td>1939</td>
<td>1600</td>
</tr>
<tr>
<td>TOM</td>
<td>1924</td>
<td>1605</td>
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Table 6: Mean and standard deviation minimum travel time fireline intensity (MTT FLIN) and arrival time for the 90th and 97.5th percentile fire weather condition for Sagehen Experimental Forest. S1, S2, S3, and S4 are the SPLAT treatments created using a fireshed assessment. Finney and TOM are the theoretical SPLAT treatments.
Figures

Figure 1: Figure depicting the layout for strategically placed area treatment units (adapted from Finney 2001).

Figure 2: Location and dominant vegetation types for Sagehen Experimental Forest.
Figure 3: Four proposed strategically placed area treatment plans (SPLATs) for Sagehen Experimental Forest created using the fireshed assessment process by the Truckee Ranger District on the Tahoe National Forest. Additional units incorporated in the S2, S3, and S4 SPLATs not present in the S1 SPLAT are pointed out using blue arrows.
Figure 4: Two theoretically derived strategically placed area treatment (SPLAT) designs a) Finney and b) TOM created for Sagehen Experimental Forest. The Finney SPLAT was created using the theory outlined by Finney (2001) and the TOM SPLAT was created using the treatment optimization model in FlamMap (Finney 2006). The area not available for treatment using the treatment optimization model is represented in c) and the ignition line and wind direction of the problem fire in d).
Figure 5: Maps showing the change in minimum travel time fireline intensity for the 90th percentile weather scenario for Sagehen Experimental Forest. All maps represent the difference between the baseline data and the a) S1, b) S2, c) S3, d) S4, e) Finney, and f) TOM SPLATs. The SPLAT outlines are included in red.
Figure 6: Maps showing the change in minimum travel time arrival time for the 90th percentile weather scenario for Sagehen Experimental Forest. All maps represent the difference between the baseline data and the a) S1, b) S2, c) S3, d) S4, e) Finney, and f) TOM SPLATs. The SPLAT outlines are included in red.
Chapter 4: Assessing the longevity of strategically placed area treatments to reduce fire behavior in a complex landscape, Sagehen Experimental Forest

**Abstract**

Effective fuel treatments reduce flame length, fireline intensity and the occurrence of crown fire. The most successful way to change potential fire behavior is to reduce surface fuel loading, increase canopy base height and decrease canopy bulk density. Current theory has proven that strategically placed area fuel treatments (SPLATs) can alter fire behavior at the landscape-level by treating around one-third of the landscape. Through the use of forest growth simulations and fire behavior modeling it is possible to determine the future effectiveness of fuel treatments. The duration of fuel treatment effectiveness to reduce fire severity depends on many factors such as accumulation and decomposition of dead and downed fuels and site productivity. At Saghen Experimental Forest lower mean flame length and fireline intensity were modeled for a SPLAT treatment from 2005 until 2055 compared to an untreated landscape. In addition, after 2010 the proportion of modeled surface fire was higher for the treated landscape than for the untreated landscape. The less productive xeric conditions contribute to the expected longevity of the proposed SPLAT plan. However, forest growth models have their limitations. Currently, models available do not directly model shrub establishment and understory plant growth possibly creating a simplistic depiction of reality. Nonetheless, modeling can inform management decisions.
Introduction

Fuel treatments are used to alter potential wildland fire intensity and severity. Effective fuel treatments reduce flame length, fireline intensity and the occurrence of crown fire. Under most weather conditions fuel treatments modify fire behavior; however, under the most extreme cases this might not be true (Pollet and Omi 2002, Finney et al. 2003). Typically fuel treatments that alter more than one component of the vegetation or use more than one treatment type are more effective (i.e. Stephens and Moghaddas 2005, Schmidt et al. 2008). The most successful way to change potential fire behavior is to reduce surface fuels (typically with pile or broadcast burning), increase the canopy base height (through removal of ladder fuels and/or pruning of existing trees) and reduce canopy bulk density (removal of trees). This multi-tiered approach breaks up the continuity of surface, ladder and crown fuels (i.e. Van Wagner 1977, Agee at al. 2000, Scott and Reinhardt 2001, Agee and Skinner 2005). Benefits of fuel treatments at the stand-level have been well studied and proven effective at reducing wildland fire intensity and severity (Pollet and Omi 2002, Martison and Omi 2003, Finney et al. 2005, Moghaddas and Craggs 2007). However, the effectiveness of fuel treatments to reduce potential fire behavior at the landscape-level is less well understood (Finney et al. 2005).

Unlike stand-level treatments, landscape-level fuel treatments need to alter potential fire behavior across the whole landscape. A fireshed assessment is a collaborative landscape-scale fuels management process (Bahro and Perrot 2006, Husari et al. 2006). The idea of the fireshed assessment is to target high risk fire areas by implement strategically placed area treatments (SPLATs) to reduce potential fire behavior across a landscape (Finney 2001). Ideally by employing these treatments on a
fraction of the landscape the overall impacts of a wildland fire event, such as size and severity, will be moderated because fire intensity and spread will be dampened. Recent work by Finney (2001 and 2007) and Schmidt et al. (2008) has assessed different designs for landscape-level fuel treatments. Through iterative fire behavior modeling SPLATs have proven much more effective than randomly placed treatments of equal area for reducing relative fire size, spread rate, flame length and fireline intensity on both simplistic and complex landscapes (Finney 2001, Finney 2007, Finney et al. 2007, Schmidt et al. 2008). Schmidt et al. (2008) found an increase in modeled area burned for randomly placed mechanical treatment units (treating 20 to 27% of the landscape) when compared to an untreated control.

The above-mentioned work assesses effectiveness of SPLATs for the time immediately following treatment. Few studies have evaluated the longevity of fuel treatments to effectively reduce potential fire behavior at either the stand or landscape-level. The duration of treatment effectiveness will vary between sites within a given forest type due to differences in microclimate, soils and other factors which influence site productivity (Keyes and O’Hara 2002). Existing research estimate the effectiveness of treatments to last less than 20 years (Biswell et al. 1973, van Wagendonk and Sydoriak 1987, van Wagendonk 1995, Finney et al. 2005). The idea of landscape-level treatments is relatively new and the ability monitor the longevity of effectiveness in the field is not possible at this time. Forest growth and yield models can be used to assist land managers in determining the potential effectiveness of a given fuel treatment over time. Currently the Forest Vegetation Simulator (Crookston and Stage 1991) with the Fire and Fuels
Extension (Reinhardt and Crookston 2003) are utilized in the United States to model forest growth and fuel changes into the future.

The fireshed assessment process (Bahro et al. 2007) was implemented at Sagehen Experimental Forest (Sagehen) by the Tahoe National Forest and the University of California, Berkeley (UCB) to create potential SPLAT treatments. The SPLATs increased modeled surface fire, and decreased mean flame length and fireline intensity immediately following treatment (Vaillant Chapter 3 this dissertation). The goals of this research are to: 1) assess the effectiveness of one of the SPLAT treatments designed for Sagehen to reduce modeled flame length and fireline intensity and increase the proportion of surface fire from 2005 until 2055 and 2) discuss the limitations for modeling forest and vegetation growth into the future.

**Methods**

**Study Area**

Sagehen Experimental Forest (Sagehen) is a 4594 ha watershed on the eastern slope of the Sierra Nevada about 32 km north of Lake Tahoe (Figure 1). The watershed extends east from the crest of the Sierra Nevada at 2670 m to Highway 89 at 1862 m. Slopes are typically mild, averaging 18% but can reach 70% in parts of the watershed. Soils are generally Andic and Ultic Haploxeralfs derived from volcanic parent material (Pacific Southwest Research Station 2008).

Sagehen is in both the montane and subalpine vegetation ranges of the Sierra floristic province (Barbour et al. 2007). Sagehen is a diverse watershed with the majority of the landscape occupied by conifer forests (Figure 1). Tree species present include
lodgepole pine (*P. contorta*), Jeffrey pine (*P. jeffreyi*), sugar pine (*P. lambertiana*),
western white pine (*P. monticola*), white fir (*Abies concolor*), red fir (*A. magnifica*),
mountain hemlock (*Tsuga mertensiana*), and quaking aspen (*Populus tremuloides*). The
non-forested areas include fens, wet and dry montane meadows, and shrub fields. The
shrub cover type is dominated by tobacco brush (*Ceanothus velutinus*), mahala mat (*C.
prostratus*), greenleaf manzanita (*Arctostaphylos patula*), wax currant (*Ribes cereum*),
and woolly mule-ears (*Wyethia mollis*). Sagehen is divided into 47 stands which were
delineated using an aerial photograph grouping similar vegetation types or densities into
individual units (Figure 2, Appendix C: Tables 1 and 2).

Sagehen has a Mediterranean climate with warm, dry summers and cold, wet
winters. Average low and high winter (January) temperatures measured at 1943 m from
1953 to present are -10 and 4 °C; average summer (July) temperatures are 3 and 26 °C.
Average annual precipitation is 85 cm with snowfall accounting for about 80% of annual
precipitation (515 cm on average in snowfall per year) (climate data available at
http://www.wrcc.dri.edu/).

**Baseline Data Creation**

**Plot Selection**

A systematic grid of 522 permanent, georeferenced 0.05 ha circular plots was
installed, based on a random starting point within Sagehen. The grid consists of three
different densities, 500 m, 250 m, and 125 m spacing. The entire watershed is sampled
by plots spaced on a 500 m interval. Areas not occupied by Jeffrey pine plantations were
sampled at 250 m spacing. The 125 m spacing was used in 10 unique forest types to
conduct high density sampling. At each plot, plot center and elevation were recorded
using a hand held global positioning system (GPS) unit. In addition, aspect and slope were noted using a compass and clinometer.

*Vegetation Measurements*

Tree measurements (species, diameter at breast height (DBH), height, canopy base height, and tree crown position (dominant, codominant, intermediate or suppressed)) were recorded for all live trees greater than 5 cm DBH. Overstory trees (≥19.5 cm DBH) were tagged and measured in the whole plot (0.05 ha); pole-sized trees (≥5 cm DBH to <19.5 cm DBH) were measured in a randomly selected third of the plot (0.017 ha). Saplings, trees <5 cm DBH, were tallied by species and diameter class (1 cm increments) along a two meter belt encompassing three 12.62 m transects (0.0072 ha). In addition, snags greater than 5 cm DBH had species, DBH and height recorded. Canopy cover (CC) was measured at 25 points in a five by five grid with 5 m spacing using a canopy sight tube (Gill et al. 2000) in all the plots for the 125 m spaced grid and any plots initiated after these were installed (113 plots).

Tree measurements (live trees ≥5 cm) were used to calculate average canopy base height (CBH), canopy height (CH) and canopy bulk density (CBD) using Fuels Management Analyst (FMA) at the plot level (Carlton 2005). FMA incorporates established published methodologies for computing canopy bulk density, canopy base height, fire behavior, and predicted scorch and mortality by species (Stephens and Moghaddas 2005a, Stephens and Moghaddas 2005b). FMA uses information from field measurements (i.e. tree species, DBH, tree crown ratio, tree crown position and tree height) to estimate average canopy base height and canopy bulk density for a stand or plot (Reinhardt et al. 2000). Canopy bulk density for each plot is calculated using a
running mean along the height of the canopy. Canopy base height for each plot is determined as the height above the ground where the first canopy layer has a high enough density to support the vertical movement of fire (Carlton 2005). The running mean window was set to the defaults in FMA for CBH, CH (both 0.91 m), and CBD (4.57 m); the critical CBD is also set to the default, 0.011 kg/m³. Defaults were used in FMA because they are the same as is used in the Forest Vegetation Simulator (Crookston and Stage 1991) with the Fire and Fuels Extension (Reinhardt and Crookston 2003).

Shrub measurements were taken along the same three 12.62 m transects used to measure seedlings. Species, average height, and length along the transect were recorded for all shrubs present. In addition, an ocular estimate of percent cover classes (in 5% increments) of grasses, herbaceous species, and shrubs were noted for each whole plot.

*Fuel Measurements*

Surface and ground fuels were measured along the shrub transects in each of the plots using the line-intercept method (Van Wagner 1968, Brown 1974). Tallies of 1-hr (diameter less than 0.64 cm) and 10-hr (diameter from 0.64 to 2.54 cm) time lag fuels were recorded from 0 to 2 m, and 100 hr (greater than 2.54 to 7.62 cm diameter) from 0 to 3 m. Species, diameter, and decay status (rotten or sound) were recorded for all 1000-hr fuels (diameter greater than 7.62 cm) along the whole transect (12.62 m). Litter, duff, and fuel bed depth measurements were taken at two points along each transect (at 5 m and 10 m).

Surface and ground fuel loads were calculated using coefficients arithmetically weighted specific to the average basal area fraction of the tree species at each plot (van Wagendonk 1996, van Wagendonk et al. 1996, Stephens 2001, Vaillant et al. 2006).
Fuel models (FM) were then assigned to plots based on the calculated surface fuel loads, vegetation type, and the presumed carrier of fire (Scott and Burgan 2005).

_Sagehen Experimental Forest Geographic Information System (GIS) Layers_

The GIS layers created for Sagehen consists of five meter resolution raster data derived from LiDAR, field plots an aerial photograph. Topographical information (elevation, slope and aspect) was derived directly from LiDAR data (dual pulse LiDAR flights took place in the summer of 2005). The LiDAR data was initially sampled at 0.25 m resolution and was aggregated up to one meter resolution. A five-by-five grid of one meter cells was next averaged to create the five meter resolution cells used to make the digital elevation model (DEM). Slope and aspect were derived from the DEM.

Data layers for canopy characteristics were created using both LiDAR and field data. The canopy height (CH) layer was created the same way as the DEM with an additional step to check the accuracy against the field data. The canopy cover (CC) layer was derived from canopy height data and compared to the field data. A binary grid of five-by-five one meter cells was created to denote a “hit or miss,” much like is done with a canopy tube in the field, to calculate percent canopy cover for each five meter cell. Finally, the data was filtered to only include canopy cover where trees taller than five meters were present.

The canopy base height (CBH) layer was created using a Kriging interpolation. A Kriging interpolation determines the value of an unknown field based on value of nearby fields using a linear least squares estimation (Goovaerts 1997). The interpolation for the canopy base height layer was based on a combination of the calculated CBH at each plot and the canopy height GIS layer. The canopy bulk density layer was also created using
the values calculated in FMA (Carlton 2005). A global multiple-regression equation was used to calculate the CBD and create the raster layer in GIS. The regression equation used to create the CBD layer was:

\[
CBD \ (kg/m^3) = \{0.03867 + [\text{canopy height (m)} \times (-0.0022)] + [\text{canopy base height (m)} \times 0.0018] + [\text{canopy cover (\%)} \times 0.0023]\}.
\]

The fuel model layer was created using field data and aerial photography. An object-based image analysis (Jain 1988) was performed using a current aerial photograph to determine unique clusters and create the associated polygons based on vegetation characteristics in GIS. The fire carrying fuel type (litter, shrub, grass, or a combination), average calculated fuel load, and stand characteristics (i.e. basal area by tree species and shrub cover) at each plot was used to select appropriate fuel models from the extended set (Scott and Burgan 2005). A nearest-neighbor interpolation was used to populate polygons in GIS with fuel models. A nearest-neighbor interpolation is a technique for assigning data to non-valued cells in GIS by using the value of the nearest point (ESRI 2008). Finally, local expert opinion from the Tahoe National Forest was used to validate the fuel model selections. Experts were the Fuels Manager, Fuels Officer, Silviculturist and Timber Operation Manager from the Truckee Ranger District on the Tahoe National Forest.

**SPLAT Creation**

Four SPLAT designs (S1, S2, S3 and S4) were created for Sagehen Experimental Forest in conjunction with UCB and the Tahoe National Forest interdisciplinary (ID)
team using fireshed assessment strategies. The ID team was comprised of at least one Fuels Specialist, Silviculturalist, Hydrologist, Wildlife Biologist, District Ranger, Engineer and Archeologist. The UCB group primarily supplied technical support in the form of FlamMap (Finney 2006) and FARSITE (Finney 1998) fire behavior and spread modeling. The creation of these SPLATs was an ongoing process with several revisions.

The four SPLAT designs take into account accessibility, cost, increased forest health, landownership and ecological objectives. The S1 and S2 SPLATs only differ in the addition of a 25 ha treatment unit in the south-central region of Sagehen for the S2 SPLAT. The S3 and S4 SPLATs included a larger treatment unit in the eastern part of the basin which was not present in the S1 and S2 SPLATs. The difference between the S3 SPLAT and the S4 SPLAT was the inclusion of the same 25 ha unit as the S2 SPLAT for the S4 SPLAT. For this study only the S2 SPLAT will be evaluated to assess the longevity of the fuel treatment effectiveness (Figure 3). The S2 SPLAT was chosen for two reasons. First, the S2 alternative treats about one-third (33.5%) of the landscape. Second, the S2 SPLAT experiences similar spread rate changes to the S3 and S4 SPLAT alternatives which treated a larger proportion of the landscape whereas the S1 SPLAT does not (Vaillant Chapter3 in this dissertation).

**Modeling Forest Growth into the Future**

The Forest Vegetation Simulator (FVS) is a commonly used forest growth and yield program in the United States (Crookston and Stage 1991). FVS is a stand-level growth model which requires tree lists to be compiled for each stand. Stands were delineated for Sagehen using an aerial photograph; 47 stands were created for this study based on similar vegetation types (Figure 2, Appendix C: Tables 1 and 2). The
information used in the tree list includes tree species, height, live crown ratio, DBH, and status (live or dead). Trees greater than 5 cm DBH from the 522 plot grid were used to create tree lists for the 47 stands in Sagehen. Trees smaller than 5 cm DBH were not used because the data set did not include the measurements required for running FVS.

The Fire and Fuels Extension (FFE) for FVS can be used to predict fire outputs including potential fire behavior, expected mortality, fuels consumption and predicted smoke emissions (Reinhardt and Crookston 2003). In addition, FFE includes treatment options such as pile burning which is not available in FVS. FVS and FFE have multiple variants associated with different forest types across the United States which incorporate equations for specific tree species, growth rates and fuel types; for this research the Western Sierra Nevada variant was selected. Although the name indicates the variant is specific for the western Sierra Nevada it is suggested to be used for the entire Sierra Nevada by FVS. By utilizing FVS with the FFE extension it was possible to create a treatment scenario similar to the prescriptions determined using the fire assessment approach which were described in Chapter 3 of this dissertation.

FVS calculates stand dynamics at multi-year cycles up to 400 years into the future. The user can determine the length of the cycles for the output data. For this study 11 five-year cycles were completed for 50 years into the future starting in 2005 and ending in 2055. Two scenarios were run to assess the longevity of the S2 SPLAT over time. The first scenario included only natural regeneration of the baseline data, this will be referred to as the untreated landscape. The ESTAB and NATURAL keywords were using in FVS to establish natural regeneration in each stand. The number of seedlings for regeneration was determined by calculating the average number of small trees (<5 cm
DBH) per acre by species using the data collected from the 522 plots in Sagehen. Species specific numbers were then multiplied by the existing basal area of the overstory trees (>5 cm DBH) by species in each stand to determine the number of seedlings to establish within FVS. Regeneration was initiated at the start of each cycle (every five years). The diameter and height of regenerated trees was set to the defaults within FVS. The resulting average canopy cover, canopy height, canopy base height, and canopy bulk density data for the stands created using FVS were utilized to create a rule set for manipulating the existing baseline GIS data created for Sagehen from 2005 to 2055. Modeled change between time steps from 2005 to 2055 was used to create multiplication factors to update the GIS layers from 2010 until 2055. The only restriction on the updated GIS layers is canopy cover could not exceed 100 percent.

The second scenario included a thinning treatment followed by pile burning of activity fuels (using the FFE extension in FVS) inside the SPLAT boundaries in 2005. In addition to the ESTAB and NATURAL keywords in FVS, THINBTA and PILEBURN were used. THINBTA thins to a density of 100 trees per acre and PILEBURN simulates pile burns of the resulting activity fuels. As with the no treatment alternative natural regeneration was initiated within the treatment units each cycle. Here the resulting average canopy cover, canopy height, canopy base height and canopy bulk density data from the thinning and pile burning treatment in conjunction with regeneration were used to create the rule set for manipulating the existing baseline GIS data for Sagehen inside the SPLAT boundaries. The same methodology as the untreated landscape was used to change the GIS layers from 2005 until 2055. The area inside and outside of treatment
units have different multiplication factors to depict the treatments. This will be called the treated landscape for the rest of this study.

The FFE extension has the ability to select a fuel model based on tree lists and average fuel loading for each stand. Unfortunately, at this point in time FFE is not able to choose from the extended set of fuel models from which the baseline GIS data was created. The untreated landscape maintained the baseline fuel models for the duration of the study. Inside the SPLAT units fuel models were altered to depict the change in surface fuels post treatment. Outside of the treatment units fuel models will be the same as the untreated landscape. Elevation, slope, and, aspect will remain constant no matter the treatment.

The ArcFuels interface (Ager et al. 2006) was used to run FVS and FFE simulations for both scenarios. ArcFuels is a GIS interface which incorporates existing programs such as FVS, FlamMap (Finney 2006), FARSITE (Finney 1998) and NEXUS (Scott 1999) to allow the user to model forest change and potential fire behavior at the landscape-level. Once manipulations of baseline GIS data were completed for both scenarios ArcFuels was used to create the landscape files required to run FlamMap (landscape files will be described in the “Fire Modeling” section below).

**Fire Modeling**

**FlamMap Inputs**

In order to run FlamMap, a landscape file (LCP) and a fuel moisture file (FMS) are required. Wind (WND) and weather (WTR) files are used for these simulations to condition the fuels. When custom fuel models are used a custom fuel model file (FMD) is required. The FMD describes the characteristics (i.e. fuel load, fuel bed depth, surface
area to volume ratio and heat content) of the custom fuel model(s). For this study one custom fuel model was used inside the treatment units. The fuel model is considered a low-load slash model. The parameters for the LCP, FMS, WND, and WTR files are described below.

The LCP is created by converting the eight raster files (elevation, slope, aspect, canopy cover, canopy base height, canopy height, canopy bulk density, and fuel model) into ASCII grid files, and importing them into FlamMap. These files need to be coregistered, have equivalent extent, and have identical resolution to work within FlamMap. For the analysis 22 unique landscape files were created. Eleven landscape files were created for each of the two scenarios (untreated and treated) for each of the five-year cycles (2005, 2010, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050, and 2055).

In addition to the landscape file, FlamMap requires non-spatial and non-temporal weather and fuel moisture information to simulate fire behavior. The FMS file defines the initial fuel moisture for dead and down as well as live fuel components. Fire Family Plus (Main et al. 1990) was used to determine the values for the 90th (high) and 97.5th (extreme) percentile fire weather conditions (Appendix B: Table 1). Forty-five years (1961 to 2006) of weather data from the Stampede Remote Access Weather Station (less than 10 km east of Sagehen) from June 1 to October 31 were analyzed to determine percentile weather conditions.

Fire Family Plus was also used to create WND and WTR files with hourly weather data for the days leading up to the Cottonwood Fire. The Cottonwood Fire was a large fire (19000 ha) that occurred just north of Sagehen in 1994. The 10 day period
(August 6 to 15, 1994) prior to the fire was used to create more realistic fuel conditions for the simulation.

*Fire Behavior Outputs*

Within FlamMap all fire behavior calculations assume windspeed, wind direction, and fuel moistures to be constant, allowing examination of spatial variability in fire behavior (Finney 2006). In addition, fire behavior values are calculated independently for each pixel across the landscape, which is ideal for planning fuel treatments (Finney 2002, Stratton 2004, Finney 2006, Husari et al. 2006). A total of 44 simulations were run to model potential fire type, flame length, and fireline intensity in FlamMap. Simulations were run for each of the 22 landscape files for the 90th and 97.5th percentile fire weather scenarios.

*Data Analysis*

Mean values for canopy cover, canopy base height, canopy height and canopy bulk density were calculated for the untreated and treated landscapes from 2005 until 2055. To compare time-since-treatment changes frequency distributions for modeled fire type were graphed from 2005 through 2055 for both the 90th and 97.5th percentile fire weather conditions. In addition, mean flame length and fireline intensity were calculated for each time step from 2005 through 2055 for both fire weather circumstances. Due to the number of assumptions associated with fire behavior models, outputs were not statistically analyzed (Stephens and Moghaddas 2005, Vaillant et al. 2006).
**Results**

Mean values for canopy cover were lower for the treated landscape as compared to the untreated landscape from 2005 until 2025 (Figure 4a). Untreated mean canopy base height values exceeded those for the treated landscape in from 2020 through 2055 (Figure 4b). Mean canopy base height values for the untreated landscape remained higher than the treated landscape from 2005 through 2055 (Figure 4c). From 2020 until 2055 mean canopy bulk density of the treated landscape is higher than that of the untreated landscape (Figure 4c). See Appendix D: Table 1 for the supporting table.

Potential fire type for the untreated and treated landscapes from 2005 to 2055 for the 90\textsuperscript{th} and 97.5\textsuperscript{th} percentile fire weather conditions are shown in Figure 5. Modeled fire type is divided into four categories, no fire, surface fire, passive crown fire and active crown fire in FlamMap. From 2010 through 2055 a higher proportion of Sagehen is modeled to burn as surface fire for the treated landscape for the 90\textsuperscript{th} percentile fire weather condition (Figure 5a). For the 97.5\textsuperscript{th} percentile fire weather condition the untreated landscape has a higher proportion of surface than the treated landscape in 2005, the opposite is true from 2010 until 2055 (Figure 5b). After 2010 and 2015 a larger proportion of Sagehen burns as passive crown fire for the treated landscape when compared to the untreated landscape for the 90\textsuperscript{th} and 97.5\textsuperscript{th} percentile fire weather conditions. Under the 90\textsuperscript{th} and 97.5\textsuperscript{th} percentile fire weather conditions smaller proportion of the landscape burns as active crown fire for the treated landscape compared to the untreated landscape. Please refer to Appendix D for detailed information.

Mean modeled flame length was lower for the treated landscape than the untreated landscape for both the fire weather scenarios (Figure 6). Maximum modeled
flame length for the treated landscape exceeded the untreated landscape in 2035 for the 90th percentile fire weather condition (Figure 7a) and 2030 for the 97.5th percentile fire weather condition. Modeled mean (Figure 8) and maximum (Figure 9) fireline intensity (Figure 8) followed the same trends as flame length. See Appendix D: Tables 3 and 4 for details on modeled flame length and fireline intensity. Maps of modeled flame length for the untreated, treated and the difference between the untreated and treated landscapes are shown in Figure 10 for 2005, 2015, 2025, 2035, 2045, and 2055.

**Discussion**

The National Fire Plan, 10-Year Comprehensive Strategy and Healthy Forests Restoration Act were enacted to address the problem of elevated fuel loads and facilitate the reduction of wildland fire risk (Stephens and Ruth 2005). In California the Sierra Nevada Forest Plan Amendment was initiated in part to pursue more aggressive fuel reduction treatments (USDA Forest Service 2004). As a result landscape-level fuel treatments have become one of the dominant strategies employed by land managers in the Sierra Nevada today. Computer simulations can aid land managers in understanding the long term effectiveness of different treatment locations and prescriptions to reduce wildland fire intensity and severity (Ager et al. 2007). This research used FVS with FFE to simulate natural regeneration of seedlings and growth of existing trees creating a rule set to alter canopy data (canopy cover, canopy base height, canopy height and canopy bulk density) over time to assess the effectiveness of a proposed SPLAT treatment using modeled fire behavior metrics.
From 2010 until 2055 the proportion of modeled surface fire was higher in the treated landscape than the untreated landscape for the 90\textsuperscript{th} and 97.5\textsuperscript{th} percentile fire weather conditions (Figure 5). Modeled fire behavior outputs show the treated landscape maintained lower mean flame length and fireline intensity than the untreated scenario from 2005 until 2055 (Figures 6 and 8). The increased land burning as surface fire and the lower mean flame lengths and fireline intensity implied the treated landscape maintained effectiveness for longer than the 20 year threshold assumed by past work (Biswell et al. 1973, van Wagtendonk and Sydoriak 1987, van Wagtendonk 1995, Finney et al. 2005). Although average values were lower for the duration of the simulation, in 2030 and 2035 the maximum values for both flame length (Figure 7) and fireline intensity (Figure 9) for the treated landscape exceeded those of the untreated landscape for the 97.5\textsuperscript{th} and 90\textsuperscript{th} percentile weather conditions respectively. This might indicate a point in time where the effectiveness of the SPLAT treatment starts to degrade.

The duration of fuel treatment effectiveness to reduce potential wildland fire intensity will depend on a combination of the type of treatment used and location of the landscape in question. The proposed treatment examined in this study involves thinning followed by pile burning. The existence of post-treatment logging slash was considered in this simulation. Post-treatment fuel models were often chosen to be low-load slash models to accurately depict treated conditions for this study. The proposed dual treatment of thinning followed by burning has been found to be more effective at reducing potential fire behavior than prescribed fire alone (Stephens and Moghaddas 2005, Scmidt et al 2008).
The location of the area in question will also contribute the expected longevity of a fuel treatment to effectively reduce wildland fire intensity. Decomposition and accumulation of dead and downed fuel will partially dictate the longevity of a fuel treatment. Decomposition rates of surface fuels are quite variable and logging slash may remain onsite for many years influencing long term potential fire behavior (Laiho and Prescott 2004). In xeric environments, like Sagehen, thinning slash can remain onsite much longer than for wetter sites (Christiansen and Pickford 1991, Stephens 2004).

Accumulation of new surface fuels will also affect potential fire behavior. Past work by van Wagendonk and Sydoriak (1987) found fuel accumulation to return to about two-thirds of the initial values seven years after a prescribed fire treatment in Yosemite National Park, California. In addition, the relative productivity of a site, the local climate, and soil type can influence the growth of existing trees as well as the establishment and growth of seedlings and other understory vegetation. Treatments are likely to last longer in less productive sites where forest and vegetation change will be slower (Weatherspoon and Skinner 1996). Sagehen is located in the eastern Sierra Nevada which falls in the rain shadow lowering the productivity of the forest. Mean canopy height is only expected to increase about eight meters and mean canopy bulk density 0.03 kg/m$^3$ over the 50 year modeling period. The xeric conditions might explain the duration of the treatment effectiveness at Sagehen.

Forest growth models like FVS have their limitations. FVS does not directly model shrub establishment and understory growth. In some areas of Sagehen, if the overstory canopy layer is thinned it is possible to establish dense brush in the understory elevating the potential fire behavior by increasing the ladder fuel hazard. Although shrub
establishment is not guaranteed, where it does occur potential fire behavior may increase sooner than predicted by this modeling exercise. The FFE extension does have the capability to assign fuel models to stands over time. Fuel models are used in fire behavior modeling to describe fuel properties as inputs to calculate potential fire behavior metrics such as flame length, fireline intensity and fire type (Anderson 1982). Fuel models can indirectly be used to quantify understory characteristics.

Although the fuel model data layers were different for both the treated and untreated landscapes within the SPLAT perimeters, they were held constant for the duration of this research project. The decision to maintain the fuel models was twofold. First, FFE does not include the extended set of fuel models which were used to create the baseline GIS data for Sagehen. Second, the fuel models assigned using the FFE extension created an overly simplistic depiction of Sagehen. The simplicity exists in the inability to select from the extended set of fuel models and the way in which FFE assigns the fuel models. A single fuel model is selected for each of the 46 stands, greatly decreasing the resolution of the baseline data. Further research into establishment and growth of understory vegetation would be of interest to better understand the longevity and effectiveness of fuel treatments in this ecosystem.

Maintenance of existing fuel treatments or establishment of new treatments is of interest to land managers. Longevity of landscape level fuel treatments to effectively reduce fire intensity and severity is not well studied or documented. For this research the SPLAT treatment was projected to last 50 years based on reduced average modeled flame lengths and fireline intensity. Many factors contribute to the longevity of fuel treatments across a landscape. Sagehen is a diverse watershed with multiple forest types (Figure 1)
where different SPLAT treatment units might last for different periods of time. More research is needed to document fuel accumulation and long term changes in fuel strata (Finney 2001). With the establishment of the 522 plot grid in the basin it will be possible to monitor change over time in both treated and untreated areas. Modeling forest growth and fire behavior can be a simplistic depiction of reality; however, modeling can still inform management decisions.

**Literature Cited**


Figures

Figure 1: Location and dominant vegetation types of Sagehen Experimental Forest.

Figure 2: Stands with identification numbers used for forest regeneration and growth simulations for Sagehen Experimental Forest.
Figure 3: Strategically placed area treatment plan for Sagehen Experimental Forest.
Figure 4: Mean values for a) canopy cover, b) canopy base height, c) canopy height and 
d) canopy bulk density for the untreated and treated landscapes from 2005 to 2055 for 
Sagehen Experimental Forest.
Figure 5: Modeled fire type for the a) 90th percentile and b) 97.5th percentile fire weather conditions from 2005 to 2055 for Sagehen Experimental Forest.
Figure 6: Mean modeled flame length (m) for the a) 90th and b) 97.5th percentile fire weather conditions for Sagehen Experimental Forest.

Figure 7: Maximum modeled flame length (m) for the a) 90th and b) 97.5th percentile fire weather conditions for Sagehen Experimental Forest.
Figure 8: Mean average modeled fireline intensity (kW/m) for the a) 90th and b) 97.5th percentile fire weather conditions for Sagehen Experimental Forest.

Figure 9: Maximum modeled fireline intensity (kW/m) for the a) 90th and b) 97.5th percentile fire weather conditions for Sagehen Experimental Forest.
Figure 10: Modeled flame length (m) maps created using FlamMap for the untreated (left column), treated (middle column) and difference between untreated and treated (right column) landscapes from 2005 until 2055 for Sagehen Experimental Forest.
Appendix A

Appendix A includes the FHX2 outputs for the individual fire scar samples.

Data following the “Information on fire history:” line is: Year of fire scar, season of fire scar, fire scar FI (interval between fire years).


Series 1 : SEF100
Inner Ring : 1747
Bark Date : 2006
Length of sample : 260
Number in final analysis : 260
Information on fire history :
   1769 U fire scar
   1783 D fire scar FI = 14
   1804 U fire scar FI = 21
   1813 U fire scar FI = 9
   1822 D fire scar FI = 9
   1829 D fire scar FI = 7
   1843 L fire scar FI = 14
   1852 D fire scar FI = 9
   1868 L fire scar FI = 16
   1880 D fire scar FI = 12
   1914 D fire scar FI = 34
   1951 U fire scar FI = 37
   1990 U fire scar FI = 39
Total number of fire scars : 13
Total number all indicators : 13
Average number years per fire : 20.0
Sample mean fire interval : 18.4

Series 2 : SEF101
Inner Ring : 1735
Bark Date : 2006
Length of sample : 272
Number in final analysis : 272
Information on fire history :
   1795 D fire scar
   1804 E fire scar FI = 9
   1813 D fire scar FI = 9
   1822 L fire scar FI = 9
   1829 D fire scar FI = 7
1843 L fire scar  FI = 14
1852 D fire scar  FI = 9
1868 D fire scar  FI = 16
1914 L fire scar  FI = 46
Total number of fire scars    : 9
Total number all indicators   : 9
Average number years per fire : 30.2
Sample mean fire interval     : 14.9

Series 3 : SEF102
Inner Ring : 1745
Bark Date  : 2006
Length of sample : 262
Number in final analysis : 262
Information on fire history :
   1795 D fire scar
   1813 D fire scar  FI = 18
   1822 A fire scar  FI = 9
   1829 D fire scar  FI = 7
   1843 L fire scar  FI = 14
   1852 D fire scar  FI = 9
   1868 D fire scar  FI = 16
   1880 D fire scar  FI = 12
   1914 L fire scar  FI = 34
Total number of fire scars    : 9
Total number all indicators   : 9
Average number years per fire : 29.1
Sample mean fire interval     : 14.9

Series 4 : SEF103
Inner Ring : 1755
Bark Date  : 2006
Length of sample : 252
Number in final analysis : 252
Information on fire history :
   1804 U fire scar
   1914 L fire scar  FI = 110
Total number of fire scars    : 2
Total number all indicators   : 2
Average number years per fire : 126.0
Sample mean fire interval     : 110.0

Series 5 : SEF104
Inner Ring : 1791
Bark Date  : 2006
Length of sample : 216
Number in final analysis : 216
Information on fire history :
   1804 M fire scar
   1813 U fire scar  FI = 9
   1830 U fire scar  FI = 17
   1868 U fire scar  FI = 38
   1876 D fire scar  FI = 8
   1914 L fire scar  FI = 38
   1923 U fire scar  FI = 9
   1985 U fire scar  FI = 62
Total number of fire scars    : 8
Total number all indicators   : 8
Average number years per fire : 27.0
Sample mean fire interval     : 25.9

Series  6   : SEF105
Inner Ring  : 1641
Outer Ring  : 1941
Length of sample : 301
Number in final analysis : 301
Information on fire history :
   1750 D fire scar
   1763 A fire scar  FI = 13
   1776 L fire scar  FI = 13
   1796 M fire scar  FI = 20
   1807 L fire scar  FI = 11
   1818 D fire scar  FI = 11
   1830 L fire scar  FI = 12
   1843 D fire scar  FI = 13
   1860 D fire scar  FI = 17
   1868 L fire scar  FI = 8
   1916 D fire scar  FI = 48
Total number of fire scars    : 11
Total number all indicators   : 11
Average number years per fire : 27.4
Sample mean fire interval     : 16.6

Series  7   : SEF106
Inner Ring  : 1737
Outer Ring  : 1929
Length of sample : 193
Number in final analysis : 193
Information on fire history :
   1766 M fire scar
   1771 D fire scar  FI = 5
   1789 L fire scar  FI = 18
1793 D fire scar  FI = 4
1795 L fire scar  FI = 2
1800 D fire scar  FI = 5
1822 L fire scar  FI = 22
1843 D fire scar  FI = 21
1860 D fire scar  FI = 17
1878 L fire scar  FI = 18
1889 D fire scar  FI = 11
1914 U fire scar  FI = 25
Total number of fire scars : 12
Total number all indicators : 12
Average number years per fire : 16.1
Sample mean fire interval : 13.5

Series  8 : SEF108
Pith Date : 1694
Outer Ring : 1923
Length of sample : 230
Number in final analysis : 230
Information on fire history :
   1763 U fire scar
   1776 U fire scar  FI = 13
   1783 D fire scar  FI = 7
   1786 D fire scar  FI = 3
   1823 M fire scar  FI = 37
   1831 D fire scar  FI = 8
   1843 M fire scar  FI = 12
   1852 U fire scar  FI = 9
   1889 U fire scar  FI = 37
   1904 U fire scar  FI = 15
   1914 L fire scar  FI = 10
   1923 D fire scar  FI = 9
Total number of fire scars : 12
Total number all indicators : 12
Average number years per fire : 19.2
Sample mean fire interval : 14.5

Series  9 : SEF109
Inner Ring : 1761
Outer Ring : 1930
Length of sample : 170
Number in final analysis : 170
Information on fire history :
   1771 A fire scar
   1776 U fire scar  FI = 5
   1832 M fire scar  FI = 56
1848 D fire scar  FI = 16
1868 L fire scar  FI = 20
1892 M fire scar  FI = 24
Total number of fire scars : 6
Total number all indicators : 6
Average number years per fire : 28.3
Sample mean fire interval : 24.2

Series 10  : SEF110
Pith Date  : 1612
Outer Ring : 1934
Length of sample : 323
Number in final analysis : 323
Information on fire history :
  1672 D fire scar
  1689 L fire scar  FI = 17
  1721 D fire scar  FI = 32
  1723 D fire scar  FI = 2
  1747 D fire scar  FI = 24
  1771 A fire scar  FI = 24
  1778 D fire scar  FI = 7
  1788 D fire scar  FI = 10
  1813 D fire scar  FI = 25
  1831 D fire scar  FI = 18
  1878 U fire scar  FI = 47
  1886 U fire scar  FI = 8
  1914 D fire scar  FI = 28
Total number of fire scars : 13
Total number all indicators : 13
Average number years per fire : 24.8
Sample mean fire interval : 20.2

Series 11  : SEF368
Inner Ring : 1679
Bark Date : 2006
Length of sample : 328
Number in final analysis : 328
Information on fire history :
  1723 D fire scar
  1740 L fire scar  FI = 17
  1769 D fire scar  FI = 29
  1776 L fire scar  FI = 7
  1784 D fire scar  FI = 8
  1795 L fire scar  FI = 11
  1800 D fire scar  FI = 5
  1801 D fire scar  FI = 1
1804 D fire scar  FI = 3
1819 D fire scar  FI = 15
1829 D fire scar  FI = 10
1843 D fire scar  FI = 14
1868 D fire scar  FI = 25
1914 L fire scar  FI = 46
1921 D fire scar  FI = 7
Total number of fire scars : 15
Total number all indicators : 15
Average number years per fire : 21.9
Sample mean fire interval : 14.1

Series 12 : SEF056
Inner Ring : 1731
Bark Date : 2006
Length of sample : 276
Number in final analysis : 276
Information on fire history :
   1731 U fire scar
   1744 D fire scar  FI = 13
   1753 L fire scar  FI = 9
   1763 L fire scar  FI = 10
   1773 M fire scar  FI = 10
   1782 D fire scar  FI = 9
   1796 D fire scar  FI = 14
   1808 M fire scar  FI = 12
   1816 E fire scar  FI = 8
   1822 D fire scar  FI = 6
   1830 M fire scar  FI = 8
   1843 D fire scar  FI = 13
   1895 D fire scar  FI = 52
   1905 U fire scar  FI = 10
Total number of fire scars : 14
Total number all indicators : 14
Average number years per fire : 19.7
Sample mean fire interval : 13.4

Series 13 : SEF058
Inner Ring : 1856
Outer Ring : 1959
Length of sample : 104
Number in final analysis : 104
Information on fire history :
   1896 U fire scar
   1902 D fire scar  FI = 6
   1905 U fire scar  FI = 3
1926 D fire scar  FI = 21
1942 D fire scar  FI = 16
Total number of fire scars    : 5
Total number all indicators   : 5
Average number years per fire : 20.8
Sample mean fire interval     : 11.5

Series 14   : SEF059
  Inner Ring  : 1742
  Outer Ring  : 1967
  Length of sample : 226
  Number in final analysis : 226
  Information on fire history:
    1796 M fire scar
    1816 D fire scar  FI = 20
    1822 A fire scar  FI = 6
    1838 D fire scar  FI = 16
    1876 M fire scar  FI = 38
    1922 U fire scar  FI = 46
    1942 U fire scar  FI = 20
  Total number of fire scars    : 7
  Total number all indicators   : 7
  Average number years per fire : 32.3
  Sample mean fire interval     : 24.3

Series 15   : SEF060
  Inner Ring  : 1821
  Outer Ring  : 1967
  Length of sample : 147
  Number in final analysis : 147
  Information on fire history:
    1876 D fire scar
    1922 D fire scar  FI = 46
    1936 A fire scar  FI = 14
    1945 D fire scar  FI = 9
    1947 L fire scar  FI = 2
  Total number of fire scars    : 5
  Total number all indicators   : 5
  Average number years per fire : 29.4
  Sample mean fire interval     : 17.7

Series 16   : SEF061
  Inner Ring  : 1750
  Outer Ring  : 1965
  Length of sample : 216
  Number in final analysis : 216
Information on fire history:
1822 D fire scar
1826 A fire scar  FI = 4
1827 D fire scar  FI = 1
1835 M fire scar  FI = 8
1843 D fire scar  FI = 8
1861 D fire scar  FI = 18
1902 U fire scar  FI = 41
1920 U fire scar  FI = 18
1936 U fire scar  FI = 16
1956 U fire scar  FI = 20
Total number of fire scars : 10
Total number all indicators : 10
Average number years per fire : 21.6
Sample mean fire interval : 14.9

Series 17 : SEF064
Inner Ring : 1697
Outer Ring : 1914
Length of sample : 218
Number in final analysis : 218
Information on fire history:
1776 A fire scar
1801 D fire scar  FI = 25
1816 A fire scar  FI = 15
1822 D fire scar  FI = 6
1837 A fire scar  FI = 15
1848 A fire scar  FI = 11
1868 D fire scar  FI = 20
1882 D fire scar  FI = 14
1890 D fire scar  FI = 8
1898 D fire scar  FI = 8
1908 A fire scar  FI = 10
Total number of fire scars : 11
Total number all indicators : 11
Average number years per fire : 19.8
Sample mean fire interval : 13.2

Series 18 : SEF065
Inner Ring : 1722
Outer Ring : 1937
Length of sample : 216
Number in final analysis : 216
Information on fire history:
1798 U fire scar
1833 D fire scar  FI = 35
1873 U fire scar FI = 40
1886 D fire scar FI = 13
1897 L fire scar FI = 11
1908 L fire scar FI = 11
Total number of fire scars : 6
Total number all indicators : 6
Average number years per fire : 36.0
Sample mean fire interval : 22.0

Series 19 : SEF066
Inner Ring : 1575
Outer Ring : 1918
Length of sample : 344
Number in final analysis : 344
Information on fire history :
  1616 D fire scar
  1723 D fire scar FI = 107
  1726 D fire scar FI = 3
  1732 D fire scar FI = 6
  1736 D fire scar FI = 4
  1749 L fire scar FI = 13
  1812 D fire scar FI = 63
  1838 L fire scar FI = 26
  1850 D fire scar FI = 12
  1865 D fire scar FI = 15
  1873 D fire scar FI = 8
  1877 A fire scar FI = 4
  1890 D fire scar FI = 13
  1898 U fire scar FI = 8
  1908 L fire scar FI = 10
  1916 D fire scar FI = 8
Total number of fire scars : 16
Total number all indicators : 16
Average number years per fire : 21.5
Sample mean fire interval : 20.0

Series 20 : SEF067
Inner Ring : 1587
Outer Ring : 1913
Length of sample : 327
Number in final analysis : 327
Information on fire history :
  1704 M fire scar
  1778 D fire scar FI = 74
  1887 D fire scar FI = 109
  1893 D fire scar FI = 6
1895 U fire scar  FI = 2
Total number of fire scars    : 5
Total number all indicators   : 5
Average number years per fire : 65.4
Sample mean fire interval     : 47.8

Series 21   : SEF068
Inner Ring : 1670
Outer Ring : 1911
Length of sample : 242
Number in final analysis : 242
Information on fire history :
  1786 L fire scar
  1797 A fire scar  FI = 11
  1800 M fire scar  FI = 3
  1817 L fire scar  FI = 17
  1820 D fire scar  FI = 3
  1838 D fire scar  FI = 18
  1855 L fire scar  FI = 17
  1890 U fire scar  FI = 35
  1898 U fire scar  FI = 8
Total number of fire scars    : 9
Total number all indicators   : 9
Average number years per fire : 26.9
Sample mean fire interval     : 14.0

Series 22   : SEF069
Inner Ring : 1596
Outer Ring : 1908
Length of sample : 313
Number in final analysis : 313
Information on fire history :
  1824 D fire scar
  1837 D fire scar  FI = 13
  1855 L fire scar  FI = 18
  1861 U fire scar  FI = 6
  1869 U fire scar  FI = 8
  1882 U fire scar  FI = 13
Total number of fire scars    : 6
Total number all indicators   : 6
Average number years per fire : 52.2
Sample mean fire interval     : 11.6
Series 23 : SEF070
Inner Ring : 1731
Outer Ring : 1917
Length of sample : 187
Number in final analysis : 187
Information on fire history :
  1731 U fire scar
  1772 L fire scar FI = 41
  1798 D fire scar FI = 26
  1827 D fire scar FI = 29
  1843 D fire scar FI = 16
  1854 D fire scar FI = 11
  1882 D fire scar FI = 28
Total number of fire scars : 7
Total number all indicators : 7
Average number years per fire : 26.7
Sample mean fire interval : 25.2

Series 24 : SEF071
Inner Ring : 1598
Outer Ring : 1912
Length of sample : 315
Number in final analysis : 315
Information on fire history :
  1605 M fire scar
  1643 D fire scar FI = 38
  1660 D fire scar FI = 17
  1668 D fire scar FI = 8
  1718 A fire scar FI = 50
  1731 L fire scar FI = 13
  1749 M fire scar FI = 18
  1760 L fire scar FI = 11
  1807 L fire scar FI = 47
  1818 D fire scar FI = 11
  1839 U fire scar FI = 21
  1846 D fire scar FI = 7
  1848 U fire scar FI = 2
  1892 D fire scar FI = 44
Total number of fire scars : 14
Total number all indicators : 14
Average number years per fire : 22.5
Sample mean fire interval : 22.1
Series 25 : SEF073
Inner Ring : 1790
Outer Ring : 1913
Length of sample : 124
Number in final analysis : 124
Information on fire history :
  1806 D fire scar
  1817 L fire scar  FI = 11
  1840 U fire scar  FI = 23
  1867 D fire scar  FI = 27
  1881 L fire scar  FI = 14
Total number of fire scars   : 5
Total number all indicators : 5
Average number years per fire : 24.8
Sample mean fire interval : 18.8

Series 26 : SEF074
Inner Ring : 1745
Bark Date : 2006
Length of sample : 262
Number in final analysis : 262
Information on fire history :
  1806 D fire scar
  1839 D fire scar  FI = 33
  1870 U fire scar  FI = 31
  1975 U fire scar  FI = 105
Total number of fire scars   : 4
Total number all indicators : 4
Average number years per fire : 65.5
Sample mean fire interval : 56.3

Series 27 : SEF075
Inner Ring : 1793
Outer Ring : 1904
Length of sample : 112
Number in final analysis : 112
Information on fire history :
  1793 U fire scar
  1806 L fire scar  FI = 13
  1828 A fire scar  FI = 22
  1839 D fire scar  FI = 11
  1857 L fire scar  FI = 18
  1867 D fire scar  FI = 10
  1897 L fire scar  FI = 30
Total number of fire scars   : 7
Total number all indicators : 7
Average number years per fire : 16.0
Sample mean fire interval : 17.3

Series 28 : SEF076
Inner Ring : 1742
Bark Date : 2006
Length of sample : 265
Number in final analysis : 265
Information on fire history :
   1806 U fire scar
   1856 U fire scar $FI = 50$
   1867 U fire scar $FI = 11$
   1891 U fire scar $FI = 24$
   1929 U fire scar $FI = 38$
Total number of fire scars : 5
Total number all indicators : 5
Average number years per fire : 53.0
Sample mean fire interval : 30.8

Series 29 : SEF077
Inner Ring : 1717
Outer Ring : 1897
Length of sample : 181
Number in final analysis : 181
Information on fire history :
   1729 U fire scar
   1754 L fire scar $FI = 25$
   1781 A fire scar $FI = 27$
   1806 L fire scar $FI = 25$
   1857 M fire scar $FI = 51$
   1864 D fire scar $FI = 7$
   1867 U fire scar $FI = 3$
   1881 D fire scar $FI = 14$
Total number of fire scars : 8
Total number all indicators : 8
Average number years per fire : 22.6
Sample mean fire interval : 21.7

Series 30 : SEF078
Pith Date : 1756
Outer Ring : 1973
Length of sample : 218
Number in final analysis : 218
Information on fire history :
   1799 A fire scar
   1809 L fire scar $FI = 10$
1832 D fire scar  FI = 23
1863 D fire scar  FI = 31
1944 U fire scar  FI = 81
Total number of fire scars : 5
Total number all indicators : 5
Average number years per fire : 43.6
Sample mean fire interval : 36.3

Series 31 : SEF079
Inner Ring : 1725
Bark Date : 2006
Length of sample : 282
Number in final analysis : 282
Information on fire history :
  1775 M fire scar
  1799 D fire scar  FI = 24
  1801 D fire scar  FI = 2
  1830 D fire scar  FI = 29
  1856 D fire scar  FI = 26
  1864 U fire scar  FI = 8
  1872 U fire scar  FI = 8
Total number of fire scars : 7
Total number all indicators : 7
Average number years per fire : 40.3
Sample mean fire interval : 16.2

Series 32 : SEF080
Inner Ring : 1793
Outer Ring : 1889
Length of sample : 97
Number in final analysis : 97
Information on fire history :
  1793 U fire scar
  1806 U fire scar  FI = 13
  1817 U fire scar  FI = 11
  1828 D fire scar  FI = 11
  1839 L fire scar  FI = 11
  1842 D fire scar  FI = 3
Total number of fire scars : 6
Total number all indicators : 6
Average number years per fire : 16.2
Sample mean fire interval : 16.2

Series 33 : SEF081
Inner Ring : 1651
Outer Ring : 1917
Length of sample : 267
Number in final analysis : 267
Information on fire history :
   1801 E fire scar
   1821 D fire scar  FI = 20
   1839 D fire scar  FI = 18
   1852 A fire scar  FI = 13
   1872 M fire scar  FI = 20
   1887 M fire scar  FI = 15
   1904 U fire scar  FI = 17
Total number of fire scars : 7
Total number all indicators : 7
Average number years per fire : 38.1
Sample mean fire interval : 17.2

Series 34 : SEF082
Inner Ring : 1925
Bark Date : 2006
Length of sample : 82
Number in final analysis : 82
Information on fire history :
   1960 D fire scar
   1966 A fire scar  FI = 6
Total number of fire scars : 2
Total number all indicators : 2
Average number years per fire : 41.0
Sample mean fire interval : 6.0

Series 35 : SEF083
Pith Date : 1910
Bark Date : 2006
Length of sample : 97
Number in final analysis : 97
Information on fire history :
   1960 D fire scar
   1996 D fire scar  FI = 36
   2001 U fire scar  FI = 5
Total number of fire scars : 3
Total number all indicators : 3
Average number years per fire : 32.3
Sample mean fire interval : 20.5

Series 36 : SEF084
Inner Ring : 1931
Bark Date : 2006
Length of sample : 76
Number in final analysis : 76
Information on fire history :
   1960 D fire scar
   1993 D fire scar  FI = 33
   2001 D fire scar  FI = 8
Total number of fire scars  : 3
Total number all indicators : 3
Average number years per fire : 25.3
Sample mean fire interval : 20.5

Series 37  : SEF085
Pith Date  : 1644
Outer Ring  : 1941
Length of sample : 298
Number in final analysis : 298
Information on fire history :
   1710 L fire scar
   1744 M fire scar  FI = 34
   1758 A fire scar  FI = 14
   1765 A fire scar  FI = 7
   1775 D fire scar  FI = 10
   1788 D fire scar  FI = 13
   1798 D fire scar  FI = 10
   1808 M fire scar  FI = 10
   1839 D fire scar  FI = 31
   1848 D fire scar  FI = 9
   1857 U fire scar  FI = 9
   1864 U fire scar  FI = 7
   1904 U fire scar  FI = 40
Total number of fire scars : 13
Total number all indicators : 13
Average number years per fire : 22.9
Sample mean fire interval : 16.2
Appendix B

<table>
<thead>
<tr>
<th>Fuel Moisture (%)</th>
<th>90&lt;sup&gt;th&lt;/sup&gt;</th>
<th>97.5&lt;sup&gt;th&lt;/sup&gt;</th>
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Table 1: 90<sup>th</sup> and 97.5<sup>th</sup> percentile fuel moisture and wind conditions as calculated with Fire Family Plus for use in FlamMap for Sagehen Experimental Forest.
Appendix C

Figure 1: Stands with identification numbers for Sagehen Experimental Forest.
<table>
<thead>
<tr>
<th>Stand ID</th>
<th># of Plots</th>
<th>Area (ha)</th>
<th>% of Sagehen</th>
<th>Mean Canopy Height (m)</th>
<th>Mean BA (m²)</th>
<th>Mean Density (TPH)</th>
<th>Trees &gt; 5cm DBH</th>
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Table 1: Stand and live tree characteristics for Sagehen Experimental Forest.
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Table 2: Percent of total basal area (m²) by species and mean percent shrub cover for the 47 stands in Sagehen Experimental Forest.
## Appendix D

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Table 1: Mean modeled values for canopy bulk density (CBD), canopy base height (CBD), canopy height (CH) and canopy cover (CC) from 2005 to 2055 in Saghen Experimental Forest.
| a) 90<sup>th</sup> Percentile | Untreated     | Treated      |   |   |   |
|-----------------------------|---------------|--------------|---------------|---------------|
|                             | SF  | PCF  | ACF | SF  | PCF  | ACF |
| 2005                        | 0.7 | 0.25 | 0.04 | 0.7 | 0.27 | 0.02 |
| 2010                        | 0.73| 0.22 | 0.03 | 0.78| 0.19 | 0.02 |
| 2015                        | 0.75| 0.21 | 0.03 | 0.82| 0.16 | 0.01 |
| 2020                        | 0.76| 0.19 | 0.03 | 0.82| 0.14 | 0.02 |
| 2025                        | 0.77| 0.17 | 0.04 | 0.84| 0.12 | 0.02 |
| 2030                        | 0.78| 0.15 | 0.05 | 0.85| 0.1  | 0.03 |
| 2035                        | 0.79| 0.14 | 0.06 | 0.86| 0.09 | 0.03 |
| 2040                        | 0.79| 0.14 | 0.06 | 0.86| 0.09 | 0.03 |
| 2045                        | 0.78| 0.14 | 0.06 | 0.86| 0.09 | 0.04 |
| 2050                        | 0.79| 0.14 | 0.06 | 0.87| 0.09 | 0.03 |
| 2055                        | 0.79| 0.14 | 0.05 | 0.87| 0.09 | 0.03 |

| b) 97.5<sup>th</sup> Percentile | Untreated     | Treated      |   |   |   |
|---------------------------------|---------------|--------------|---------------|---------------|
|                                 | SF  | PCF  | ACF | SF  | PCF  | ACF |
| 2005                            | 0.68| 0.24 | 0.07 | 0.65| 0.29 | 0.05 |
| 2010                            | 0.71| 0.21 | 0.07 | 0.74| 0.21 | 0.04 |
| 2015                            | 0.73| 0.2  | 0.06 | 0.78| 0.17 | 0.03 |
| 2020                            | 0.74| 0.17 | 0.07 | 0.79| 0.15 | 0.04 |
| 2025                            | 0.75| 0.15 | 0.08 | 0.81| 0.12 | 0.06 |
| 2030                            | 0.76| 0.13 | 0.09 | 0.82| 0.09 | 0.07 |
| 2035                            | 0.77| 0.12 | 0.1  | 0.83| 0.08 | 0.07 |
| 2040                            | 0.77| 0.12 | 0.1  | 0.84| 0.07 | 0.08 |
| 2045                            | 0.77| 0.12 | 0.1  | 0.84| 0.07 | 0.08 |
| 2050                            | 0.77| 0.12 | 0.09 | 0.84| 0.07 | 0.07 |
| 2055                            | 0.77| 0.12 | 0.09 | 0.85| 0.07 | 0.07 |

Table 2: Proportion of Saghen Experimental Forest burning as surface fire (SF), passive crown fire (PCF) and active crown fire (ACF) from 2005 through 2055 for the a) 90<sup>th</sup> and b) 97.5<sup>th</sup> percentile fire weather conditions.
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Table 3: Mean, standard deviation and maximum modeled flame length (FL, m) for the untreated and treated landscapes for the 90th and 97.5th percentile fire weather scenarios from 2005 to 2055 in Sagehen Experimental Forest.
Table 4: Mean, standard deviation and maximum modeled fireline intensity (FLIN, kW/m) for the untreated and treated landscapes for the 90th and 97.5th percentile fire weather scenarios from 2005 to 2055 in Sagehen Experimental Forest.
Appendix E

The following is a glossary of terms often used in the forestry and fire fields.

Active crown fire (ACF): sustained fire which exists on both the surface and in the crowns of trees at the same time.

Anthropogenic: caused or produced by humans, not naturally caused.

ASCII grid file: ASCII stands for American standard code for information interchange and is a file structure which can contain either characters or numbers and is often used in GIS.

Basal area: the cross sectional area of the trunk of a tree measured at breast height (4.5 ft above the ground), or the combined area for all trees in a given area.

Composite fire interval (CFI): number of years between fires that scarred a certain proportion of trees in an area which must be defined. For example, C01 includes all fire scarred trees, and C10 includes fires which scarred 10% and at least two trees in the sample.

Canopy: the upper level of a forest composed of tree crowns.

Canopy cover (CC): the percent of the ground area covered by the vertical projection of the canopy.

Canopy base height (CBH): the height of the bottom most portion of a tree crown that can propagate fire vertically.

Canopy bulk density (CBD): the density of available canopy fuel in a stand.

Cross-dating: a method used in fire history research where tree rings are compared to a master chronology to assign calendar years to fire scars.

Crown fire: fire that burns in the crowns of trees and shrubs.

Crown (canopy) fuel: fuel in the crown (canopy) of a tree(s).

Crown position: a classification for trees based on the position of their crowns relative to the crowns of other trees in the stand. The can be dominant (receiving full sunlight), codominant (receiving full sunlight from above but not the sides), intermediate (receiving little direct sunlight from above and typically none from the sides, but with crowns extending into the same vertical space as the dominant and codominant trees), or suppressed (receiving little to no direct sunlight, usually shorter than the above three classes).
Cull: harvesting of trees.

Dendrochronology: the scientific method for dating trees based on counting rings.

Diameter at breast height (DBH): the diameter of a tree measured at 4.5 ft above the ground.

Digital elevation model (DEM): a digital representation of topography.

Duff: The partially decomposed organic matter found between the mineral soil and litter layers on the forest floor.

Earlywood: the part of an annual tree ring which forms during the early part of the growing season.

Evapotranspiration: the combined net loss of plant transpiration and evaporation from the earth’s surface into the atmosphere.

FARSITE: a fire behavior and growth simulator.

Fire intensity: the heat energy released in a fire.

Fire interval: number of years between two successive fires in a designated area (point or composite).

Fireline intensity (FLIN): the rate of heat release per unit time per unit length of fire front.

Fire Family Plus: a program which analyses and summarizes historical weather observations.

Fire regime: describes the frequency, size, severity, synergy, and seasonality of fire patterns. It can also include factors such as climate and land use.

Fire scar: the physical scar left on a tree after a fire event.

Fire severity: the amount an area has been altered by fire.

Flame length: the length of a flame measured along the slant of the flame.

FlamMap: a fire propagation and behavior modeling program.

Fuel: living and dead vegetation that can be ignited.

FUEL CALC: a tool used for calculating both surface and canopy fuel loads.
Fuel bed depth: the height of dead and downed fuels as measured from the bottom of the litter layer.

Fuel continuity: descriptions of the distribution of fuel both horizontally and vertically.

Fuel load: the weight per unit area of fuel.

Fuels Management Analyst (FMA): a forest and fire modeling program.

Fuel model: a compilation of many factors (surface area to volume, moisture of extinction, fuel load, etc.) characterizing the surface and possibly ladder fuels of a given area. Fuel models are used in fire behavior modeling. The categories of fuel models include: grass, grass-shrub, shrub, timber litter, timber understory, and slash blowdown.

Fuel moisture: percent of oven dry weight of fuel.

Fuel treatment: a manipulation of surface, ladder and/or crown fuels.

Forest Vegetation Simulator (FVS): a forest growth and yield modeling program.

Geographic Information System (GIS): any program used to store, analyze, and manage data which can be spatially referenced.

Ground fuel: comprised of the duff and litter layers.

Head fire: usually the most active portion of a fire.

Hillshade: a raised relief map to showcase elevation, aspect, and slope which can be created in GIS.

Kriging interpolation: a method of interpolation that predicts values for areas with unknown values based on locations with known values.

Ladder fuel: shrubs, small trees, dead branches, and moss that provide continuous fuel from the forest floor into the crowns trees.

Landscape Fire and Resource Management Planning Tools Project (Landfire): a project producing comprehensive maps and data for vegetation, fuels, and fire regimes across the whole United States.

Latewood: the part of an annual tree ring which forms during the late part of the growing season, it is typically darker in color than the earlywood.

Light detection and ranging (LiDAR): a remote sensing system which uses lasers attached to airplanes used to collect topographic data.
Litter: recently fallen plant material.

Mastication: grinding, shredding or chopping material, often used in forest stands to alter the ladder fuel strata.

Mean fire interval: the average of all fire return intervals in a given area over a set period of time (either point or composite).

Minimum travel time (MTT): is a two-dimensional fire growth model in FlamMap.

Nearest neighbor interpolation: a simplistic way of assigning values to pixels with no data in GIS, the value becomes that of the nearest neighboring pixel.

Passive crown fire (PCF): fire which burns in the crown of a single tree or groups of trees.

Point fire interval (PFI): number of years between fire scars on a single tree.

Polygon: in GIS this is defined as any area fully encompassed by lines, it does not need to have any particular shape.

Prescribed fire or prescribed burn: any fire started for management purposes.

Problem fire: one which escapes initial suppression tactics and grows large.

Protected area centers (PACS): the land surrounding the nest site of a sensitive or threatened bird species such as the California spotted owl.

Raster (or grid) data: a grid of equally sized cells continuously covering and area, used in GIS.

Risk: the probability of a fire igniting multiplied by the loss caused by the fire.

Stewardship and Fireshed Assessment data (SFA): a GIS data set created by the USFS for fuel treatment and fire planning.

Snag: a standing dead tree.

Stand: an area of a forest that has similar tree species, age, size and density.

Stand Visualization System (SVS): a program which creates graphic images of stand conditions through depiction of trees, shrubs, and downed material.

Strategically placed area treatment (SPLAT): a landscape level fuel treatment plan where the individual units are optimally placed to limit fire spread.
Surface fire (SF): fire burning on the surface of the forest floor.

Surface fuel: fuels on the forest floor, typically comprised of dead and downed woody material and litter.

Thinning: the cutting of smaller diameter trees typically used to reduce the overall density of a stand.

Timelag fuel classes: dead fuels that are classed as 1-hr (<0.64 cm), 10-hr (0.64 to 2.54 cm), 100-hr (2.54 to 7.62 cm), or 1000-hr (>7.62 cm) based on the time needed for fuel moisture to come into equilibrium with the environment and their diameter.

Treatment optimization model (TOM): an option in FlamMap which identifies areas where treatments will have the most effect at reducing fire spread across the landscape.

United States Forest Service (USFS): Federal agency in charge of the National Forests in the United States.

Vector data: two dimensional line data in GIS.

Wildland fire: a fire that is burning in a wildland.

Wildland urban interface (WUI): any land where structures and wildlands meet and intermix.