# Fire Regime Attributes of Wildland Fires in Yosemite National Park, USA

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## ABSTRACT

Past attempts to suppress all fires in some western forests have altered historic fire regimes. Accumulated debris and dense understories of shade tolerant species coupled with a warmer climate have led to catastrophic wildfires. Prescribed fires and wildland fire use fires are used by land managers to reduce fuels and restore natural conditions. Little is known about how wildfires, prescribed fires, and wildland fire use fires differ in their fire regime attributes. We compared the attributes of start date, duration, 95th percentile burning index, size, fire rotation and fire return interval, and fire severity of 144 fires >40 ha that occurred in Yosemite National Park from 1974 through 2005, and mean patch size and patch squareness (an index of complexity) of 106 fires that occurred from 1984 through 2005. We used fire history, weather records, and the Relative differenced Normalized Burn Ratio (RdNBR) derived from satellite imagery to make the comparisons. Prescribed fires started both earlier and later than wildfires and wildland fire use fires, and had the shortest return intervals. Prescribed fires burned during periods with a lower 95th percentile burning index (an estimate of potential flame length and fire line intensity), and resulted in larger patches that were unchanged or that burned with low severity. Wildfires were the largest in size and had the largest percent area burned at moderate and high severity. Wildfires also had the largest moderate and high severity patches, and the high severity patches were the most square. The significant differences in fire regime attributes suggest that land managers seeking to restore natural fire regimes and forest composition and structure must consider more than the metrics of area burned or fuel loading.

*Keywords*: fire intensity, fire return interval, fire rotation, fire seasonality, fire severity, fire size, fire spatial complexity, prescribed fire, wildfire, wildland fire use

*Citation:* van Wagtendonk, J.W., and J.A. Lutz. 2007. Fire regime attributes of wildland fires in Yosemite National Park, USA. Fire Ecology 3(2): 34-52.

## INTRODUCTION

Fire has been an ecological force in western US ecosystems for millennia. Flammable fuels, abundant ignition sources, and hot, dry summers combine to produce conditions conducive to an active fire role. Fire regimes include the temporal, spatial, and magnitude attributes of fire, and together those attributes describe the role fires play in different ecosystems. Past attempts to suppress all fires in some western forests have altered historic fire regimes (Skinner and Chang 1996). Accumulated debris on the forest floor, dense understories of shade tolerant species, and a warmer climate have led to larger areas being burned and higher tree mortality (van Wagtendonk and Fites-Kaufman 2006).

Land managers have a variety of methods to manage fire in these altered landscapes. Although mechanical thinning can sometimes be used to reduce fuel loading and tree density in National Parks, fire is the only treatment that can be used over large areas. Prescribed fires are set by land managers to reduce fuels and to restore ecological function in areas that have departed from natural conditions. A prescription is used to define burning conditions that are safe and effective in meeting management objectives. Wildland fire use, defined as the management of wildland fires for resource benefits, is a strategy that allows fires ignited by lightning to burn only if they meet pre-defined conditions specified in a management plan. Fire suppression remains an important management strategy for human-caused fires and wildland fires that are out of prescription. These suppressed fires are called wildfires.

There is currently a great deal of effort being devoted to reducing fuels using mechanical methods or prescribed burns. However, areas needing treatment are so large and the opportunities to implement them so infrequent, that these efforts alone may prove futile. Stephens *et al.* (2007) recommend that wildland fire use be implemented in remote areas inside and outside of wilderness to increase the area treated with fire. Parsons (2000) states that none of the five federal wilderness management agencies (Bureau of Indian Affairs, Bureau of Land Management, Forest Service, National Park Service, U.S. Fish and Wildlife Service) have been able to restore naturally occurring fire to a level that approaches pre-settlement fire regimes. He concludes that prescribed fire should be used to aid in restoring natural fire regimes in wilderness areas. Both prescribed fires and wildland fire use fires will be necessary to reverse the effects of decades of fire exclusion. There is some concern that prescribed fires are not sufficiently intense to mimic naturally occurring fires (Miller and Urban 2000). Because one of the goals for managing parks and wilderness areas is to restore natural fire regimes and characteristic vegetation structure and composition, it is important to know the extent to which prescribed fires and wildfires deviate from those regimes.

Sugihara *et al.* (2006) classified fire regimes based on distributions for seven fire regime attributes grouped into categories of time, space, and magnitude. Temporal attributes include seasonality and fire return interval; spatial attributes include fire size and spatial complexity of the fires; and magnitude attributes include fireline intensity, fire severity, and fire type. Although there are many other attributes that they could have used, Sugihara *et al.* (2006) state that those seven attributes were the ones that were that are most commonly considered to be important to ecosystem function.

Fire seasonality is defined as a combination of the date a fire starts and its duration. Fire return interval is the length of time between fires at a specific point on the landscape and can be expressed as a mean, median, minimum, or maximum. Other measures related to fire return interval include fire rotation, which is the time necessary for fire to burn an area equivalent to the total area of an ecosystem (Heinselman 1978), and fire frequency, which is the inverse of fire return interval. Fire size is the area burned by the fire, and spatial complexity is defined as the variability in the patchiness and gradient structure of the burned area. Fireline intensity is the rate of energy release per unit of fire flaming front. Although other measures of fire intensity, such as reaction intensity, might be better related to fire effects, fireline intensity can be visualized through its relationship with flame length (Byram 1959) and the burning index, an estimate of potential flame length and fireline intensity (Deeming *et al.* 1977). Fireline intensity is also the measure of fire magnitude that is most commonly understood and used by fire behavior analysts. Fire severity is defined as the magnitude of the effect that a fire has on the environment (van Wagtendonk 2006). It is commonly measured using remote sensing indexes, but other methods such as field surveys of fire effects are also used (Key 2006, Key and Benson 2004). Fire type describes the vegetation and fuel layers through which a fire propagates and includes ground fires, surface fires, and crown fires. Van Wagner (1977) defined three phases of crown fires: passive crown fires torch individual trees or groups of trees, active crown fires spread through the crowns in conjunction with a surface fire, and independent crown fires spread far ahead of or in the absence of a surface fire.

Fire regimes in Sierra Nevada forests are altered by human activities in several ways. Fire seasons are extended by human-caused ignitions during periods of time when lightning strikes are negligible or absent. Fire durations are shortened and fire return intervals increased as fire suppression efforts extinguish many fires when they are still small. As a result, most fires are smaller in size, but those fires that do escape control become much larger than would occur naturally because of the increase in fuel loading (Running 2006). These large fires burn with greater intensity and have large patches of severe effects. Although surface fires are still common, active crown fires and independent crown fires have begun to appear. Independent crown fires have been extremely rare in the Sierra Nevada in the past (van Wagtendonk and Fites-Kaufman 2006).

Our objective is to quantify fire regime attributes for prescribed fires, wildfires, and wildland fire use fires to determine if there were differences. Based on this information, land managers can make more informed decisions about the alternative strategies for managing wildland fires.

## METHODS

### *Study Area*

Yosemite National Park is a 302,688 ha reserve in the Sierra Nevada of California, USA. Elevations range from 600 m in the foothills to 4,000 m at the crest. The park has hot, dry summers and cold, moist winters. Temperature ranges from a July maximum temperature normal (1971–2000) of 35 °C in the lowest canyons to a January minimum temperature normal of -14 °C at the crest of the range. Annual normal precipitation for the same period varies from 800 mm at lower elevations and in local rain shadows to 1,720 mm at higher elevations, with most precipitation at higher elevations falling as snow (Daly *et al.* 2002, Daly 2006).

The vegetation responds to climate and topography with broad zones roughly corresponding to elevation. Chaparral woodlands occur in the foothill zone; conifer forests cover much of the lower montane, upper montane, and subalpine zones; and meadows occupy the alpine zone above tree line (van Wagtendonk and Fites-Kaufman 2006) (Figure 1). The dry chaparral woodlands consist of a manzanita (*Arctostaphylos viscida*) and ceanothus (*Ceanothus cuneatus*) understory beneath a canyon and interior live oak (*Quercus chrysolepsis*, *Q. wislizenii*) and foothill pine (*Pinus sabiniana*) overstory. As elevation increases, the foothill vegetation is replaced with lower montane forest consisting of ponderosa pine (*P. ponderosa*) stands mixed with incense-cedar (*Calocedrus decurrens*), sugar pine (*P. lambertiana*), California black oak (*Q. kelloggii*), white fir (*Abies concolor*), and isolated groves of giant sequoia (*Sequoiadendron giganteum*). This mixture

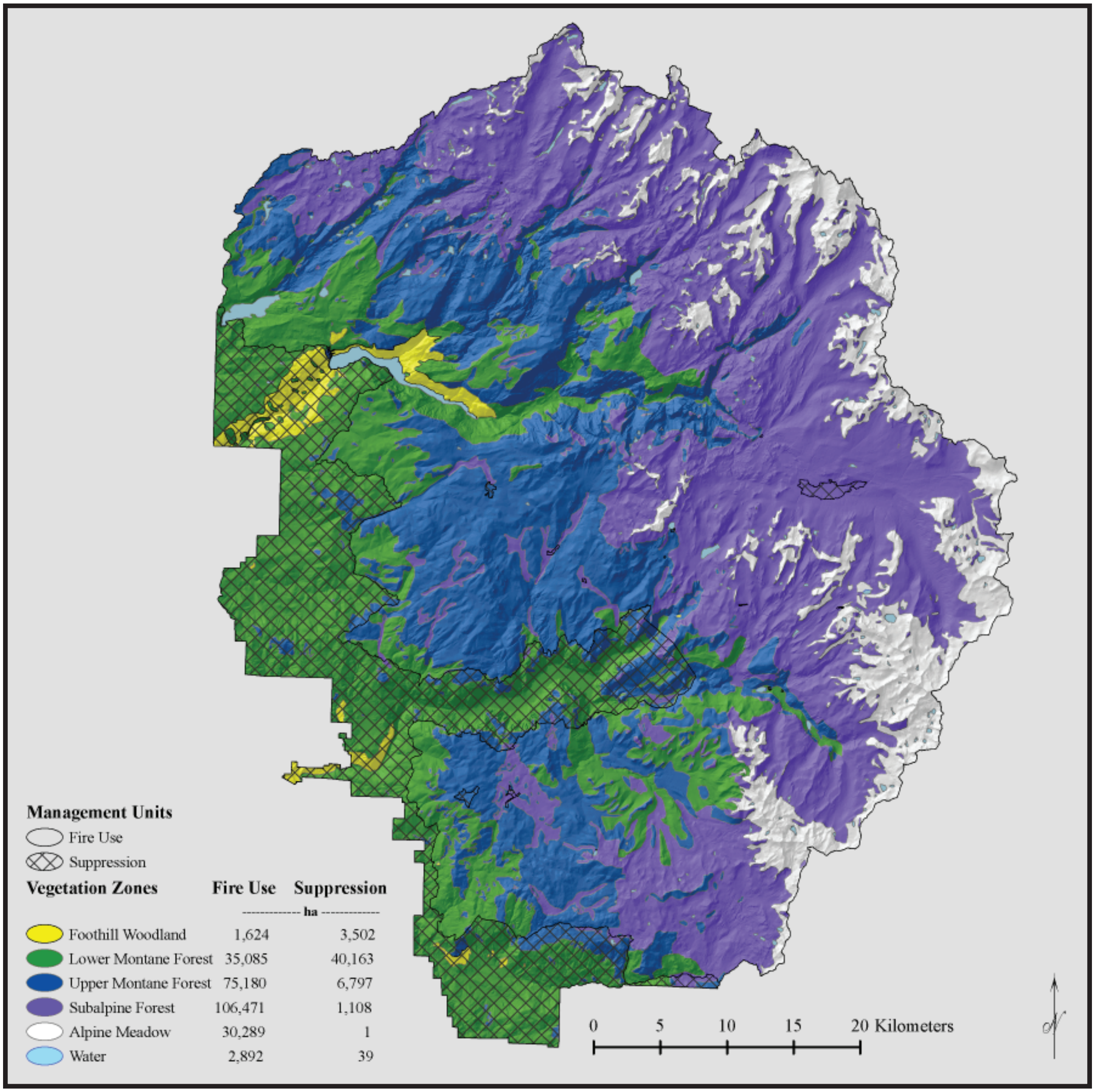


**Figure 1.** Fire management zones and vegetation zones in Yosemite National Park. In the fire use zone, most lightning fires are allowed to burn under prescribed conditions. In the suppression zone, all human-caused and lightning-caused fires are suppressed. Prescribed fires are used to reduce hazardous fuels and restore natural conditions in both zones.

gives way to the upper montane forest of nearly pure red fir (*A. magnifica*) forests with western white pine (*P. monticola*), western juniper (*Juniperus occidentalis*), and Jeffrey pine (*P. jeffrey*) occurring on exposed granitic ridges. Montane chaparral occurs in patches beneath the upper montane forest. The subalpine forest is dominated by lodgepole pine (*P. contorta*), which, as treeline is approached, is replaced by mountain hemlock (*Tsuga mertensiana*) and whitebark pine *(P. albicaulis*). Meadows consisting of herbs, grasses, sedges, and shrubs occur at all elevations.

Fire scars are a primary source of information for documenting the historic fire regimes. Several studies in Yosemite have determined that fires were frequent in the past but decreased sharply after the mid-1800s, coinciding with Euro-American settlement of the Yosemite region. Swetnam (1993) reported fire scar records in five giant sequoia groves located from Yosemite to Sequoia National Park that confirmed the presence of fire in the Sierra Nevada for the past 3,000 years. Between 1300 and the mid-1800s, intervals free of fire scars ranged from less than 13 yr during dry periods to between 15 yr and 30 yr during cool periods. Swetnam *et al.* (2000) examined fire scars in the southwestern part of Yosemite along a transect from 1,090 m to 2,425 m. They found that mean fire return intervals for fires recorded by 25 % or more of the fire-scarred trees ranged from 4.94 yr in ponderosa pine at the lowest elevation to 10.57 yr in Jeffrey pine at the highest. Swetnam *et al.* (2000) also found that 55 % of the fire scars occurred in the latewood part of the tree ring, indicating that these fires burned between July and early October. An additional 21 % occurred between June and July and 17 % between mid-September and December.

Scholl (2007) found similar results for lower montane forests north and south of Yosemite Valley. In the northern location, the mean return interval for fires recorded by 25 % of the trees was 10.0 yr, while south of the valley it was 6.9 yr. He reconstructed fire size from fire scars and found that 22 % of the fires were <25 ha and 1 % were between 1,275 ha and 2,125 ha. Gassaway (2007) recorded fire scars from 62 trees in her study area in Yosemite Valley and determined a composite mean fire return interval of 1.92 yr. She attributed those frequent fires to intentional burning done by Native Americans because Yosemite Valley experiences few lightning ignitions (van Wagtendonk 1994).

Collins and Stephens (2007) cross dated 420 trees in the Illilouette Creek basin just south of Yosemite Valley and calculated a mean fire return interval of 6.3 yr for the period between 1700 and 1900. Based on scars recorded between 1972 and 2000, when the wildland fire use program started, they concluded that the number and extent of fires approached historical levels.

Fire suppression in Yosemite National Park began in 1891 when the U.S. Army was assigned the responsibility for protecting the park (Rothman 2007). When the National Park Service was established in 1916, it continued the total suppression program. In 1968, Park Service policy changed and the use of prescribed fires and natural fires was permitted. Yosemite initiated prescribed burning in 1970 and has allowed wildland fires to burn under prescribed conditions since 1972. The wildland fire use program was based on an analysis of natural fire return intervals and the magnitude of departures from these intervals for each of the vegetation types in the park (van Wagtendonk *et al.* 2002). Areas of the upper montane and subalpine zones, where departures are generally two or fewer return intervals, have been categorized as wildland fire use zones (Figure 1). In these areas, lightning fires that meet specific prescriptions are allowed to burn to meet land management objectives, but human-caused wildfires are suppressed. Approximately 83 % of the park is in this zone. In the remaining 17 %, primarily in lower montane forests, all human-caused and lightning-caused wildfires are suppressed. These areas have not burned in three or more fire return intervals, have unnaturally high fuel accumulations, and are close to developed areas or park boundaries. The park uses prescribed fires in the upper and lower montane forests to reduce fuel hazards and to restore natural conditions. Between 1930 and 2005 there have been 1,594 wildfires. Of these, 585 were caused by humans and 1,009 ignited by lightning.

For this analysis, we aggregated fires into three management types: prescribed fires (management ignited), wildfires (ignitions by humans and those lightning-ignited fires that were suppressed), and wildland fire use (lightning ignitions allowed to burn under prescribed conditions). Some wildland fire use fires exceeded their prescriptions and subsequently were converted to wildfires and suppressed. In those cases, we assigned the entire fire to the fire management type in which it had the largest burned area.

*Data Sources*

We used data from a fire atlas maintained by the park, fire weather records, and satellite imagery to determine fire regime attributes. The fire atlas contains the fire name, final area burned, fire management type, cause, start date, end date, and digitized perimeter of all of the fires that have occurred in the park since 1930. Daily weather records maintained by the Forest Service were available for a weather station centrally located in the park that had records dating back to 1974 (http://famweb.nwcg.gov/). In addition to weather and fuel moisture observations, the fire weather records include fire behavior potential and occurrence indices from the National Fire Danger Rating System (Deeming *et al.* 1977). Satellite imagery became available in 1974, soon after the prescribed burning program began in 1970 and the wildland fire use program in 1972. Therefore, we had to limit our analysis to the period between 1974 and 2005.

Thode (2005) and Miller and Thode (2007) previously compiled fire severity data from satellite imagery for all fires >40 ha in the Sierra Nevada. This data set included 144 fires in Yosemite National Park including 37 prescribed fires, 75 wildland fire use fires, and 32 wildfires that burned a total of 44,062 ha within the foothill woodland, lower montane forest, upper montane forest, and subalpine forest zones (Table 1, Figure 2).

Miller and Thode (2007) used Landsat Multitemporal Spectral Scanner (Landsat MSS) imagery and the Normalized Difference Vegetation Index (NDVI) at a resolution of ~80 m to map the severity of fires between 1974 and 1983. They used Landsat Thematic Mapper (Landsat TM) imagery and the Normalized Burn Ratio (NBR) at a resolution of 30 m to map fires from 1984 through 2005. Thode (2005) concluded that there was no significant difference between severity maps derived from the NDVI and NBR; therefore, we were able to use the entire Landsat record (1974-2005) for our analysis. When fires extended beyond the boundary of the park into the adjacent Stanislaus National Forest, we analyzed the entire fire. Differences in NDVI and differences in NBR (dNBR) depend on the pre-fire vegetation, which varies by forest type and successional stage (Miller and Thode 2007). Therefore, to account for heterogeneity of pre-fire vegetation among fires, we used relative measures of fire severity: the Relative

**Table 1.** Area burned (ha) within vegetation zones by prescribed fires, wildfires, and wildland fire use fires >40 ha in Yosemite National Park, 1974 through 2005.

| | Fire management type | | | |
|---|---|---|---|---|
| **Vegetation zone** | **Prescribed fire** | **Wildfire** | **Wildland fire use** | **All fires** |
| Foothill Woodland | 275 | 709 | 47 | 1,031 |
| Lower Montane Forest | 10,627 | 8,635 | 8,977 | 28,239 |
| Upper Montane Forest | 1,064 | 3,275 | 8,188 | 12,527 |
| Subalpine Forest | 25 | 213 | 2,026 | 2,264 |
| Alpine Meadow | 0 | 0 | 0 | 0 |
| Total | 11,991 | 12,832 | 19,238 | 44,061 |

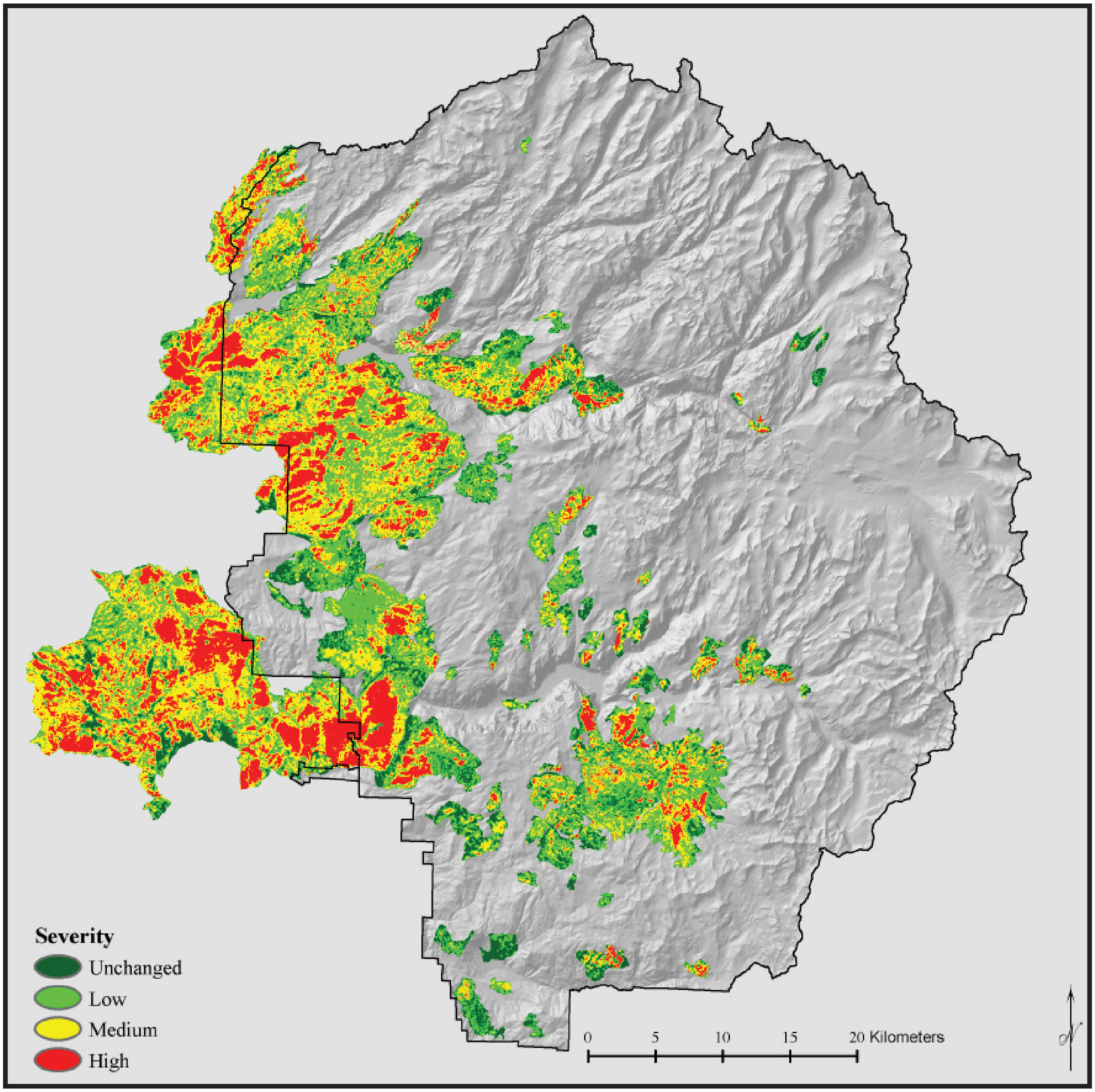


**Figure 2.** Fire severity levels for all fires >40 ha, Yosemite National Park, 1974 through 2005. Where fires have reburned the same area, the fire severity of the most recent fire is shown. The fires west of the park burned in the Stanislaus National Forest.

differenced NBR (RdNBR) for fires mapped with Landsat TM and the Relative NDVI (RNDVI) for fires mapped with Landsat MSS (Thode 2005, Miller and Thode 2007).

In her analysis of fires throughout the Sierra Nevada including Yosemite, Thode (2005) determined numerical thresholds to distinguish between portions of a fire that burned at low, moderate, and high severities, as well as areas that were unchanged between pre-fire and post-fire satellite images. Unchanged areas usually reflected low intensity surface fires that burned beneath the overstory canopy and that did not burn or scorch the overstory canopy. She classified areas within the digitized fire history perimeters as unchanged if the severity was so low that she could not detect a change in the images that were one year post-fire, and she extended the perimeters to include areas that showed a change due to fire but were outside of the recorded perimeters. The RNDVI thresholds were: unchanged – less than 25; low – greater than or equal to 25 and less than 198; moderate – greater than or equal to 198 and less than 419; and high– greater than or equal to 419. The RdNBR thresholds were: unchanged – less than 42; low – greater than or equal to 42 and less than 220; moderate – greater than or equal to 220 and less than 566; and high – greater than or equal to 566.

*Calculation of Fire Regime Attributes*

We chose to evaluate six of the seven fire regime attributes described by Sugihara *et al.* (2006): seasonality, return interval, size, spatial complexity, intensity, and severity. Fire type (ground, surface, or crown fire) was not considered because historic data on type were not available. In addition to fire return interval for each fire, we also calculated fire rotation for the vegetation zones. We used start date and duration to depict seasonality and the burning index to represent fire line intensity. We determined fire size, return interval, rotation, severity, and spatial complexity from the satellite-derived fire severity maps. We used mean patch size (MPS) and patch squareness (SqP) to represent spatial complexity (Frohn 1998). Mean patch size is a measure of fragmentation, and patch squareness is a measure of complexity. Patch squareness is an index that runs from 0 for square, minimally complex patches, to 1 for patches that were least square-like and highly complex. Unlike contagion and fractal dimension, MPS and SqP are optimized for use with data arranged in rasters, as with Landsat data (Frohn 1998).

Some differences in fire regime attributes among fire management types could be due to differences in vegetation. Because vegetation zones correspond to elevation, we used the average elevation of each fire to adjust for the effect of vegetation zones on fire regimes. The elevations were used as a covariate in the analysis.

*Start date and fire duration.* We converted start dates to Julian dates to indicate the season of burning. Because no fires burned from December into January, we were able to calculate duration by subtracting the start date from the end date. For wildland fire use fires, the park recorded the date of the first winter storm as the end date.

*Burning index, flame length, and fireline intensity*. Because peak weather has the greatest influence on fire behavior and effects, we used the 95$^{th}$ percentile burning index calculated from the daily values during a fire to represent that fire rather than the average daily burning index. Daily values ranged from zero to 58. If we had used the average over the duration of a fire (which was often two months or more), we would have diluted the influence of peak weather periods. For example, one fire burned for 144 days and had an average burning index of 24 while the 95$^{th}$ percentile value was 41. We converted 95$^{th}$ percentile burning index values to flame length and fireline intensity using equations in Deeming *et al.* (1977) and Byram (1959).

*Fire size, return interval, and rotation.* Because Kolden (2007) concluded that manually-mapped perimeters correlated poorly with remotely-sensed fire perimeters, we used the fire perimeters derived by Thode (2005) from satellite imagery to calculate the areal extent of each fire. We determined the fire return interval for each fire that reburned areas burned by previous fires by calculating the number of years between fires weighted by the reburned area including areas that burned multiple times. For example, if a 1,000 ha fire reburned 100 ha of a 9 yr old fire and 200 ha of a 15 yr old fire, the return interval for that fire would be 13 [(9 x 100)/300 + (15 x 200)/300]. Fire rotation was calculated by dividing the area in each vegetation zone (Figure 1) by the area burned in that zone for all fires and each fire management type (Table 1).

*Fire severity.* We calculated the percent area burned in each fire severity level by fire management type (prescribed fire, wildfire, wildland fire use) from the RNDVI and RdNBR data compiled by Thode (2005) and Miller and Thode (2007).

*Mean patch size and patch squareness.* Because spatial complexity measures are affected directly by the spatial resolution of the satellite data, we used only the 30 m Landsat TM images from 1984 to 2005 (106 fires) and not the coarser resolution data from the Landsat MSS for spatial complexity analysis. We analyzed the RdNBR data with FRAGSTATS (McGarigal *et al.* 2002) and used the output to calculate mean patch size and patch squareness metrics (Frohn 1998).

### *Statistical Analysis*

We used one-way analysis of covariance with elevation as a covariate to test for differences among fire management types for start date, duration, burning index, percent fire severity level, size, and return interval. For the percent fire severity analysis, we analyzed each severity level separately using the arcsine square root transformation to normalize the data. We used two-way analysis of covariance with elevation as a covariate to test for differences among fire management types and fire severity levels for the spatial complexity metrics. We normalized SqP values with the arcsine square root transformation. All hypotheses tests were 2-tailed and at the 0.05 significance level. Bonferroni multiple comparison tests were used to detect differences among means. For these comparisons, the significance levels were adjusted to 0.0167 for one-way ANOVAs and to 0.0083 two-way ANOVAs.

## RESULTS

Management type was significant for all of the fire regime attributes except fire return interval. Fire severity level was significant for both patch size and patch squareness. Elevation was not significant for the 95$^{th}$ percentile burning index, fire return interval, patch squareness, and the low and high percent severity levels.

*Start date and fire duration.* Mean fire start dates varied by fire management type ($F_{2, 140}$ = 3.91, $P$ = 0.022) (Table 2). Prescribed fires tended to have two seasons, one in the spring and another in the fall (Figure 3). The number of lightning fire ignitions that were allowed to burn as part of the wildland fire use program reached a peak in July, while wildfires started primarily in August. Multiple comparison tests showed that prescribed fire start dates were significantly different ($P \leq 0.001$) from start dates for both wildfires and wildland fire use fires.

Fire duration was also significantly affected by fire management type ($F_{2, 140}$ = 12.478, $P \leq$ 0.001) (Table 2). Most prescribed fires and wildfires lasted less than 20 days, while the most common duration of wildland fire use

**Table 2.** Start date and duration (days) and for prescribed fires, wildfires, and fire use fires >40 ha in Yosemite National Park, 1974 through 2005.

| Fire management type | Start date | | Duration | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| | date | ·········· days ·········· | | |
| Prescribed fire | 7/21 | 102.2 | 25.3 | 23.9 |
| Wildfire | 8/19 | 40.5 | 37.3 | 40.8 |
| Fire use | 8/2 | 30.4 | 85.5 | 37.4 |
| All fires | 8/3 | 61.0 | 58.6 | 44.6 |

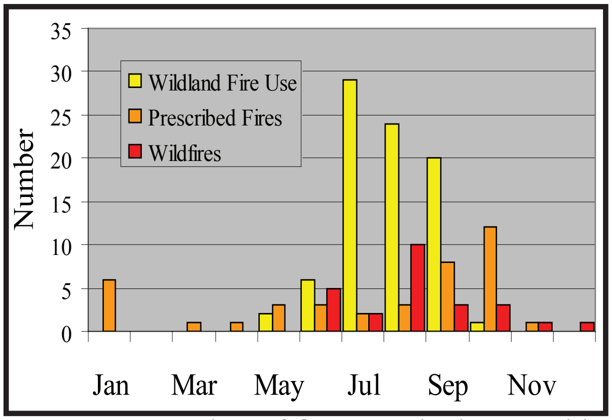


**Figure 3.** Number of fires >40 ha by monthly start dates for prescribed fires, human-caused wildfires, lightning-caused wildfires, and lightning-caused wildland fire use fires, Yosemite National Park, 1974 through 2005.

fires was from 101 days to 120 days. Multiple comparisons showed that there were no significant differences between prescribed fires and wildfires ($P \leq 0.001$), and that wildland fire use fires burned significantly longer than the other two fire management types.

*Burning index, flame length, and fireline intensity.* The mean 95$^{th}$ percentile burning index varied significantly by fire management type ($F_{2,\,140} = 15.21$, $P \leq 0.001$) (Table 3). The modal number of prescribed fires occurred when the 95$^{th}$ percentile burning index was between 6 and 10. Wildfires burned most frequently when the 95th percentile burning index was between 31 and 35, while wildland fire use fires most often occurred when the 95th percentile burning index was between 36 and 40. The multiple comparisons showed that the mean 95th percentile burning index for prescribed fires differed significantly from the index for either wildfires or wildland fire use fires ($P \leq 0.001$). The estimated mean flame length for prescribed fires was 0.31 m less than wildfires and 0.45 m less than wildland fire use fires ($F_{2,\,140} = 15.31$, $P \leq 0.001$) (Table 3). Similarly, fireline intensities were 118.08 kW m$^{-1}$ and 123.60 kW m$^{-1}$ less, respectively ($F_{2,\,140} = 11.87$, $P \leq 0.001$) (Table 3).

*Fire size, return interval, and rotation.* Fire size was significantly affected by fire management type ($F_{2,\,140} = 6.29$, $P = 0.002$) (Table 4). Wildland fire use fires were significantly larger than prescribed fires, and the mean area burned by wildfires was more than four times the mean area burned by wildland fire use fires ($P$ =0.012). Most of the difference was a result of two large wildfires that were greater than 19,000 ha.

Fire return intervals were calculated for the 82 fires that reburned 13,838.7 ha in previous fires (Table 4, Figure 4). Fire management type did not significantly affect fire return intervals ($F_{2,\,78} = 2.34$, $P = 0.103$). Return interval values for the reburned areas ranged from 7.3 yr for prescribed fires to 11.4 yr for wildland fire use fires. Fire rotations for

**Table 3.** 95th percentile burning index, estimated flame length (m), and estimated fireline intensity (kW m$^{-1}$) based on the 95th percentile weather data for prescribed fires, wildfires, and fire use fires >40 ha in Yosemite National Park, 1974 through 2005.

| Fire management type | 95th percentile burning index | | Flame length | | Fireline intensity | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| | ·········· index ·········· | | ·········· m ·········· | | ·········· kW m$^{-1}$ ·········· | |
| Prescribed fire | 20.0 | 10.7 | 0.61 | 0.33 | 120.10 | 126.36 |
| Wildfire | 30.1 | 9.1 | 0.92 | 0.28 | 238.18 | 127.07 |
| Fire use | 34.9 | 7.7 | 1.06 | 0.24 | 311.97 | 133.11 |
| All fires | 29.8 | 10.9 | 0.91 | 0.33 | 243.70 | 152.51 |

**Table 4.** Fire size (ha) and the number of fires considered in the return interval calculation, the area (ha) reburned by those fires, and the return interval (yr) for prescribed fires, wildfires, and fire use fires >40 ha in Yosemite National Park, 1974 through 2005.

| Fire management type | Size | | Return interval | | | |
|---|---|---|---|---|---|---|
| | Mean | SD | Fires | Area | Mean | SD |
| | ha | | no. | ha | yr | |
| Prescribed fire | 481.4 | 544.8 | 25 | 6,963.3 | 7.3 | 5.9 |
| Wildfire | 2,059.2 | 5,438.7 | 20 | 2,266.5 | 8.9 | 6.8 |
| Fire use | 503.0 | 723.5 | 37 | 4,608.9 | 11.4 | 5.4 |
| All fires | 835.9 | 2,654.2 | 82 | 13,838.7 | 9.6 | 6.1 |

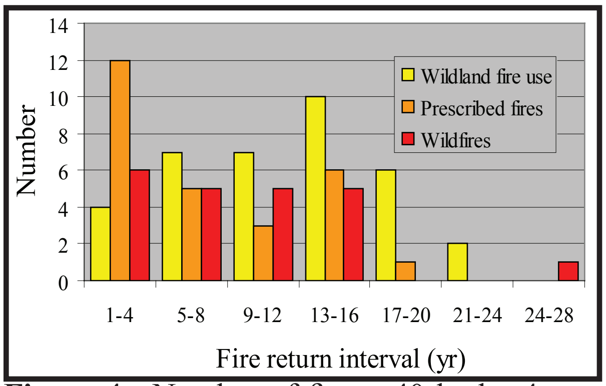


**Figure 4.** Number of fires >40 ha by 4-year fire return intervals for prescribed fires, human-caused wildfires, lightning-caused wildfires, and lightning-caused wildland fire use fires, Yosemite National Park, 1974 through 2005.

the foothill woodland zone ranged from 224 yr for wildfires to 3,381 yr for wildland fire use fires (Table 5). Rotations for the lower montane forest zone were similar for the three management types, from 220 yr to 270 yr. In the upper montane forest and subalpine forest zones, prescribed fires had the longest rotations and wildland fire use fires the shortest. When all fire management types and zones were considered together, the rotation was 213 yr.

*Fire severity.* Fire management type significantly affected the percentage of unchanged fire severity within a fire ($F_{2,\ 140}$ = 9.372, $P \leq 0.001$). Wildfires had significantly less percent area at the unchanged level than either prescribed fires ($P \leq 0.001$) or wildland fire use fires ($P = 0.023$). For the unchanged severity level, prescribed and wildland fire use fires did not significantly differ (Figure 5). The percentage of low severity fire differed significantly among fire management types ($F_{2,\ 140}$ = 4.56, $P$ = 0.012). Prescribed fires had more low severity fire than wildfires ($P$ = 0.009) but did not differ significantly from wildland fire use fires. There were significant differences in the percent of low severity between wildfires and wildland fire use fires (Figure 5). The percent burned at moderate severity also was significantly affected by fire

**Table 5.** Fire rotation (yr) by vegetation zone for prescribed fires, wildfires, and fire use fires >40 ha in Yosemite National Park, 1974 through 2005.

| Vegetation zone | Fire management type | | | |
|---|---|---|---|---|
| | Prescribed fire | Wildfire | Wildland fire use | All fires |
| | yr | | | |
| Foothill Woodland | 578 | 224 | 3,381 | 154 |
| Lower Montane Forest | 220 | 270 | 260 | 83 |
| Upper Montane Forest | 2,388 | 776 | 310 | 203 |
| Subalpine Forest | 133,398 | 15,657 | 1,646 | 1,473 |
| Total | 784 | 732 | 488 | 213 |

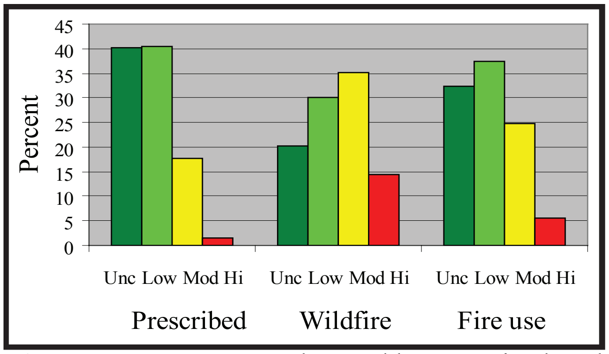


**Figure 5.** Percent area burned by severity level for prescribed fires, wildfires, and fire use fires >40 ha, Yosemite National Park, 1974 through 2005.

management type ($F_{2,\ 140}$ = 15.25, $P \leq 0.001$), with wildfires having a significantly greater percentage than both prescribed fires ($P \leq 0.001$) and wildland use fires ($P = 0.010$). Fire management type was also significant for the percent of high severity burned area ($F_{2,\ 140}$ = 21.44, $P \leq 0.001$). Each fire management type differed significantly from the other two ($P \leq 0.001$) with respect to the proportion burned at high severity (Figure 5).

*Mean patch size and patch squareness.* Fire management type ($F_{2,\ 411}$ = 3.02, $P$ = 0.050), fire severity level ($F_{3,\ 411}$ = 2.83, $P$ = 0.038), and their interaction ($F_{6,\ 411}$ = 6.54, $P \leq 0.001$) all had significant effects on mean patch size (Figure 6). Prescribed fires had the largest unchanged and low severity patches, while wildfires had the largest moderate and high severity patches. Wildland fire use fires had relatively even size distribution of unchanged, low, and moderate severity patches, while high severity patches were comparatively smaller. When severity patches were considered together, there were no significant differences among management types. However, when fire management types were lumped within severity levels, multiple comparisons showed significant differences in patch sizes between high severity and moderate severity levels ($P$ = 0.016).

Patch squareness differed significantly by fire management type ($F_{2,\ 411}$ = 11.64, $P \leq 0.001$) and fire severity level ($F_{3,\ 411}$ = 41.41, $P \leq 0.001$), but their interaction was not significant ($F_{6,\ 411}$ = 1.68, $P$ = 0.124). Unchanged and low severity patches tended to be the least square for all management types, and high severity patches the most square (Figure 7). Patch squareness for prescribed fires differed significantly from wildfires when severity levels were combined ($P$ = 0.019). When fire management types were combined into severity levels, all comparisons between levels were significant ($P \leq 0.001$) except between unchanged patches and both low and moderate severity patches.

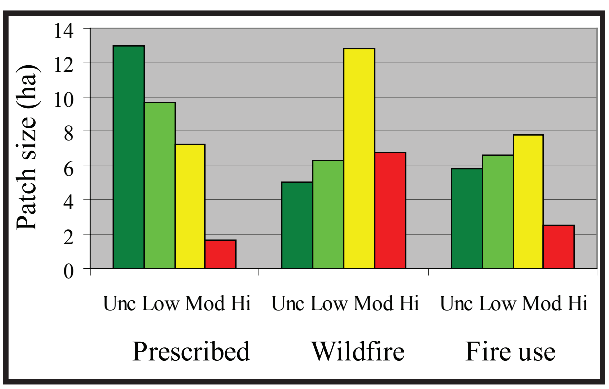


**Figure 6.** Mean patch size (ha) by severity level for prescribed fires, wildfires, and fire use fires >40 ha, Yosemite National Park, 1984 through 2005.

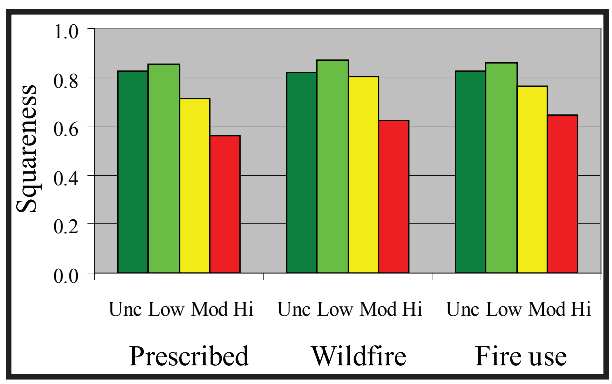


**Figure 7.** Patch squareness by severity level for prescribed fires, wildfires, and fire use fires >40 ha, Yosemite National Park, 1984 through 2005.

## DISCUSSION

The effect of fire management type, whether prescribed, wildfire, or wildland fire use, was pronounced for some fire regime attributes and non-existent for others. The causes of those differences were not always evident but can be explained by examining the management objectives of the fires and the conditions under which they burned.

Although the mean start dates were within a month of each other, the distribution of dates over the year showed considerable differences. Prescribed fires were most frequently ignited by managers in October and September with a small peak in January. This is because conditions in the fall and early spring are suitable for safe but effective burning. Wildland fire use fires and wildfires ignited by lightning followed storm patterns with most ignitions occurring in July, August, and September (van Wagtendonk 1994), consistent with the findings of Swetnam *et al.* (2000).

Given the objectives for the fire management types, it is not surprising that fire duration differed significantly. Wildland fire use fires are allowed to burn over long periods of time as long as prescriptions are met. The average duration for those fires was over twice as long as either wildfires or prescribed fires. Wildfires are extinguished as soon as practicable, usually within 20 days. Prescribed fires are designed to be accomplished in a short period of time, although several long-duration prescribed fires lasted as long as 40 days.

The low 95th percentile burning index, flame length, and fireline intensity values for prescribed fires were well within the prescription limits set for Yosemite. Because the objective for these burns was to incrementally reduce heavy accumulations of fuels, the prescriptions were more conservative than conditions for naturally occurring fires. Wildfires and wildland fire use fires occurred primarily in the summer; consequently, the mean 95th percentile burning indexes, flame lengths and fireline intensities were higher. The value of these attributes for wildland fire use fires were slightly higher than for wildfires because wildland fire use fires were allowed to burn over long durations, which often included periods of extreme weather.

Prescribed fires and wildland fire use fires averaged about 500 ha in size. Because it was an objective to allow these fires to burn, they reach relatively large sizes. These fires were twice as large as the fires that Scholl (2007) reconstructed from fire scars, but underreporting is often a problem with fire scar reconstructions (Collins and Stephens 2007). Wildfires, on the other hand, were suppressed as soon as possible, but those few that escaped suppression often grew to very large sizes. The average size of wildfires was five times that of both prescribed and wildland fire use fires. Most of this difference is attributable to three large wildfires that burned a total of over 51,000 ha. Such large fires did not occur in the wildland fire use zone, where there appears to be a practical maximum size for freely burning fires that is limited by natural barriers such as exposed rock, areas of lower productivity and fuel accumulation, or areas where recent fires have decreased fuel loading (Collins *et al.* in press).

Fire return intervals for reburned areas of all fire management types were within the ranges reported by other authors for the same vegetation zones (Skinner and Chang 1996, Swetnam *et al.* 2000, Collins and Stephens 2007, Scholl 2007). It is important to note that these values apply only to areas that have reburned since 1974 and do not represent area-wide return intervals, which would be longer. On the other hand, the lengths of the fire rotations indicate that fire has occurred less often than in previous centuries.

There were pronounced differences in the percent fire severity levels among the fire management types. Prescribed fires had a much larger percentage of unchanged and low severity burned area than wildfires and slightly more than wildland fire use at those severity levels. Because the objective of prescribed fires is to reduce fuels safely and effectively, it was expected that severity would remain low to unchanged. Wildfires and wildland fire use fires burned under hotter and drier conditions that produced large high severity patches. The percent moderate severity burned area for wildfires was twice that of prescribed fires and half again as much as wildland fire use. Wildfires had 10 times as much high severity burned percentage as prescribed fires and nearly three times as much as wildland fire use.

Fire regime attributes cannot be considered in isolation from each other, as it is the combination of attributes that defines the ecological effect of a given fire. Fires of comparable size but typical of each of the three different management types yielded strikingly different landscape patterns (Figure 8). The prescribed South Fork Fire was ignited in October, 2002. It burned 1,404 ha with predominantly low severity on north-facing slopes. The Tuolumne Fire began as a wildland fire use fire in August, 2003, but was converted to a wildfire when it exceeded its prescription. Most of the area burned while in suppression status. It was controlled at 1,484 ha, and most of the large patches of high severity occurred after the conversion. The 1988 East LeConte Fire was managed as part of the wildland fire use program. It grew to 1,547 ha between September 1 and November 19. Although there were some patches of high severity, most of the area burned with moderate severity. These three fires all show a range of severity levels, which led in turn to a range of post-fire vegetation and fuels.

Mean size of unchanged patches was more than twice as large for prescribed fires as for wildfires or wildland fire use fires. The size

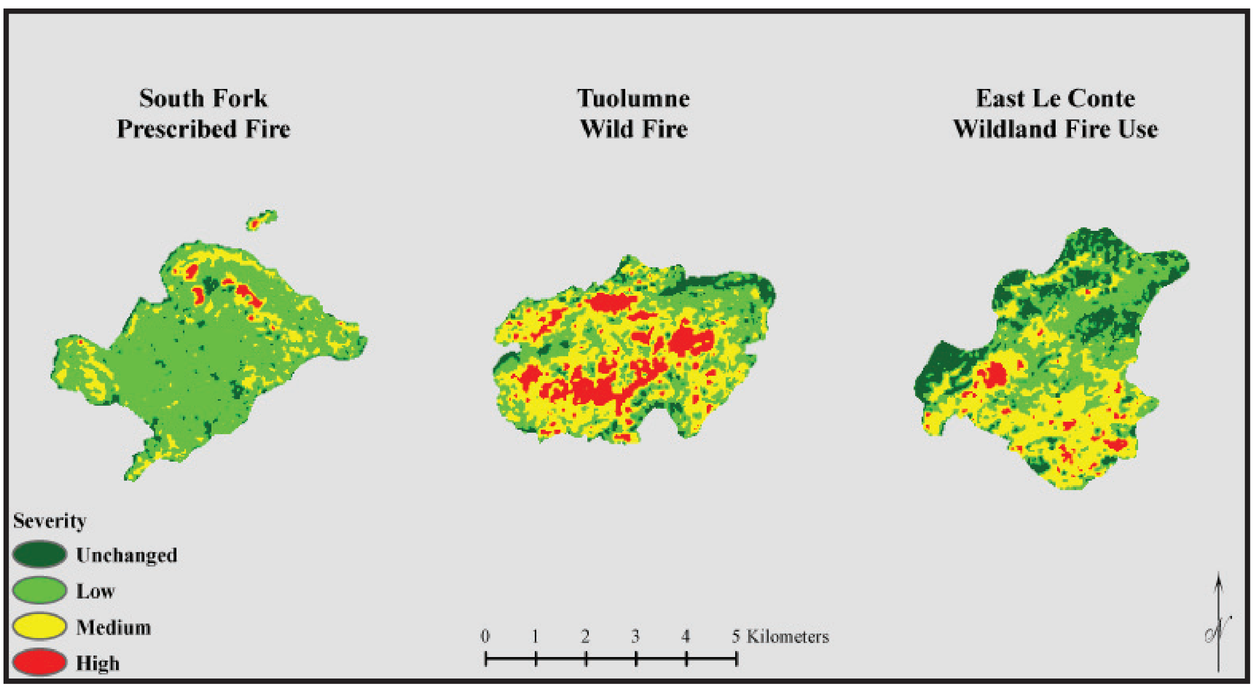


**Figure 8.** Example prescribed fire, wildfire, and wildland fire use fire severity maps. The prescribed South Fork Fire burned 1,404 ha in 2002. It has a large area of low severity fire typical of prescribed burns in Yosemite. The Tuolumne wildfire burned 1,484 ha in 2003 and has large patches of high severity. The 1988 wildland fire use East LeConte Fire burned 1,547 ha and has a mosaic of unchanged, low, moderate and high severity patches.

differential also occurred for low severity patches, but it was not as great. Because prescribed fires tended to be low intensity surface fires, they were less likely to open the canopy, and therefore resulted in the large unchanged patches mapped by Thode (2005). Wildfires had the largest patches of moderate severity patches with some nearly twice as large as prescribed and wildland fire use fires. As intensity increases, severity increases creating larger patches. Wildfires had high severity patches that were three times as large as the other two management types, but these patches were only half the size of the moderate severity patches. Most high severity areas occured where fires burned through the canopy for a short period of time and then dropped back down to the surface. Sustained independent crown fires, which can create large patches of high severity, have been rare and occurred in only the three largest wildfires under extreme weather conditions.

Forests of the Sierra Nevada are partially characterized by their patchiness at large (100 ha to 1000 ha) scales, particularly in late successional old-growth (Franklin and Fites-Kaufman 1996). Within large forests, species composition and structure vary considerably at smaller (1 ha to 10 ha) scales (Langley 1996). Relative to areas of uniform forest cover, the patchiness of Sierra Nevada forests may be responsible for higher levels of plant and animal diversity, and at least some of this small scale heterogeneity has been maintained by vegetation-fire feedbacks (Miller and Urban 1999, Stephens 2001). Fires can increase or decrease landscape heterogeneity through the creation of varying sized patches burned at a given severity.

Patch size may have implications for future landscape heterogeneity and fires. Compared to wildland fire use, prescribed burns have more contiguous patches of low severity. While this may reduce fuel loading in the near term, the lack of canopy mortality may be creating a larger area of more uniform canopy fuels. Although high intensity canopy fires have been rare in the park, perpetuation of large areas of uniformly dense canopy cover could make future large-scale high severity fire more likely. Climate change may also be increasing the possibility of previously rare fire events (McKenzie *et al.* 2004, Hessburg *et al.* 2005, Running 2006, Westerling *et al.* 2006).

Patch squareness, which measures the complexity of areas of burn severity, was similar for unchanged and low severity patches. Moderate and high severity patches for prescribed fires were slightly more square than those of wildfires and wildland fire use fires. This could be attributed to the small size of those patches; small patches tend to be less complex than large ones. As patches increase in size, there are more opportunities for convoluted shapes to occur. For example, small high severity patches comprised only 0.1 % of the 1993 prescribed North Fire (Figure 9). The high severity patch squareness value was 0.39, indicating a relatively simple patch shape. On the 1985 wildland fire use Kendrick Fire, high severity patches were larger and comprised 9.6 % of area burned (Figure 9). The patch squareness for high severity patches was 0.85, indicating relatively more complex patch shape.

The most important ecological implication that can be drawn from these results is that prescribed fires differ in their fire regime attributes from both wildfires and wildland fire use fires. When one or more fire attributes differ from the natural fire regime, the presence and abundance of plant and animal species could be altered. For example, out-of-season burning could affect germination, growth and flowering of herbaceous plants and shrubs (Kauffman and Martin 1990, but see Knapp *et al.* 2007) and could impact breeding populations of nesting animals. While there is justification for the timing of prescribed fires, attempts should be made to shift the burning season toward the

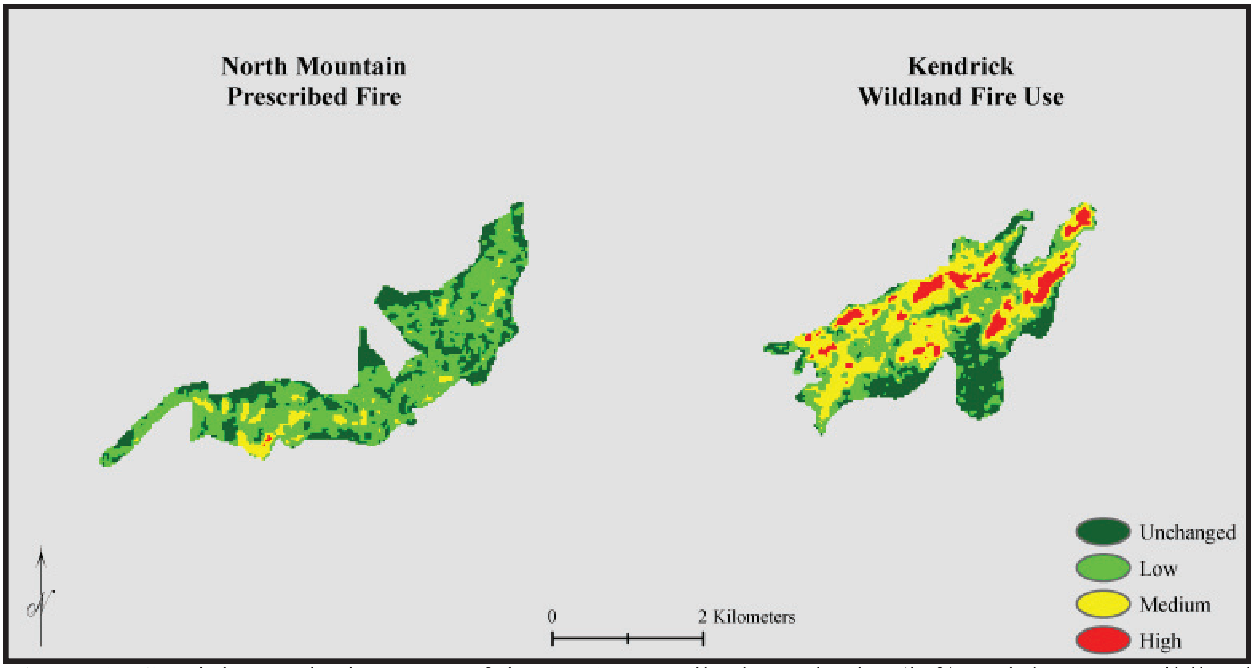


**Figure 9.** Spatial complexity maps of the 1993 prescribed North Fire (left) and the 1985 wildland fire use Kendrick Fire (right). The North Fire had a patch squareness value for high severity patches of 0.39, indicating relatively simple patch shape. The wildland fire use Kendrick Fire had a patch squareness value for high severity patches of 0.85, indicating relatively more complex patch shape.

summer and early fall. Similarly, attempts should be made to burn with higher intensities. This will result in a greater proportion of the area being burned with moderate and high severity, better mimicking the natural fire regime.

The significant differences in fire regime attributes suggest that land managers seeking to restore natural fire regimes and characteristic forest composition and structure must consider more than just the amount of area burned or fuels reduced. Prescribed fires, as currently implemented, and wildfires produce patch structures that are probably different from historic conditions. There are many tradeoffs between wildfires and wildland fire use, but paramount is the return to more natural fire regimes and more structurally heterogeneous forests that have less potential for large, catastrophic fires. More areas need to be treated by prescribed fire and wildland fire use to prevent the increase in high severity catastrophic fires. As more areas are treated with prescribed fires, the areas can be placed in the wildland fire use zone, and the incidence of wildfires will be reduced.

## ACKNOWLEDGEMENTS

We would like to thank the U.S. Department of the Interior and Department of Agriculture Forest Service, Joint Fire Science Program (JFSP 00-1-3-01) for funding the initial work on this project. J. A. Lutz received funding from the NSF IGERT Program (0333408) and the Seattle ARCS Foundation. J. D. Miller and A. E. Thode graciously provided the classified satellite imagery. K. A. van Wagtendonk prepared the GIS layers used in the analysis and produced the maps.

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