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Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA

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Abstract. Continental-scale studies of western North America have attributed recent increases in annual area burned and fire size to a warming climate, but these studies have focussed on large fires and have left the issues of fire severity and ignition frequency unaddressed. Lightning ignitions, any of which could burn a large area given appropriate conditions for fire spread, could be the first indication of more frequent fire. We examined the relationship between snowpack and the ignition and size of fires that occurred in Yosemite National Park, California (area 3027 km^2), between 1984 and 2005. During this period, 1870 fires burned 77 718 ha. Decreased spring snowpack exponentially increased the number of lightning-ignited fires. Snowpack mediated lightning-ignited fires by decreasing the proportion of lightning strikes that caused lightning-ignited fires and through fewer lightning strikes in years with deep snowpack. We also quantified fire severity for the 103 fires >40 ha with satellite fire-severity indices using 23 years of Landsat Thematic Mapper data. The proportion of the landscape that burned at higher severities and the complexity of higher-severity burn patches increased with the $\log_{10}$ of annual area burned. Using one snowpack forecast, we project that the number of lightning-ignited fires will increase 19.1% by 2020 to 2049 and the annual area burned at high severity will increase 21.9%. Climate-induced decreases in snowpack and the concomitant increase in fire severity suggest that existing assumptions may be understated – fires may become more frequent and more severe.

Additional keywords: burn severity, climate change, climate variability, fire regime attributes, landscape flammability, normalized burn ratio, patch complexity, RdNBR, Sierra Nevada, snowpack, snow water equivalent.

Introduction

Large-scale studies of western North America show recent increases in annual area burned and fire size (McKenzie *et al*. 2004; Flannigan *et al*. 2005; Westerling *et al*. 2006). These studies have focussed on large fires rather than all ignitions, and have left the issues of fire severity and ignition patterns unaddressed. Satellite fire-severity indices (Key 2006; Key and Benson 2006; Miller and Thode 2007) allow quantification of the current fire-severity regimes, and the 23-year record of Landsat Thematic Mapper (Landsat TM) data extends over a range of fire severities, reflecting fires occurring in varying climatic conditions and forest types. Climate has been shown to affect the annual area burned by fires (Heyerdahl *et al*. 2001; Littell *et al*. 2009), but relationships between climate and fire severity have been less studied. The present study examines the antecedent climate conditions of fire seasons in Yosemite National Park, a large contiguous management unit that experiences multiple fires every year, and also the severity of fires occurring during an entire fire season. This study attempts to bridge the work that has been done predicting the behavior of single fires and the continental-scale predictions arising from climatic forecasts.

Study area

Yosemite National Park is a contiguous management unit of 3027 km^2 (latitude 37.7°N, longitude 119.7°W) located in the central Sierra Nevada of California. Elevations range from 657 m at the western park boundary to 3997 m at the summit of Mt Lyell on the Sierra Nevada crest. Approximately 84% of the park is vegetated. Yosemite National Park has been in protected status since 1890 (Russell 1992; Rothman 2007).

Yosemite National Park's climate is Mediterranean. July mean minimum and maximum temperatures are 2 and 13°C above 3700-m elevation and 16 and 35°C below 800-m elevation. Annual precipitation ranges from 800 to 1720 mm, with most precipitation falling in the winter as snow. The highest levels of precipitation (above 1300 mm year^{-1}) occur at 2500 to 3200-m elevation, and the lowest levels of precipitation (below 1000 mm year^{-1}) occur below 2000 m and in local rain shadows (Lutz 2008). Most moisture eventually made available to plants comes from the spring snowpack. As well as providing moisture to plants in the growing season, the snowpack keeps surface fuels wet, and surface fuels become drier after the snowpack has melted.

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The forests of Yosemite National Park include lower montane, upper montane, and subalpine vegetation. Lower montane forest occurs on the west side of the Sierra Nevada from 1000 to 1800 m and comprises 15.3% of park area. Major vegetation types include: California black oak (*Quercus kelloggii*), ponderosa pine (*Pinus ponderosa*), white fir (*Abies concolor*) mixed conifer, Douglas-fir (*Pseudotsuga menziesii*) mixed conifer, and mixed evergreen forests. Upper montane forest extends from 1800 to 2750 m and comprises 26.2% of park area. Forests within this zone include extensive stands of red fir (*Abies magnifica*) along with occasional stands of western white pine (*Pinus monticola*). Woodlands with Jeffrey pine (*Pinus jeffreyi*) and mountain juniper (*Juniperus occidentalis*) occupy exposed ridges while meadows and quaking aspen (*Populus tremuloides*) stands occur in moist areas. The subalpine forest zone ranges from 2750 to 3450 m and consists of lodgepole pine (*Pinus contorta*) and mountain hemlock (*Tsuga mertensiana*) forests, as well as whitebark pine (*Pinus albicaulis*) woodlands and numerous large meadow complexes. *Pinus contorta* forests comprise 21.7% of park area, and *Pinus albicaulis–Tsuga mertensiana* forests comprise 9.1% of park area (van Wagtendonk and Fites-Kaufman 2006; Fites-Kaufman *et al*. 2007; Lutz 2008).

Yosemite National Park experiences multiple fires each year, mostly lightning-ignited, and since 1972, many of these fires have been allowed to burn under prescribed conditions (van Wagtendonk 2007). Lightning-ignited fires occur almost exclusively in summer months, and are concentrated in outbreaks that last one or several days (Bartlein *et al*. 2008). The fire regime is mixed; fires burn with patches of high, moderate, and low severities at intervals ranging from years to centuries (van Wagtendonk *et al*. 2002; Sugihara *et al*. 2006; van Wagtendonk and Fites-Kaufman 2006). Before 1850, the fire point return interval for forests of Yosemite National Park ranged from 4 to 187 years (Caprio and Swetnam 1995; van Wagtendonk *et al*. 2002). Before 1850, individual trees of fire-resistant species persisted through multiple fires (e.g. *Sequoiadendron giganteum* (Kilgore and Taylor 1979; Stephens and Elliott-Fisk 1999); *Pinus jeffreyi* (Stephens 2001); *Pinus lambertiana* (van Mantgem *et al*. 2004)).

We sought to examine recent lightning-ignited fires and burn severities in Yosemite National Park to understand current fire conditions. Understanding current fire conditions may help assess future fire-related changes in park vegetation (Swetnam *et al*. 1999). Should fire frequency or severity be increasing, management actions such as prescribed burning to reduce fuels and allowing large areas of wildland fire to burn under prescribed conditions will become increasingly important to mitigate the effects of increased fire (Agee 2003; Graber 2003; van Wagtendonk and Lutz 2007; Larson *et al*. 2008).

Climate projections are for higher temperatures (Meehl *et al*. 2007), leading directly to decreased snowpack (Hayhoe *et al*. 2004; Mote *et al*. 2005; Knowles *et al*. 2006), and also for increased CO_2 levels (Keeling *et al*. 1995). Increased CO_2 levels have in turn been associated with greater convection and increased lightning strikes (Price and Rind 1994*a*). To the extent that lightning-ignited fires may depend on snowpack or on CO_2, lightning fires may become more numerous (Price and Rind 1994*b*) and annual area burned may increase (McKenzie *et al*. 2004; Flannigan *et al*. 2005; Westerling *et al*. 2006). Increased burned area is expected under future climate scenarios (Field *et al*. 2007), and a concomitant increase in fire severity would imply that ecological effects of future fires and duration of post-fire recovery may currently be underestimated (Turner *et al*. 1997; van Wagtendonk and Fites-Kaufman 2006; Collins *et al*. 2007; Miller *et al*. 2008). We sought to examine whether a climate-induced change in snowpack would affect the fire regime.

Three potential mechanisms could contribute to a relationship between decreased snowpack and increased lightning-ignited fires. First, if landscape flammability (the tendency of fuel to ignite if struck by lightning) increases continuously as fuel moisture decreases, an earlier snowmelt allows fuels to become drier by the end of the summer, and hence more readily ignited. Second, if landscape flammability depends on fuel moisture thresholds, longer snow-free periods leave fuel in an ignitable condition longer. Third, if snowmelt is earlier, increased sensible and latent heating could result in greater convection and more lightning strikes (Price and Rind 1994*a*). The strong Mediterranean climate pattern at Yosemite National Park implies that fire-season moisture trends will be strongly influenced by spring snowpack largely because subsequent precipitation during the fire season is unlikely.

Methods

We used a 22-year record of ignitions, area burned, snowpack, and satellite-derived fire-severity data for the period from 1984 to 2005. In Yosemite National Park, van Wagtendonk *et al*. (2004) found that satellite measurements of burn severity were correlated with plot measurements of the Composite Burn Index (Key and Benson 2006), a direct field measure of the ecological impact of fire on vegetation. We examined the relationship between fire severity and annual area burned as well as relationships between snowpack and lightning-ignited fires and area burned. We also examined the temporal trend in area burned. Ecological effects of individual fires differ by landscape position, forest type, years since previous burn, and date of occurrence within the fire season (Turner *et al*. 1997; van Wagtendonk and Fites-Kaufman 2006; Collins *et al*. 2007; Thompson *et al*. 2007) and also by ignition type (lightning ignition, prescribed fire, or other human ignition; van Wagtendonk and Lutz 2007). Therefore, we aggregated lightning-ignited fires and annual area burned by annual fire seasons to develop summaries for the Yosemite National Park landscape. We used a large number of fires to decrease the stochasticity associated with individual fire behavior and to generalize about fires over an entire fire season.

Data sources

Snow accumulation data were obtained from the California Department of Water Resources (CDWR 2007), which maintains 22 snow monitoring stations in Yosemite National Park. We sought a single value for the spring snowpack that would serve as an *a priori* indicator for the summer fire season. Preliminary analysis suggested that the Tuolumne Meadows snow monitoring station (elevation 2621 m) would be appropriate because snow accumulation and melting are less affected by local topography in this large meadow, and also because the Tuolumne River

watershed includes much of the area burned within Yosemite National Park. Examination of precipitation using 1971–2000 climatological means (PRISM 2007; Daly *et al*. 2008) showed that Tuolumne Meadows receives slightly less winter precipitation than the adjacent montane and subalpine areas of the park (elevation 1850–2500 m), implying that the melt dates for Tuolumne Meadows may be representative of larger portions of Yosemite National Park. Rather than snow depth, we used measurements of snowpack snow water equivalent (the water content of the snow per unit area; hereafter SWE, in cm). Because 1 April SWE is most representative of the year's snowpack in the Sierra Nevada (Church 1933, 1935; Woodhouse 2003), we used it to divide the years from 1984 to 2005 into wet, dry, and average years. Wet years were characterized by SWE $\geq$ mean SWE plus one standard deviation. Dry years were characterized by SWE $\leq$ mean SWE minus one standard deviation. Average years were characterized by SWE within one standard deviation of the mean.

Fire locations, causes of ignition, perimeters and total area burned in Yosemite National Park have been mapped on the ground and aerially. Mapping is virtually complete, even for fires as small as 8 m^2. For those fires >40 ha, the area burned was determined from satellite images and mapped fire perimeters. Landsat TM images from 1984 to 2006 were used to calculate the Relative differenced Normalized Burn Ratio (RdNBR) for each fire >40 ha in extent between 1984 and 2005 (van Wagtendonk *et al*. 2004; Thode 2005; Key 2006; Miller and Thode 2007; van Wagtendonk and Lutz 2007; Miller *et al*. 2008). RdNBR is the difference in the pre-fire and post-fire normalized burn ratio (NBR), normalized by the square root of the pre-fire value. The NBR is calculated using near-infrared (Landsat TM band 4) and short-wave infrared (Landsat TM band 7) wavelengths. The near-infrared wavelengths are sensitive to living vegetation, and the short-wave infrared wavelengths are sensitive to ash, char and water content (for satellite image selection and processing details, see Miller and Thode 2007; Miller *et al*. 2008). RdNBR accounts for heterogeneity of pre-fire vegetation and is appropriate for analyses of multiple fires (Miller and Thode 2007). Proportion of area burned at higher severity was calculated using all fires, irrespective of type of ignition. Fires straddling the Yosemite National Park boundary were clipped at the boundary. Fire severity (Key 2006; Sugihara *et al*. 2006; Miller and Thode 2007) was stratified into high-severity (nearly complete tree mortality), moderate-severity (significant tree mortality), and low-severity (little tree mortality) burn patches, as well as fire severities too low to be detected by satellite images taken 1 year after the fire (fire confined to the understorey).

Lightning strike data for Yosemite National Park from 1985 to 2000 were obtained from the National Lightning Detection Network (van Wagtendonk and Cayan 2008). The availability of lightning strike data limited related analyses to that period. We defined landscape flammability as the number of lightning-ignited fires divided by the number of lightning strikes. For relationships between lightning ignitions and SWE, we fitted a two-parameter exponential curve. For relationships between flammability and SWE, we fitted a three-parameter exponential curve. For relationships between patch size, severity and area burned, we performed linear regressions against the $\log_{10}$ of area burned. Comparisons between groups of years (dry, normal, and wet) were performed with ANOVA ($\alpha = 0.05$).

Spatial complexity and patch sizes

We analyzed the RdNBR data with *FRAGSTATS* (McGarigal *et al*. 2002) and used the output to calculate mean patch size and the Square Pixel (SqP) metric (Frohn 1998). SqP is an index that runs from 0 (square, minimum complexity) to 1 (least square-like, high complexity). Unlike contagion and fractal dimension, SqP is optimized for use with data arranged in square pixels, such as Landsat data (Frohn 1998). We fitted exponentially increasing curves with a maximum value of one (the defined maximum of the SqP metric) to examine the relationships between spatial complexity and area burned for each burn severity.

Projected future snowpack

We used the results of one climate projection for California (Hayhoe *et al*. 2004) to examine the possible consequences that decreasing snowpack might have on lightning-ignited fires. The projection, based on the Hadley Centre Climate Model, version 3 (Gordon *et al*. 2000; Pope *et al*. 2000), coupled with the Intergovernmental Panel on Climate Change (IPCC) B1 emissions scenario (Nakićenović *et al*. 2000), yielded an estimated decrease in snowpack of 24% between 2000 and 3000 m (Hayhoe *et al*. 2004). To approximate this possible future condition in Yosemite National Park while preserving the current range of variability, we took each year in our record (1984 to 2005) and generated a future scenario. We used our previous categorization for normal, wet, and dry years to characterize each year in the current dataset. For each category in the current dataset (normal, wet or dry), we averaged the 1 April SWE, number of lightning-ignited fires, area burned by lightning-ignited fires, and area burned at moderate and high severities. Then we constructed a future scenario where snowpack in each of 22 years was 24% less than the existing 22-year data record. We categorized each year in the future scenario as normal, wet, or dry using the definitions derived from the 1984 to 2005 period. We then used the category averages (normal, wet, or dry) to infer a possible 22-year average number of lightning strikes, lightning-ignited fires, area burned by lightning-ignited fires, and area burned at moderate and high severities.

Results

Between 1984 and 2005, 1870 fires burned 77 718 ha, just over 10% of the park. Lightning ignited 1113 of those fires, totalling 63 358 ha, which was 81.5% of area burned. During this period, 103 fires >40 ha burned 73 264 ha (94.3% of the area burned), of which 73 were started by lightning and burned 61 524 ha (Fig. 1).

Snow water equivalent from all 22 Yosemite National Park monitoring stations was highly correlated, and data from any snow monitoring station were a significant predictor ($P < 0.05$) of the number of lightning-ignited fires. The Tuolumne Meadows snow monitoring station provided the best relationship. Adding additional data from any other snow monitoring station did not improve the relationship (partial F-test, $\alpha = 0.05$). The 1 April SWE was inversely related to the number of lightning-ignited fires (Fig. 2) using Tuolumne Meadows SWE as the predictor of the number of lightning-ignited fires ($n = 22$, $r^2 = 0.69$,

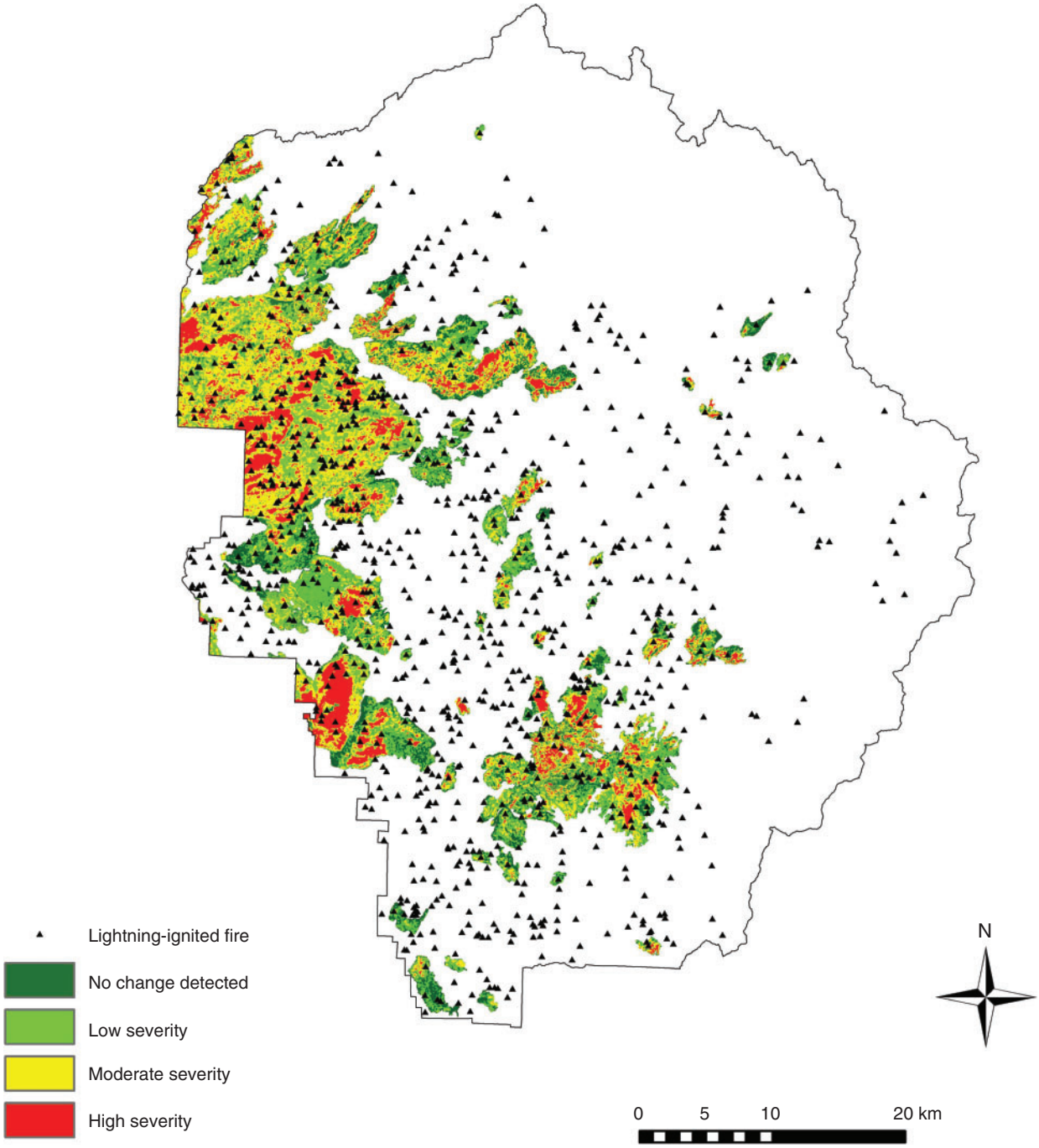

Fig. 1. Fires in Yosemite National Park from 1984 to 2005. The map shows the location of all lightning-ignited fires (black triangles) and fire severities of all fires >40 ha. Fire severity is stratified into four levels; high (red), moderate (yellow), low (light green), and surface burns undetected by satellite (dark green). For areas that were burned more than once between 1984 and 2005, the severity of the most recent fire is shown. The eastern portion of the park has fewer fires overall because it is at higher elevation and includes much of the unforested areas.

$P < 0.001$). The area burned by lightning-ignited fires was also inversely related to SWE, but because forest type, fuel loading, topography and fire weather determine individual fire behavior, area burned had a weaker relationship with SWE ($n = 22$, $r^2 = 0.13$; $P = 0.06$).

Between 1985 and 2000, there were a total of 15 527 lightning strikes, resulting in 888 lightning-ignited fires. Landscape flammability, or the proportion of strikes leading to ignitions, was 5.7% for all years between 1985 and 2000 and was relatively constant at SWE greater than or equal to the 22-year mean,

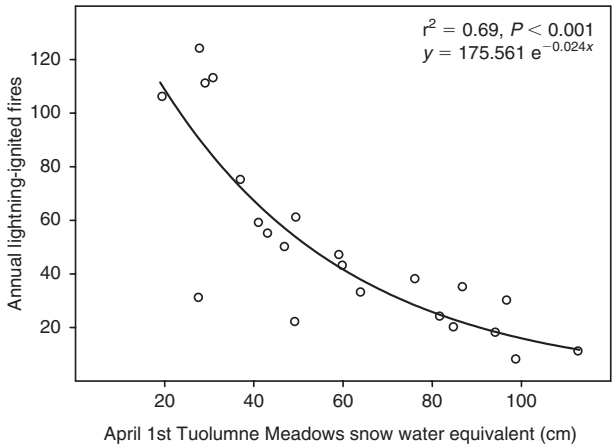

Fig. 2. Lightning-ignited fires and 1 April snow water equivalent. The number of lightning-ignited fires of all sizes for each year from 1984 to 2005 and the 1 April snow water equivalent for that year are shown.

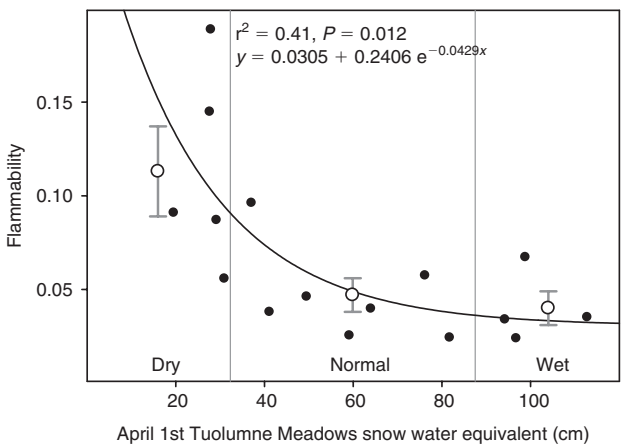

Fig. 3. Landscape flammability for Yosemite National Park from 1985 to 2000. Landscape flammability is defined as the number of lightning-ignited fires divided by the number of lightning strikes for the entire area of Yosemite National Park in each calendar year. Dry, normal, and wet years are based on the snow water equivalent (SWE) data at Tuolumne Meadows for the 1984 to 2005 period (solid circles, •). Normal years have 1 April SWE within one standard deviation ($\sigma = 27.6$ cm) of the mean ($\bar{x} = 59.9$ cm). Wet years have 1 April SWE $\geq$ mean SWE $+ 1\sigma$. Dry years have 1 April SWE $\leq$ mean SWE $- 1\sigma$. The landscape flammability of wet, average, and dry years (mean $\pm$ 1 SE) is superimposed on the annual data (open circles, ○).

but was higher when SWE was less than the mean (Fig. 3). Dry years had higher landscape flammability than normal or wet years (ANOVA(Dry, Normal, Wet), $n = 16$, $P = 0.01$). Neither flammability nor the variance of flammability differed between normal and wet years, but during dry years, landscape flammability had higher variability (Levene's test for equality of variance, $n = 16$, $P = 0.04$; Fig. 3). Plots of the data supported the difference in levels despite the heterogeneous variances, as did a comparison of dry and non-dry years (t-test with equal variances not assumed, $n = 16$, $P = 0.04$). Although the density of lightning strikes is not uniform with elevation or with forest type (van Wagtendonk 1994) and the chance of ignition

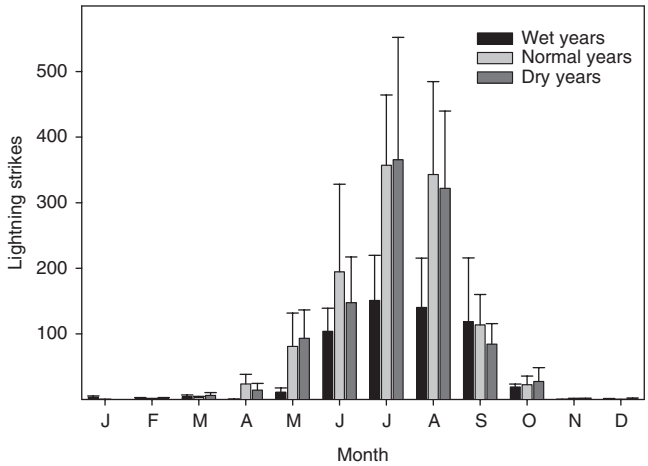

Fig. 4. Monthly distribution of lightning strikes in wet, normal, and dry years. The number of lightning strikes between 1985 and 2000 in Yosemite National Park for each month is displayed (mean $\pm$ 1 SE). Years have been categorized according to the 1 April snow water equivalent (SWE). Dry, normal, and wet years are based on the SWE data at Tuolumne Meadows for the 1984 to 2005 period. Normal years have 1 April SWE within one standard deviation ($\sigma = 27.6$ cm) of the mean ($\bar{x} = 59.9$ cm). Wet years have 1 April SWE $\geq$ mean SWE $+ 1\sigma$. Dry years have 1 April SWE $\leq$ mean SWE $- 1\sigma$. In wet years, the onset of lightning strikes is in June, whereas lightning strikes begin in May in dry or normal years. In wet years, the number of lightning strikes is lower throughout the summer compared with dry or normal years.

also depends on the polarity and number of strokes of the lightning strike (van Wagtendonk and Cayan 2008), this measure of landscape flammability (the number of lightning-ignited fires divided by the number of lightning strikes), when aggregated by year, is readily useable by land managers. Wet years had fewer lightning strikes during the summer fire season (May through September) than normal or dry years (Fig. 4), but the degree of year to year variation does not allow for strong inference (ANOVA(Dry, Normal, Wet), $n = 16$; $P = 0.09$).

We did not find a significant temporal trend in area burned by lightning-ignited fires between 1984 and 2005. However, a comparison of the area burned by lightning fires in the period from 1984 to 2005 (22 years) with the area burned in the immediately preceding 22-year period (1962 to 1983) shows that the average annual area burned in the immediate past is almost eight times that of the preceding period (2797 *v.* 358 ha year^{-1}; t-test, $P = 0.02$; fire area before 1984 from park records; fire area from 1984 to 2005 from satellite analysis). Although similar time periods, these two intervals are not strictly comparable because, beginning in 1972, some fires were allowed to run their course under prescribed conditions. However, the intensity of several large fires that were suppressed since 1990 suggests that their extent would not have been much reduced, even with active control (J. W. van Wagtendonk, pers. obs.). Considering only the period 1972 to 2005, the mean area burned by lightning-ignited fires from 1972 to 1983 was 646 *v.* the 2797 ha year^{-1} in the 1984 to 2005 period (t-test, $P = 0.03$).

Fire severity in those 103 fires analyzed with pre-fire and post-fire satellite images increased as the annual area burned became larger (Fig. 5). The proportion burned at highest severity increased with the $\log_{10}$ of annual burned area ($n = 22$, $r^2 = 0.39$;

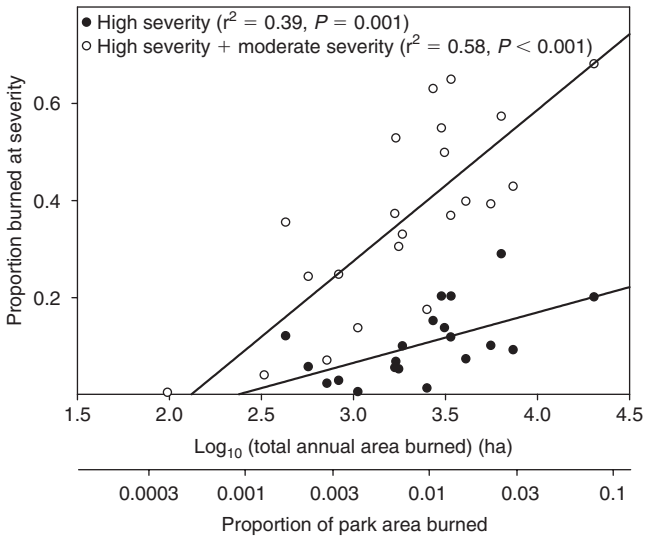

Fig. 5. Fire severity and annual area burned. The proportion of the annually burned area that burned at high severity (closed circles, •) and at a combination of high and moderate severity (open circles, ○) from 1984 to 2005 is plotted against the $\log_{10}$ of the annual area burned. The r^2 values were calculated on the total annual area burned ($\log_{10}$) values. The equivalent proportion of the park's vegetated area that burned is shown in the secondary axis.

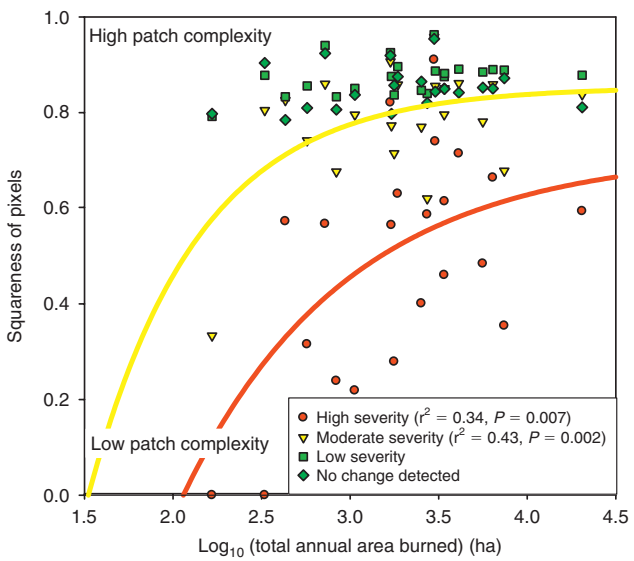

Fig. 6. Patch complexity and annual area burned. Patch complexity is illustrated with the Square Pixel metric. Values near zero indicate square patches (minimal complexity) and values near one indicate complex patches. Patch complexity of high-severity patches (red) and moderate-severity patches (yellow) increased with the $\log_{10}$ of annual area burned. The complexity of patches that burned at either low severity or a severity level that could not be detected by satellite 1 year after fire was not related to annual area burned.

$P = 0.001$), as did the proportion burned at a combination of high and moderate severity ($n = 22$, $r^2 = 0.58$; $P < 0.001$).

Spatial complexity at higher burn severities increased with annual area burned (Fig. 6). High-severity patch complexity increased with the $\log_{10}$ of annual area burned ($r^2 = 0.34$, $P = 0.007$). Moderate-severity patch complexity also increased with the $\log_{10}$ of annual area burned ($r^2 = 0.43$, $P = 0.002$). Low-severity patch complexity and patch complexity of areas where no change was detected were equally complex in all years ($P \geq 0.05$).

Using the four fire-severity classes (high severity, moderate severity, low severity, and no change detected by satellite), the average patch size for all severity classes in all fires over all years was 3.95 ha. In years where at least one high-severity patch was measured (20 of 22 years), high-severity patches averaged 3.69 ha. The size of high-severity patches showed a weak relationship with the $\log_{10}$ of annual area burned ($P = 0.083$). Moderate-severity patches, present in every year, had an average size of 6.25 ha. For moderate-severity patches, patch size increased with the $\log_{10}$ of area burned ($P = 0.005$). Low-severity patches averaged 6.20 ha and had no relationship with annual area burned. The average patch size of areas that burned at a severity lower than satellite methods could detect was 2.75 ha, and the patch size was negatively related with the $\log_{10}$ of annual area burned ($P = 0.047$).

The future scenario of lower average snowpack (Hayhoe *et al.* 2004) with current interannual variation in SWE resulted in higher incidence of fires, greater annual area burned, and a higher proportion of high-severity fire (Table 1). The projected reduction in average snowpack eliminated years currently classified as wet based on SWE (Fig. 3). The future scenario was principally composed of years that would presently be characterized as normal or dry, and the future fire regime resembled an average of current normal and dry conditions (Table 1). Considering this snowpack scenario, the predicted average number of annual lightning-ignited fires over a 22-year period increases 19.1% (from 51 to 60) and the annual area burned at high severity over a 22-year period increases 21.9% (from 446 to 543 ha year^{-1}).

Discussion

High levels of spring SWE are associated with decreased lightning strikes, decreased numbers of lightning-ignited fires, and reduced area burned (Figs 2, 3). But by early autumn, fuels are dry irrespective of spring snowpack. Because high fuel moisture limits fires early in the year, fires could still reach large sizes late in a fire season, even when that season is shortened by a late snowpack with high SWE. Conversely, even fire seasons that would be long by virtue of a low spring SWE may exhibit low area burned if ignitions are lower than average. The higher variance of lightning-ignited fires in dry years (Figs 2, 3) underscores the annual variability in lightning strikes (Fig. 4). With few lightning strikes, years otherwise dry enough for extreme fire conditions may exhibit low area burned. Flammability will also be low in drier years if lightning strikes occur in early season or in conjunction with precipitation. The reduced number of lightning strikes through May in wet years (Fig. 4) is expected, given that high levels of snowpack would keep surface temperature low, thereby decreasing convection. In wet years, soil and fuel moisture are also high, decreasing the proportion of lightning strikes that start lightning-ignited fires (Fig. 3). However, the generally decreased levels of lightning strikes throughout wet years (Fig. 4) suggest that the effects of high snowpacks continue well into the

Table 1. Current and future fire regime characteristics

A summary of 1 April snow water equivalent (SWE), lightning strikes, lightning-ignited fires, area burned by lightning-ignited fires, and higher burn severities for the present snowpack regime and for one future snowpack scenario. Dry, normal, and wet years are defined by the SWE data for the 1985 to 2005 period. Normal years have 1 April SWE within one standard deviation of the mean ($\bar{x} = 59.9$ cm). Wet years have 1 April SWE $\geq$ mean SWE $+ 1\sigma$ ($\sigma = 27.6$ cm). Dry years have 1 April SWE $\leq$ mean SWE $- 1\sigma$. Lightning strikes based on data shown in Fig. 4. Lightning-ignited fires are based on data shown in Fig. 2. Area burned by lightning-ignited fires and fire severities are taken from the means for wet, normal, and dry years, respectively (Fig. 3). The present conditions average was derived using data from the 22-year period from 1984 through 2005, and the future conditions average was derived assuming a 22-year period within the period from 2020 through 2049 following Hayhoe *et al*. (2004)

	Wet year average	Normal year average	Dry year average	Present conditions average	Future conditions average	Change (%)
1 April SWE (cm)	100.6	60.0	27.1	59.9	49.5	−17.3
Lightning strikes	555	1141	1064	1017	1116	9.8
Lightning-ignited fires	17	43	97	51	60	19.1
Burned area (ha)	499	3208	3566	2797	3322	18.8
Burned at high severity (ha)	12	532	567	446	543	21.9
Burned at moderate severity (ha)	111	1366	1061	1068	1269	18.8
Burned at high plus moderate severities (ha)	123	1898	1628	1514	1812	19.7

summer. Whatever the precise combination of mechanisms contributing to landscape flammability, 1 April SWE can provide a forecast (Fig. 3), a relationship that is strong in Yosemite National Park because summer precipitation is low.

The spatial patterns of fire are important aspects of a fire regime (Sugihara *et al*. 2006) and of post-fire forest succession. Forests of the Sierra Nevada are partially characterized by their patchiness at 100-ha to 1000-ha scales (Franklin and Fites-Kaufman 1996). Within large-scale patches, there is considerable variation in forest composition and structure at smaller (1 to 10 ha) scales (Langley 1996). At least some of this heterogeneity has been maintained by vegetation–fire feedbacks and may be responsible for higher levels of plant and animal diversity (van Wagtendonk *et al*. 1998; Miller and Urban 1999; Stephens 2001; Collins *et al*. 2007; Roberts *et al*. 2008). Higher levels of patch complexity at high and moderate fire severities are associated with increasing annual area burned (Fig. 6), which in turn suggests that the area within the perimeters of large burned areas comprises a diversity of post-fire conditions. However, although we found a general trend of higher patch complexity with increasing annual area burned, the three largest fires exhibited several extensive patches of continuous high severity, suggesting localized areas of decreased landscape heterogeneity.

In Yosemite National Park, increasing annual area burned from all fires – most of them unsuppressed – increases the proportion burned at higher severities (Fig. 5). The quantification of this relationship – suspected but not previously documented – has only been made possible by the development of satellite fire-severity analysis and the attendant calibrations of the ecological meaning of satellite fire severity measurements for the Sierra Nevada (van Wagtendonk *et al*. 2004; Thode 2005; Key 2006; Miller and Thode 2007; see also French *et al*. 2008, and references therein). The result is expected from the physical characteristics of large fires and the fire weather that causes them (van Wagtendonk 2006). Although we have shown a correlation between annual area burned and severity, both could be determined by seasonal climatic conditions or fire weather. Irrespective of the underlying mechanism, we show that the two phenomena are linked. Because our satellite-derived calculations of fire severity are largely defined by vegetation mortality (Key 2006), larger areas burned and increased proportions of areas burned at higher severity both imply a reduction in post-fire vegetation on the landscape. Higher-severity burns have been associated with stand-replacement conditions in the Sierra Nevada (Miller *et al*. 2008); larger patches of high-severity burns have been associated with longer recovery times in Yellowstone National Park (Turner *et al*. 1997); and forest succession has been found to be slower following complete stand-replacement fires (Keeton and Franklin 2005; see also French *et al*. 2008). Because areas burned at high severity retain very little of the pre-fire vegetation, post-fire recovery may take longer.

Our results hold for those areas burned in the study period, primarily lower montane and upper montane forests (see also van Wagtendonk and Lutz 2007). Although previous work has shown individual large fires to be associated with large high-severity patches (e.g. Turner *et al*. 1997; Miller *et al*. 2008), landscape-scale studies in boreal forests have previously found that increasing fire size is associated with larger unburned patches (Eberhart and Woodard 1987). Furthermore, in boreal forests, the differing vegetation and vegetation response to fire as measured by satellite techniques may preclude similar analyses (French *et al*. 2008; Verbyla *et al*. 2008). Therefore, our findings should be considered only in light of forest types similar to those of Yosemite National Park (see *Introduction*).

At snowpacks currently characterized as normal or wet (Fig. 3), the proportion of lightning strikes that result in lightning-ignited fires is relatively low and constant. The snowpack scenario developed by Hayhoe *et al*. (2004) suggests that in 20 to 30 years, snowpacks currently characterized as wet will have become rare. If mean spring SWE decreases, landscape flammability may increase and become more variable. Should climate change decrease snowpack, these mixed fire regime forests may experience more lightning-ignited fires, greater area burned, and greater proportion of area burned at higher severities. Our fire severity analysis supports suggestions that western fire regimes are changing. Reduced snowpack and warmer spring

temperatures lead to an increase in area burned (Westerling *et al*. 2006), but an increase in area burned also leads to an increase in severity. Climate-induced decreases in snowpack and the concomitant increase in fire severity suggest that existing assumptions may be understated – fires may become more frequent and more severe, with forests recovering commensurately more slowly.

Management implications

An increasingly important responsibility for land managers is to prepare for fires, to manage fires, and to plan for post-fire hydrological and vegetation conditions. Many land managers have a geographic scope similar to the 3027-km^2 extent of the present study. For fire managers in Yosemite National Park, these results may provide quantitative *a priori* estimates for the number of lightning-ignited fires within a fire season. The 1 April SWE is correlated with the number of lightning-ignited fires and area burned: when 1 April SWE is high, snow persists longer, decreasing the possibility of lightning-ignited fires during the fire season (Figs 3, 4). Whether a given number of lightning-ignited fires translates into a severe fire season depends on the forest type, fuel loading, fuel moisture, and fire weather for each individual fire.

The relationship between area burned and area burned at higher severities could assist with immediate assessment of post-fire water quality, reforestation, and animal habitat issues. The higher levels of tree mortality associated with increased proportions of high-severity fire might require higher levels of management per unit area for restoration or mitigation of runoff or hazard tree dangers. Land managers may find the relationship between area burned and severity useful in estimating post-fire conditions for species of interest. If the area burned at higher severities increases, older and larger trees may experience higher levels of mortality. In that eventuality, Yosemite National Park could experience decreases in late-successional forests.

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