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STATE OF THE SCIENCE

Sustainable fire: Preserving carbon stocks and protecting air quality as Sierra Nevada forests warm

By Leland W. Tarnay and James A. Lutz

Figure 1. Glaciers and fires have influenced the landscape of the Sierra Nevada. Glacially smoothed Mount Starr King rises behind the area burned by the 1991 Illilouette fire. The matrix of different burn severities can be seen within the fire perimeter (red outline) viewed from Glacier Point.

FIRE HAS PHYSICALLY SHAPED THE SPECIES COMPOSITION and structure of Sierra Nevada forests, just as glaciers have shaped the underlying landscape (fig. 1). The long, hot summers that occur in the Mediterranean climate of the Sierra Nevada favor fire, because they dry out vegetation and dead woody debris, creating fuel that readily burns when lightning (also common in the Sierra Nevada) strikes. Fire converts that vegetation—living or dead—into smoke. Smoke from fires contains readily inhalable fine particles that can impair human health, while also obscuring scenic vistas that visitors expect when they visit national parks (Clinton et al. 2006).

Smoke emissions also include greenhouse gases (e.g., carbon dioxide, or CO_2) that derive from the carbon in the combusted biomass. While these emissions temporarily contribute to global warming, carbon is returned to the landscape as vegetation takes up CO_2 post-fire (Hurteau and Brooks 2011). The resulting net "carbon balance" and the amount of carbon left on the landscape as biomass (i.e., the "carbon stock") can vary, depending on the period over which that stock is measured and on whether the post-fire vegetation type covering the landscape contains as much carbon as the pre-fire vegetation.

Fire suppression over the last 130 years has changed vegetation types and likely carbon stocks, leaving large portions of Sierra Nevada parks with forest stands that have not burned in almost a century. As a result, small trees and shrubs have grown in under the larger trees, providing "ladder fuels" that could carry fire into the canopy of the larger trees, which are otherwise quite fire-resistant (fig. 2). Fire entering such an overly dense understory can burn at higher intensity, grow faster, release more smoke, and kill more (potentially all) trees. Preventing fires in one year can make a future fire even more severe, perhaps even leading to post-fire vegetation characterized by shrubs instead of forest. The increased fire risk that is the legacy of fire suppression in the Sierra Nevada endangers not only carbon stocks but also our ability to manage fires in a way that minimizes air quality impacts and preserves clean and clear air for visitors and local communities. Climate change has the potential to add another dimension of urgency to this issue by creating longer, drier, hotter summers in which these higher-severity, faster-growing fires are more likely (Lutz et al. 2009b).

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Figure 2. The spatial arrangement of forests affects how much carbon a landscape can contain and also its fire risk. Dense forests (left) contain large amounts of carbon, but the horizontal and vertical fuel continuity increases the risk of high fire mortality and large smoke production. Open forests (center) include large trees that store considerable carbon, and the lower density of smaller trees reduces the risk that fire will rise into the canopy. Patchy forests (right) have areas of both high and low carbon storage, and the lack of continuous fuels both horizontally and vertically increases the chances of a mosaic of burn severities.

Abstract
Climate change may affect temperature, precipitation, snowpack, and fire in the Sierra Nevada, and the effects on various park resources may range from moderate to extreme. But any level of change has ramifications for the day-to-day work of park managers. One technique used by climate scientists and ecologists is dissecting interannual variability into normal and extreme components (i.e., warmer/cooler and wetter/drier) years and comparing differences between those categories. Because the natural range of variability of climate parameters in the Sierra Nevada is larger than recent trends, recent historical highs and lows give us insight into future conditions. Timing of snowpack melt is a key attribute that varies between hot and cool years, and interannual differences in the timing of snowmelt have been shown to have a significant association with fire activity as well as the amount of vegetation converted to smoke and greenhouse gases by fire. This article reviews the implications of these changes for fire management in the context of our current understanding of climate, historical fire suppression, fire frequency, fire severity, and the effects of climate and fire on air quality. We explore positive feedbacks among climate, fire, and air quality that may threaten forests and forest carbon stocks in the Sierra Nevada. We also discuss the potential importance of fire management as a part of an integrated NPS climate response strategy for mitigating threats to air quality, fire ecology, and carbon stock stability as the projected climate changes become manifest.

Key words: air quality, carbon storage, climate change, fine particles, fire ecology, fire severity, greenhouse gases, Sierra Nevada

This scenario highlights the tension of managing Sierra Nevada forests under a warming climate regime: lightning (and humans) will continue to ignite fires, and each suppressed fire, though minimizing immediate smoke impacts, increases the risk of larger, less manageable fires and smoke impacts in the future. Developing the optimal fire management solution requires that we reconcile what we know about fire, forests, smoke, and projected climate with the objectives of protection of life and property, minimization of smoke impacts, and the need to provide stewardship of these forests.

Forty years ago, the National Park Service realized that fire had been unnaturally excluded from the Sierra Nevada and began allowing fires to burn under prescribed conditions, first in Sequoia and Kings Canyon national parks, and soon after in Yosemite National Park. In Yosemite, NPS fire management and the U.S. Geological Survey have been partnering to develop a more quantitative, science-based approach to managing fire and the ecology of fire-adapted forests. In this article we summarize some of the lessons relevant to fire managers interested in adaptively managing such landscapes.

A science summary

Fires were more prevalent before Euro-American settlement

Our current perception of a normal fire year in terms of area burned and smoke production is very different from what likely occurred in the presettlement era. Prior to Euro-American settlement, the combination of lightning-ignited fires and the American Indian tradition of burning resulted in annually burned areas over 10 times the area burned annually from 1950 to 1999 (Stephens et al. 2007). At presettlement levels of fire activity, fires and smoke would have been prevalent on the landscape for most of the summer—always at low levels, and sometimes at very high levels.

Fire is sensitive to climate

In the Sierra Nevada, the number of lightning-ignited fires is related to the spring snowpack because very little precipitation occurs during the summer and autumn fire season. Snowpack limits fires, but low snowpack does not always imply more fire (fig. 3, next page). Wet years have very few ignitions, but in dry years the number of lightning ignitions depends on the number of lightning strikes. Declining snowpack, a projected consequence of climate change (Mote et al. 2005), could significantly decrease the snow limitation in wet years and lead to a greater number of lightning ignitions, any of which could grow to a large size (Lutz et al. 2009b). At the scale of Yosemite, there isn't yet a time trend with respect to number of fires, area burned, or burn severity.

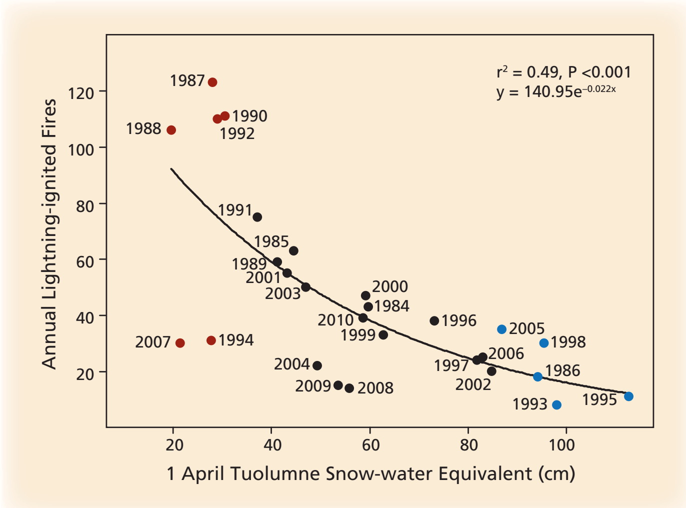

Figure 3. The graph shows the number of lightning-ignited fires of all sizes for each year from 1984 to 2010 and the Tuolumne Meadows 1 April snow-water equivalent for that year. In years with high 1 April snowpack (blue), lightning-ignited fires are less frequent because fuel remains wetter (and secondarily because of fewer lightning strikes). In years with low 1 April snowpack (red), fuel moisture content is permissive of ignition, but depends on the presence of lightning. Years with characteristic 1 April snowpack (black) generally do not feature large numbers of lightning-ignited fires.

SOURCE: ADAPTED FROM LUTZ ET AL. 2009b

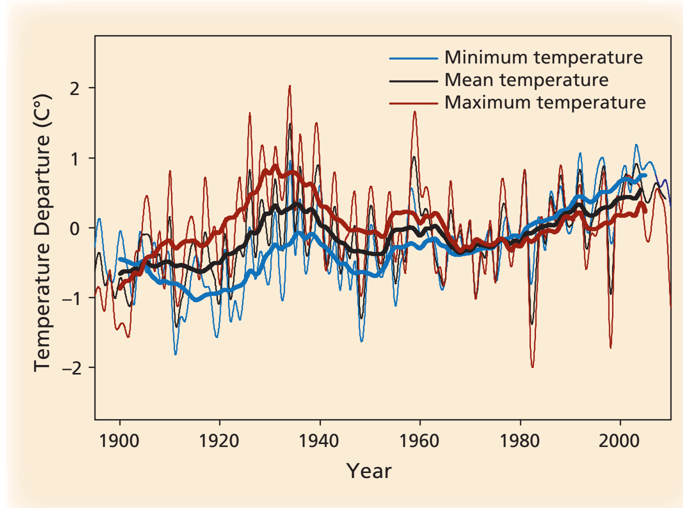

Figure 4. Trends in minimum, mean, and maximum temperatures for the Sierra Nevada from 1900 to 2010. Thin lines represent annual temperatures and thick lines represent 11-year moving averages. From 1981 to 2010, mean temperature in the Sierra Nevada increased at a rate of 2.7°C per century.

SOURCE: CALIFORNIA CLIMATE TRACKER, HTTP://WWW.WRCC.DRI.EDU/MONITOR/CAL-MON/ (ABATZOGLOU ET AL. 2009)

But at regional or continental scales, a trend of increasing fire area (Westerling et al. 2006; Littell et al. 2009) and increasing fire severity (Miller et al. 2008) has already been detected.

Normal is the new cool

Considering moisture persistence and fire behavior, 2010 appeared to local fire managers to be a relatively cool year, with uncharacteristically slow-growing fires and moderate fire behavior. However, compared with the long-term climate record for the Sierra Nevada, 2010 was actually normal from a temperature perspective (fig. 4). Minimum and average temperatures have been higher than the long-term average for each of the 10 years prior to 2010, and maximum temperatures have been higher for 8 of 10 years (Abatzoglou et al. 2009). With cold years becoming less frequent, climate in the Sierra Nevada is coming to resemble a combination of hot and normal years (Lutz et al. 2009b). Projected climate changes may increase water stress on all plants (Lutz et al. 2010) and, by drying out fuel, may increase the area burned (Littell et al. 2009). From a fire management perspective, this only increases the potential urgency for reintroducing fire to densely vegetated, lower-elevation areas when cooler conditions occur—there may be fewer opportunities to treat such areas safely as the climate warms.

Fire-resistant forest structure affects water stress and carbon sequestration

Open-canopy, old-growth forest structure is fire-resistant, and because this ecosystem type is maintained by fire, it thrives where managers are provided opportunities to allow fires to burn, reducing fuel levels and competing vegetation. The resulting open forest structure (figs. 2 and 5) is characterized by large trees—trees that sequester large quantities of carbon and provide habitat for a variety of vertebrate and invertebrate species (Lutz et al. 2009a). Because these fire-maintained forests are in turn fire-resistant, they stabilize landscape-level carbon stores for many years into the future (Hurteau and Brooks 2011). When fire is excluded, these forests experience rapid regeneration of dense stands of smaller trees and shrubs. These small trees and shrubs increase fire severity and compete with larger trees for water, which may in turn decrease the ability of large trees to rebound from fires. Some combination of increased tree densities and climate change has already caused a decline in large-diameter trees (Lutz et al. 2009a), so realizing the goal of burning larger areas at low to moderate severities will be even more important in the future for preserving these forests.

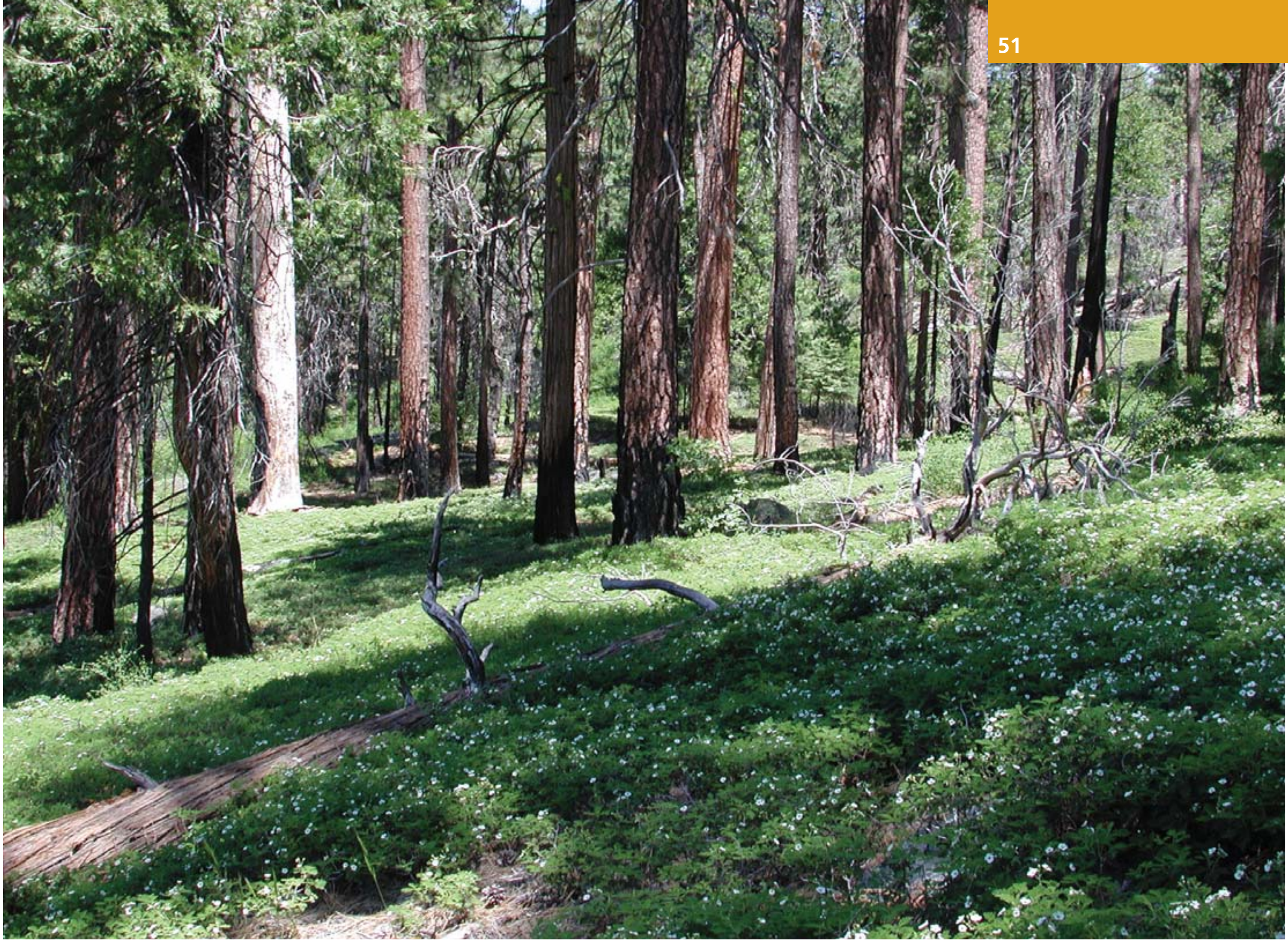

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Figure 5. A characteristic open-canopy ponderosa pine–incense cedar forest, burned in 1978 by a prescribed fire and in 1996 by a wildfire.

Forests contain large stocks of carbon, which fire can potentially convert to greenhouse gases

Preliminary estimates based on vegetation plots in Yosemite suggest that the boles (tree trunks) of all medium-sized and large trees in Yosemite contain at least 29 teragrams (Tg, or million metric tons) of carbon, which, if converted directly to CO_2 (CO_2eq, the standard unit of greenhouse gas measurement), is roughly equivalent to 110 Tg. This is more than 1,600 times the amount (0.064 Tg CO_2eq) emitted annually from all vehicles and facilities in Yosemite National Park or about 12 times the amount emitted annually from the entire city of San Francisco (8.8 Tg CO_2eq). Obviously, no fire is likely to completely convert all tree biomass in Yosemite into greenhouse gases at one time, but large fires can and do occur—one large California fire complex of 235,000 ha (580,685 ac) in timber and brush emitted approximately 6 Tg CO_2 over several days (Clinton et al. 2006).

Severity matters

Large amounts of carbon can be released by fire, either immediately through burning or indirectly through the slow decomposition of fire-killed trees. If a fire kills most of the aboveground vegetation, it is considered to have a high severity. In that case, most of the downed wood, litter, duff, small trees, shrubs, and herbs are converted immediately to smoke and greenhouse gases, but only a small portion of larger trees is consumed. If a fire leaves most of the vegetation (particularly the larger trees) alive, it is considered to be of low severity. Although few large trees are killed (fig. 2, previous spread, and fig. 6, next page), the consumption of litter and duff can still be high. In the Sierra Nevada, fires usually burn as complex mosaics of high, low, and intermediate severities. Net greenhouse gas emissions from any one fire (i.e., fire emissions and post-fire decay of fire-killed vegetation minus the incorporation of CO_2 back into biomass) can only be determined decades to centuries later, because pre-fire and post-fire vegetation may differ (Hurteau and Brooks 2011).

Climate will likely affect fire severity and increase risk of high fire severity

Fuel accumulation and longer, drier summers increase the risk that existing carbon stores will literally go up in smoke (and greenhouse gases). However, modeling and analysis show that burning biomass under conditions that preserve the large trees (i.e., low to moderate fire severities) can stabilize total forest carbon, and makes these carbon stores more resistant to future drought and fire (North and Hurteau 2011; fig. 7, next page). Computer model extrapolations show that in Yosemite's mixed-conifer forests, initial fire emissions in a frequent-fire scenario can reduce overall long-term emissions 50% to 60% (not counting post-fire decomposition of dead trees) (Wiedinmyer and Hurteau 2010). Emissions of greenhouse gases and smoke are all reduced in the frequent, lower-severity fire scenario.

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Figure 6. Prescribed burn in Yosemite Valley. The prescribed burn reduces fuel and kills smaller-diameter trees while leaving larger-diameter trees alive.

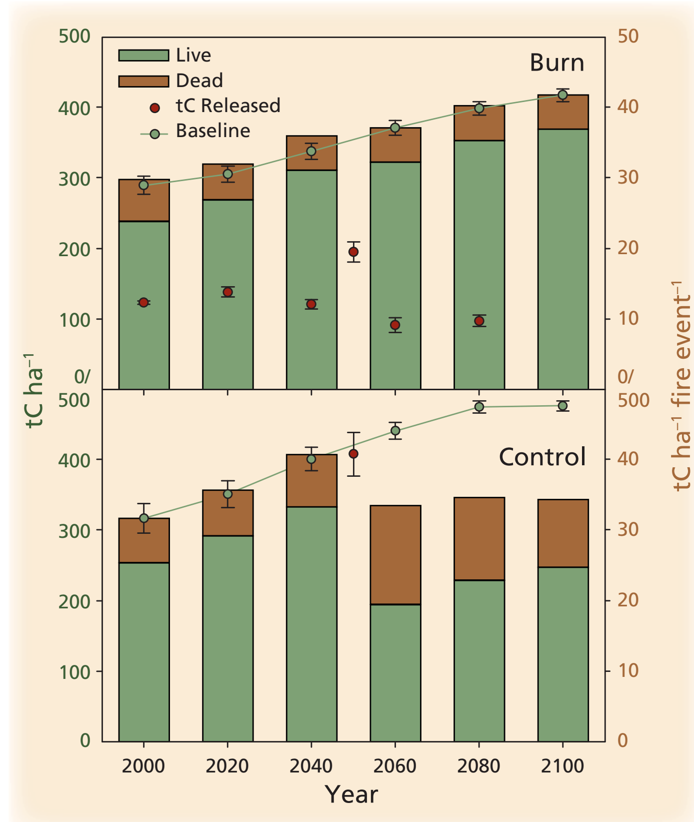

Figure 7. Modeled metric tons of carbon per hectare stored in live- and dead-tree biomass and released by a fire in 2050 in forest plots that were previously burned (top) and not previously burned (bottom).

SOURCE: ADAPTED FROM HURTEAU AND NORTH 2009

Less severe fires reduce the size of subsequent fires

Multiple less severe fires have a short-term emissions benefit and also reduce risk to forests in the long term. Fires consume fuel and limit the spread of further fires for about 10 years (Collins et al. 2009). When areas have not burned for several decades, fires can become 10 times larger than when fuel has recently been consumed (Scholl and Taylor 2010). Allowing multiple smaller fires over decades generates a patch mosaic that reduces the chances that a subsequent fire will burn most of the area at one time. Furthermore, fuel reduction through burning reduces the incidence of large, high-severity patches when fires occur. Forty years after reintroducing fire, portions of Yosemite have apparently returned to this characteristic fire regime (Collins et al. 2009) (fig. 8).

Large enough to be ecologically relevant, but small enough to be manageable

Fire is one of the few landscape-scale tools available to land managers, but those fires have to be greater than about 25 ha (62 ac) in area to be ecologically relevant at these scales. In Yosemite, 91% of lightning-ignited fires from 1984 to 2010 were small (<25 ha), and mostly burned at low severity. However, 97% of the area burned is from moderate-sized fires (>40 ha [99 ac]). Large fires (>2,000 ha [4,942 ac]) are a relatively new phenomenon, coincident with the advent of fire suppression and fuel accumulation in lower-elevation forests and woodlands that previously burned once or twice per decade. The eight largest lightning-ignited fires in Yosemite since 1930 have all occurred since 1990. These large fires have the highest proportion of area burned at high severity and they burned much of that area faster (e.g., >200 ha/day [494 ac/day]) (fig. 9). Fire size is sometimes a poor surrogate for fire effects, because severity of a fire depends much more on the fire intensity and the rate of fire growth. Nonetheless, our experience and working hypothesis are that moderately sized fires that grow at moderate rates yield heterogeneous post-fire landscapes without the type-conversion (forest to shrubland) that can occur in fires that burn at high severity.

Fire growth determines smoke impacts

Fires affect both air quality (human health), due to the release of inhalable fine particles, and visibility (haze) because these same fine particles reduce visual range (for more information see www.nps.gov/air). Tracking and, if possible, managing fire growth are essential for managing air quality during fires because the amount of fuel burned directly affects how much smoke gets into the air on a given day. Since federal land managers have been required under 1990 amendments to the Clean Air Act to minimize smoke impacts from fires, it is important to consider and, if possible, minimize potential impacts on air quality of smoke from fires. Here in Yosemite, emissions estimates of fire growth in the past

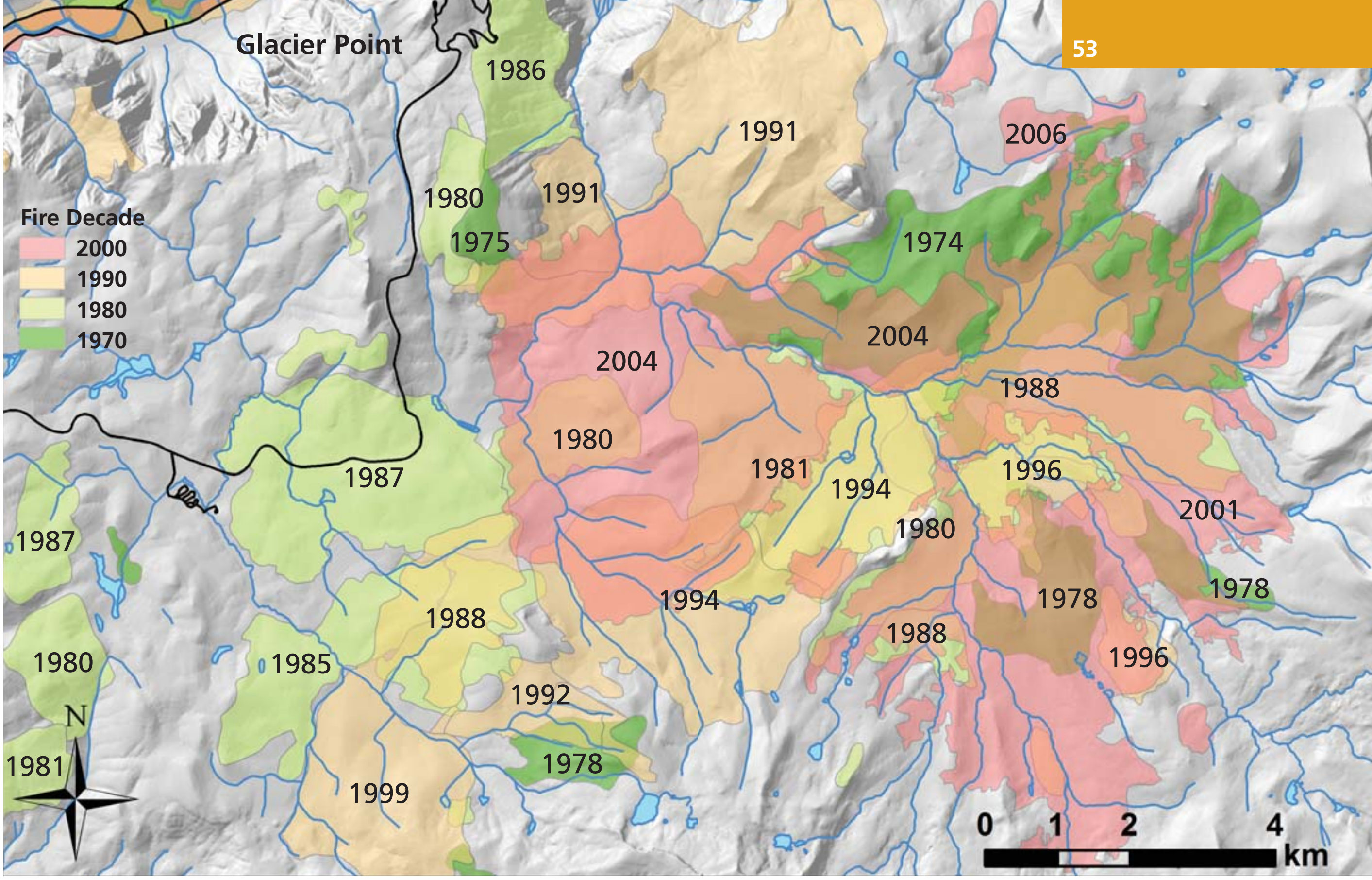

Figure 8. Lightning-ignited fires of greater than 10 ha (24.7 ac) in Yosemite's Illilouette Basin from 1970 to 2009. Much of the basin has burned at least once, and the resulting matrix of forest and fuel densities has greatly reduced the chances of a large wildfire or large smoke production. The Illilouette Basin experiences a large number of lightning strikes that provide ignition.

several years, based on the California Air Resources Board emissions estimation tool (http://www.arb.ca.gov/ei/see/see.htm), show, in general, that small fires rarely emit more than 10 tons of fine particles per day, while moderately sized, moderately growing fires emit 10 to 100 tons of fine particles per day. Our experience so far has been that emissions at these scales rarely produce more than localized impacts. Consistent daily emissions of 100 to 1,000 tons of fine particles are more characteristic of the largest fires, which rarely occur in Yosemite (e.g., Clinton et al. 2006), and result in regional, not just local, smoke impacts (e.g., McMeeking et al. 2006) (figs. 10 and 11, next spread).

Unfortunately, the technology and methods for mapping and forecasting fire growth and associated smoke impacts (i.e., fine particle concentrations) for operational use are still under development (e.g., http://firesmoke.us/wfdss/). Preliminary measurements of fine particle concentrations from a few well-monitored fires in Yosemite support the hypothesis that smoke impacts coincident from these small (<10 ha [<25 ac]) fires are usually not detectable, or are at least minimal. For moderately growing fires (10–100 tons/day), good dispersion also results in minimal smoke impacts. However, under poor dispersion conditions, smoke impacts can be substantial, even unhealthy, especially if the poor dispersion conditions persist for several days. The current smoke minimization strategy is therefore to match emissions to avail-

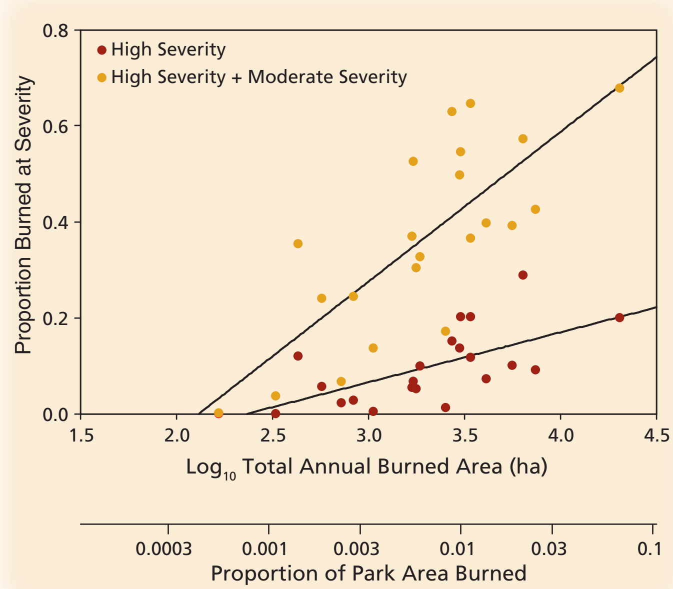

Figure 9. In Yosemite, area burned (ha) at high fire severity (dark red) and high plus moderate fire severity (orange) increases with the total (Log_{10}) annual area burned (1984 to 2005). The years with the most annual area burned show about 20% high severity and more than 60% high plus moderate severity, while the years with the least growth show very little (less than 5%) high or moderate severity.

SOURCE: LUTZ ET AL. 2009b

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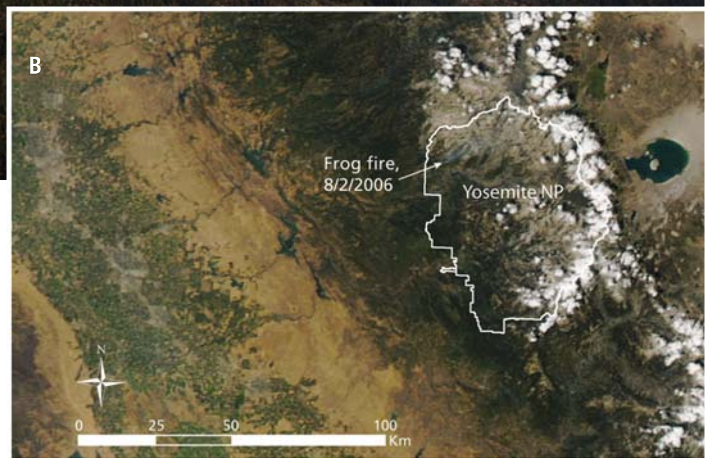

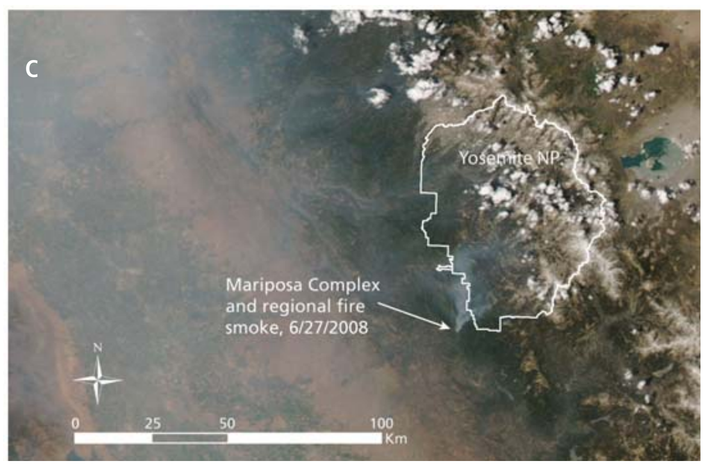

Figure 10. Smoke from the moderate-sized (2,442 ha [6,034 ac]) Frog fire in Yosemite in 2006 (panels A and B) compared with regional smoke impacts from the 2008 Mariposa Complex fires, which were among many large fires burning statewide at the time (panel c). Smoke impacts from moderate-sized fires (panels A and B) can be locally significant but are still relatively small compared with the largest, fastest-growing fires that often occur outside of Yosemite (panel C).

able dispersion, avoiding, where possible, large or moderate fire growth during poor dispersion periods while encouraging growth during periods of good dispersion. Monitoring and data acquisition to refine and evaluate these strategies are ongoing in Yosemite and Sequoia–Kings Canyon national parks, in cooperation with other federal agencies and air regulators.

Conclusion

Forest land managers have few tools with the potential to mitigate the impacts of climate change at landscape scales, but fire is one of them. Response to climate change for Sierra Nevada forests in the coming decades will likely be mediated by fire (McKenzie et al. 2004) and therefore revolve around fire management and fuels issues. The emerging science shows that the benefits of moderately sized, moderate-growth fires can be threefold in that they protect air quality, carbon stocks, and forest ecology. As the climate warms, the ability to realize these benefits hinges on the extent to which land managers can reduce forest fuels to a level that is sustainably resilient to major and minor fires. For land management agencies, this implies a substantial, even unprecedented, fire management response that erases administrative boundaries between land management agencies in favor of treating the most at-risk watersheds with midsized, moderately growing fires. On the downside, delays in restoring appropriate forest structure increase the chances of larger fires "resetting" the ecosystem, on terms that are likely to have severely negative impacts on air quality, carbon stocks, and ecosystems. To the extent that fires can improve forest structure and fire resistance, projected increases in fire activity—if properly managed—may be a way to head off, or at least delay, the worst consequences of climatic warming in the forests of the Sierra Nevada.

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Figure 11. The 1,225 ha (3,027 ac) Grouse fire burns a key piece of the Yosemite landscape with minimal smoke impacts, protecting higher-elevation forests from fires that might start at lower elevations.

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