Chapter 8.1—Air Quality

Andrzej Bytnerowicz,[1] Mark Fenn,[2] and Jonathan W. Long[3]

Summary

The major pollutants causing ecological harm in the Sierra Nevada are ozone, which can be toxic to plants, and nitrogen deposition, which can induce undesirable effects on terrestrial and aquatic ecosystems. Other airborne pollutants of concern include black carbon, particulate matter (PM), pesticides, and heavy metals, including mercury. Atmospheric pollutants that are delivered in wet and dry forms cause deposition of nitrogen to forests and other land areas. The highest potential for ozone to injure plants occurs on western, low-elevation slopes that have elevated daytime levels that coincide with the highest physiological activity of plants. However, recent evaluations of ozone injury in the Sierra Nevada are lacking. Ozone and nitrogen deposition interact with other environmental stressors, especially drought and climate change, to predispose forests to impacts of pests and diseases.

Impacts of air quality currently pose threats to public health and recreation along the western slopes of the southwestern Sierra Nevada, which experience frequent episodes of unhealthy air, as indicated by exceedances of ozone and PM air quality standards. High levels and variation in day and nighttime ozone values can also occur at remote, high-elevation locations affected by pollution from distant areas; these locations can also have sufficient ozone precursors and meteorological conditions that favor localized photochemical ozone formation.

Emissions from wildfires and prescribed fires have the potential to exceed air quality health standards, especially for particulate matter (PM2.5 and PM10). Because of the relatively low probability of wildfire in any given area, expected emissions from a regime of prescribed burning may often exceed those from wildfire. However, prescribed burning can be managed more easily to mitigate air quality impacts to people. Furthermore, the potential of prescribed fires to generate enough ozone to exceed federal or state air quality standards is limited because typically they are smaller, are less intense, and occur during periods of low potential for photochemical ozone formation. Better understanding of the impacts of wildland and prescribed fires on ambient ozone, nitrogenous pollutants, and nitrogen cycling would help improve understanding of their potential effects on human health and the sustainability of forest ecosystems.

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[1] Ecologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Dr., Riverside, CA 92507.

[2] Research plant pathologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Dr., Riverside, CA 92507.

[3] Research ecologist, U. S. Department of Agricultural, Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618.

Values at Risk From Air Pollution

Air pollution affects a variety of ecosystem services, including supply of clean water, public health, regulation of greenhouse gases, and recreational values, as well as growth and health of forests and biodiversity (Cisneros et al. 2010). However, quantifying impacts to ecosystem services will require integrative research at larger scales than the individual plants and forest stands that have been a focus of most research (Serengil et al. 2011). Several recent peer-reviewed publications address air pollution status and effects across the Sierra Nevada (Arbaugh and Bytnerowicz 2003; Fenn et al. 2003b, 2010), and others focus specifically on the central Sierra Nevada (Hunsaker et al. 2007) and Sequoia and Kings Canyon National Parks (Bytnerowicz et al. 2002). Impacts of air quality currently pose threats to public health and recreation along the western slopes of the southwestern Sierra Nevada, which experience frequent episodes of unhealthy air, as indicated by exceedances of ozone and particulate matter (PM) air quality standards (Cisneros et al. 2010). In addition, impacts of other pollutants that may have significant biological effects, such as pesticides and mercury, are not very well characterized in the Sierra Nevada, but should also be taken into account.

Ozone

In many parts of the American West—especially the southwestern portions of the Sierra Nevada (Grulke 2003)—increasing background levels of ozone have already approached thresholds of phytotoxicity. High levels of ozone have been measured in the California Central Valley and southern Sierra Nevada since the early 1970s (Miller et al. 1972). These episodes are mainly caused by transport of polluted air masses from the highly polluted San Francisco Bay Area and the Central Valley. Polluted air masses from the Bay Area move east into the Sacramento Valley, where they circulate near Sacramento and move northwest along the western slopes of the Sierra Nevada. The polluted Bay Area air masses also move southeast into the San Joaquin Valley, where they mix with the locally polluted air. Cool air masses descending from the Sierra Nevada at night create the Fresno eddies that circulate polluted air within the San Joaquin Valley along the Sierra Nevada slopes (Hayes et al. 1992). These air currents, daytime eastward movement of air up the canyons into the Sierra crest, and long-range transport of air pollution from southern California affect air pollution distribution in the Sierra Nevada (Carle 2006, Hayes et al. 1992). Distribution of ozone concentrations in summer 1999 illustrates typical summer patterns in the Sierra Nevada (fig. 1) (Frączek et al. 2003), which occur on 72 percent of the warm-season days (Carroll et al. 2003) (see box 8.1-1 regarding efforts to update these maps). These general patterns were confirmed in

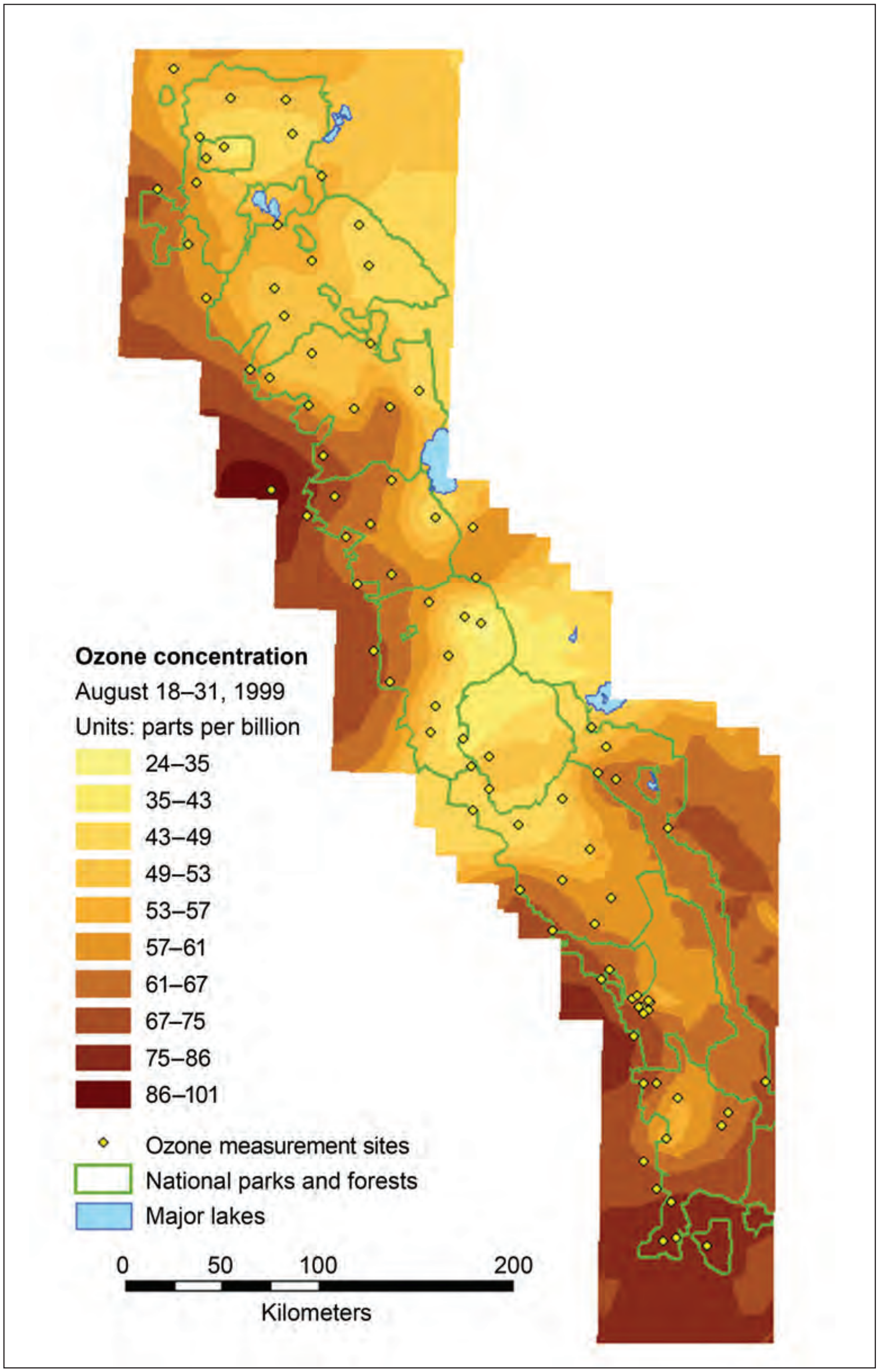

Figure 1—Distribution of ozone during the second part of August, with the intrusion of ozone into the Sierra Nevada from the California Central Valley to the west of the study area, as well as high concentrations of ozone in the southern part of the range and in the Owens Valley to the east of the study area. Reprinted from Frączek et al. (2003) with permission from Elsevier.

Box 8.1-1

Pending Research on Air Quality in the Sierra Nevada

Pacific Southwest Research Station researchers have obtained information on nitrogen air pollution and deposition in the Sierra Nevada using a variety of methods. They have generated maps of ozone air pollution for the entire Sierra Nevada and for the Lake Tahoe basin, and they are working with the University of California–Berkeley's Center for Forestry and the National Park Service to update maps of ozone distribution. They are also developing maps of critical levels for ozone, yielding a potential management tool for the Sierra Nevada, particularly the southern region. They are also developing maps of other pollutants (nitrogen oxides, ammonia, nitric acid, and sulfur dioxide) with data collected during 2006–2008 as part of research funded by the Joint Fire Sciences Program (JFSP). The southern Sierra Nevada has been a focus of air quality research, including a JFSP study that yielded several publications (both published and pending publication), including one on the ozone status of Devils Postpile National Monument in a low fire year (2007) and a high fire year (2008) (Bytnerowicz et al. 2013a). In addition, in 2010, research was conducted on characterization of spatial and temporal distribution of ozone, its precursors, and nitrogen deposition in the Lake Tahoe basin (Bytnerowicz et al. 2013b). In 2012, intensive study was conducted on ozone formation in the low- and high-elevation sites of the Lake Tahoe basin.

various recent studies; for example, elevated concentrations of ozone were reported in western parts of Sequoia and Kings Canyon National Parks (Bytnerowicz et al. 2002), western and southern portions of Yosemite National Park (Burley and Ray 2007), and the western side of the Sequoia National Forest (Cisneros et al. 2010). Although ambient mean ozone concentrations show only a slight decline along a west-east Sierra Nevada transect along the wide San Joaquin River drainage (Cisneros et al. 2010), the highest phytotoxic ozone potential occurs on western, low-elevation slopes that have elevated daytime values that coincide with the highest physiological activity of plants. In locations that are close to the urban areas in the Central Valley, nighttime ozone concentrations are much lower than daytime concentrations owing to titration of ozone by nitric oxide (Burley and Ray 2007, Bytnerowicz et al. 2002).

High diurnal ozone variation and elevated daytime values can also occur at remote, high-elevation locations affected by long-range transport of polluted air masses; these locations also have sufficient ozone precursors and meteorological conditions that favor local photochemical ozone formation (Bytnerowicz et al. 2013a). Some high-elevation sites may experience elevated evening and nighttime concentrations owing to transport of free-troposphere ozone (Burley and Ray 2007), whereas others may have low nighttime values when such transport does not occur and deposition to wet surfaces (meadows) takes place (Burley and Ray 2007, Bytnerowicz et al. 2013a). Background summertime ozone concentrations measured at remote Sierra Nevada locations are generally comparable with measurements in high elevations (2200 to 4340 m) of the White Mountains (fig. 2), with a summertime average of approximately 40 to 50 ppb (Burley and Bytnerowicz 2011). During several summer days, levels at a site at Devils Postpile National Monument exceeded the California standards for protection of human health (Bytnerowicz et al. 2013a). The same study also showed a potential threat to forest health as levels exceeded a secondary standard proposed by the U.S. Environmental Protection Agency to protect vegetation. These findings indicate that some remote locations in

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Figure 2—Air pollution monitoring site with active ozone instrument and passive samplers in the White Mountains of California during 2007. Research was conducted by collaborators from the USDA Forest Service Pacific Southwest Research Station, University of California, and Saint Mary's College.

the synthesis area occasionally experience potentially phytotoxic ozone exposures. Because of a possible increase in background ozone in the Western United States caused by a changing climate (Doherty et al. 2013), the potential threat to sensitive vegetation may increase in future years. The increase in background concentrations of ozone in the Western United States observed during the 1990s (Jaffe and Ray 2007) has recently slowed (Oltmans et al. 2013). However, more frequent and prolonged episodes of high temperature caused by climate change may reverse this trend (Sitch et al. 2007) and increase the potential impacts of ozone on sensitive vegetation in coming years.

Ozone negatively affects vegetation in the Sierra Nevada; effects on pines and other conifers were first reported east of Fresno in the western portions of Sequoia National Forest and Sequoia National Park (Miller and Millecan 1971). Permanent plots of forest health assessment (including effects of ozone) were established in 1974 and 1975 by Forest Service Forest Pest Management (FPM). Monitoring results showed that chlorotic mottle and premature needle senescence, well-known ozone injury symptoms (fig. 3), were common and widespread, especially among ponderosa (*Pinus ponderosa*) and Jeffrey (*P. jeffreyi*) pines. Such symptoms, although less pronounced, were also reported for a few other species (Williams et al. 1977). Between 1977 and 1987, a network of ozone injury evaluation plots was established throughout the Sierra Nevada. On that network, ozone injury was evaluated using the ozone injury index (OII) method developed by Miller et al. (1996), in

Photos by Pierre Vollenweider

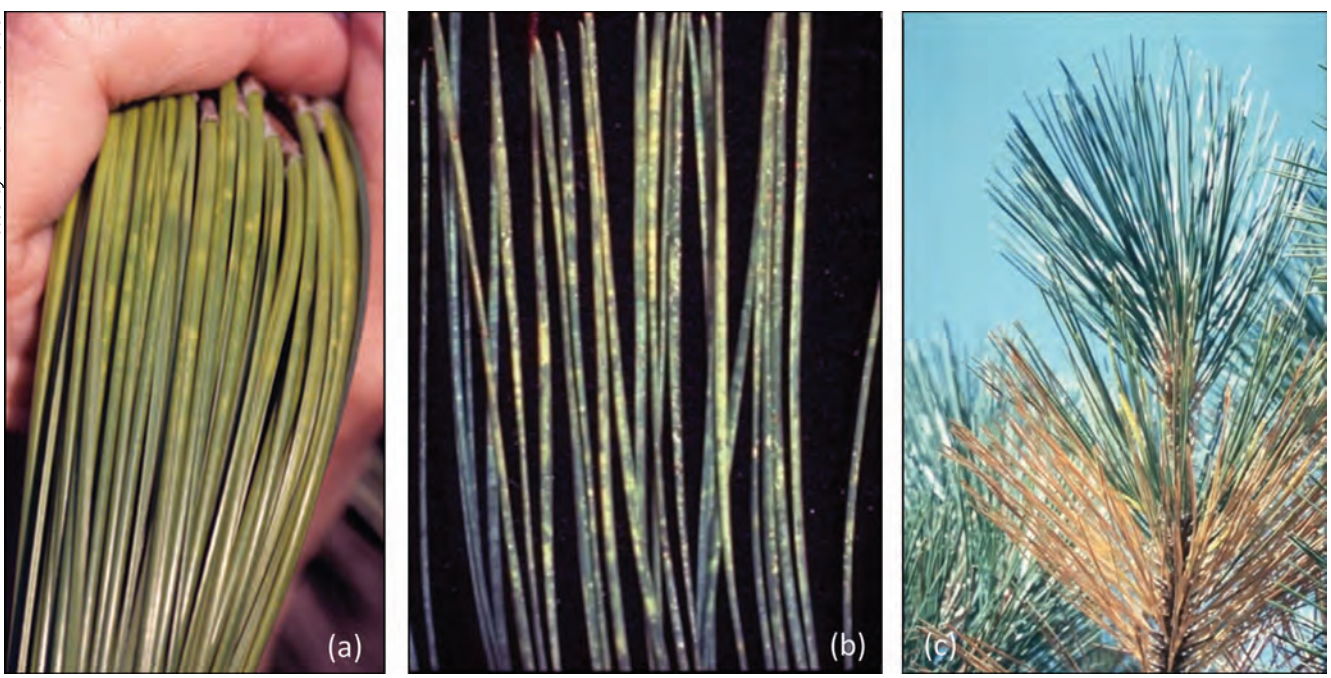

Figure 3—Symptoms of severe ozone injury in ponderosa pine foliage include chlorotic mottling of current-year foliage (a) and older foliage (b), senescence or yellowing (c), and premature falling off of older needles.

which chlorotic mottle and needle retention are the basis of the assessment (Grulke 2003). Between 1977 and 1987, symptoms of ozone injury were found all over the Sierra Nevada in more than 20 percent of the sampled ponderosa and Jeffrey pines. Severity of injury ranged from slight in the north to moderate/severe in the south, with the worst injury at elevations below 1800 m. Injury decreased from the west to the east across the Sierra Nevada as distance from the source of photochemical smog (largely from the Central Valley) increased (Carroll et al. 2003). Highest injury to the surveyed pines was determined in Sequoia and Kings Canyon National Parks (39 percent of pines with chlorotic mottle), and Yosemite National Park (29 percent of rated trees with injury symptoms). Ozone injury evaluation was repeated on a subset of the FPM plots in the Sierra and Sequoia National Forests in 2000. That survey showed a major increase of trees with chlorotic mottle—from 21 percent of all trees in 1977 to 40 percent in 2000. On the southern Sierra Nevada plots, severe ozone injury resulted in 7 percent of mortality of trees over a period of 23 years (Carroll et al. 2003). Although ozone was a predisposing damaging factor in tree mortality, other factors, including drought (exacerbated by climate change, densification of stands, and nitrogen deposition) and various species of bark beetles (such as western bark beetle (*Dendrocronus brevicomis*), Jeffrey pine beetle (*D. jeffreyi*), or mountain pine beetle (*D. ponderasae*)), are the ultimate cause of tree mortality (Fenn et al. 2003b, Minnich and Padgett 2003). It should be stressed that ozone phytotoxicity depends on the amount (dose) of ozone taken up by stomata and various abiotic and biotic factors (Matyssek et al. 2007). For the ponderosa pine stands in the foothills, only 37 percent of total ozone deposition was shown to occur in summer, and stomatal uptake accounted for less than half of that deposition (Goldstein et al. 2003). More recent evaluation of tree health in relation to ozone effects would help improve understanding of the condition of forests in the synthesis area.

Nitrogen Deposition

Forests on the western slopes of the Sierra Nevada receive substantial amounts of airborne nutritional nitrogen that could have effects on nitrogen cycling, water quality, tree health, biodiversity, and sensitive indicator species, including lichens (fig. 4) (Fenn et al. 2010). Fenn et al. (2010) showed that overall nitrogen deposition ranges from about 2 to 20 ha^{-1} yr^{-1} in the Sierra Nevada, with the lowest levels in the northern region and the eastern side of the mountains, moderate levels (5 to 12 ha^{-1} yr^{-1}) in the central Sierra Nevada, and the highest levels of deposition (ranging from 15 to 20 kg ha^{-1} yr^{-1} or greater) occurring in the southwest part of the region (fig. 5). Concentrations of the nitrogen pollutants that are the main drivers of nitrogen dry deposition drop significantly in the Sierra Nevada as air masses move

Mark Fenn

Figure 4—Sierra Nevada communities of tree-inhabiting lichens such as wolf lichen (*Letharia vulpina*) begin to change with atmospheric nitrogen deposition levels as low as 3 kg ha^{-1} yr^{-1}.

eastward (Cisneros et al. 2010). Polluted air masses can move deep into the Sierra Nevada range up the canyons and valleys; for example, the San Joaquin River drainage functions as a corridor for transport of pollutants to the eastern side of the Sierra Nevada (Cisneros et al. 2010).

Nitrogen deposition (fig. 5) can have a fertilizing effect on trees, reflected by increased aboveground growth and higher nitrogen tissue concentrations. Although fertilization has potential to enhance timber production, it poses a threat to forest composition, sustainability and function, as it alters nutrient cycles. Forecasting effects on forest composition is a challenge, but some have predicted that increases in soil nitrogen and ozone may reinforce shifts in forest composition associated with fire suppression by favoring firs over pines (Takemoto et al. 2001). Pines are generally more sensitive to ozone and excess nitrogen than firs and cedars (Fenn et al. 2003b, Grulke et al. 2010, Miller et al. 1983), and they are an important component of the mixed-conifer forest. Nitrogen enrichment can have other negative effects on biodiversity and ecological functions; for example, increased

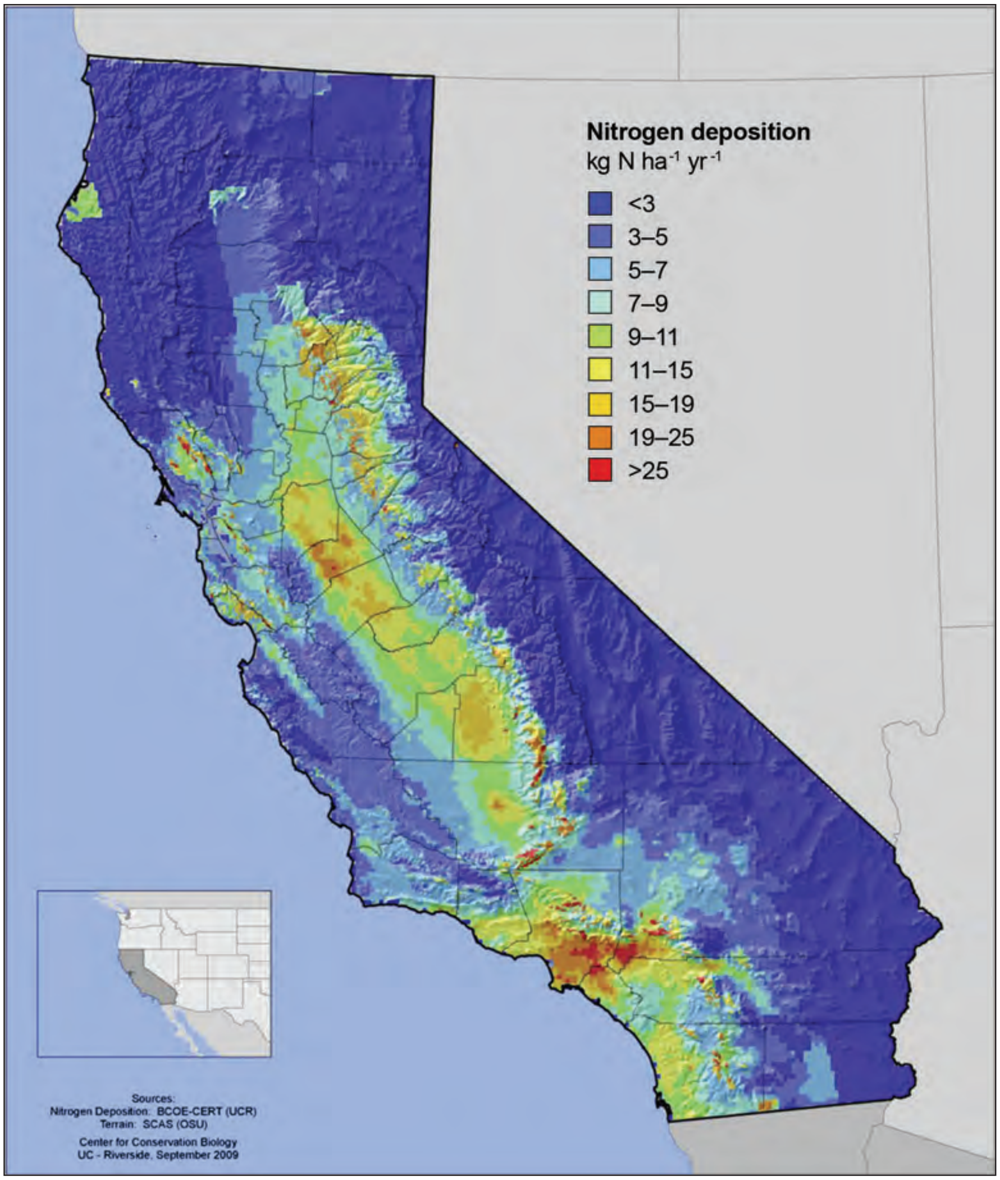

Figure 5—Map of total annual nitrogen (N) deposition in California based on simulations. Deposition inputs in the Sierra Nevada and other montane regions have been adjusted based on empirical deposition measurements. Reprinted from Fenn et al. (2010) with permission from Elsevier.

nitrogen can promote invasive grasses (Fenn et al. 2010), including cheatgrass (*Bromus tectorum*) (He et al. 2011), which can in turn have transformative effects on ecosystems by altering fire regimes, reducing carbon storage, and degrading forage quality (Bradley 2009).

Excess nitrogen deposition can also contaminate streams and groundwater with nitrate, although throughout most of the Sierra Nevada, nitrogen appears to be well retained in the vegetation and soils. Fenn et al. (2010) identified "critical loads" (CL) of atmospheric nitrogen deposition below which sensitive elements of an ecosystem are not harmed (fig. 6). In Sierra Nevada mixed-conifer forests, they found elevated nitrate leaching in streams to be limited, with the most severe leaching losses less than 1 kg ha^{-1} yr^{-1} (fig. 6b). This is in contrast to epiphytic lichen-related CL (6a), which are subject to widespread exceedances of nitrogen deposition throughout the range. Exceedances have also been noted for other vegetation types that occur in the Sierra Nevada, including pinyon-juniper, chaparral, and oak woodland. Furthermore, though nitrate leaching is limited, researchers have suggested that high-elevation lakes throughout the region may be experiencing eutrophication, which could result in increasingly severe ecological effects in the next several decades (Fenn et al. 2003a, Sickman et al. 2003). Accordingly, research is needed to evaluate the extent and impact of nitrogen deposition on high-elevation lake chemistry and biota in the Sierra Nevada.

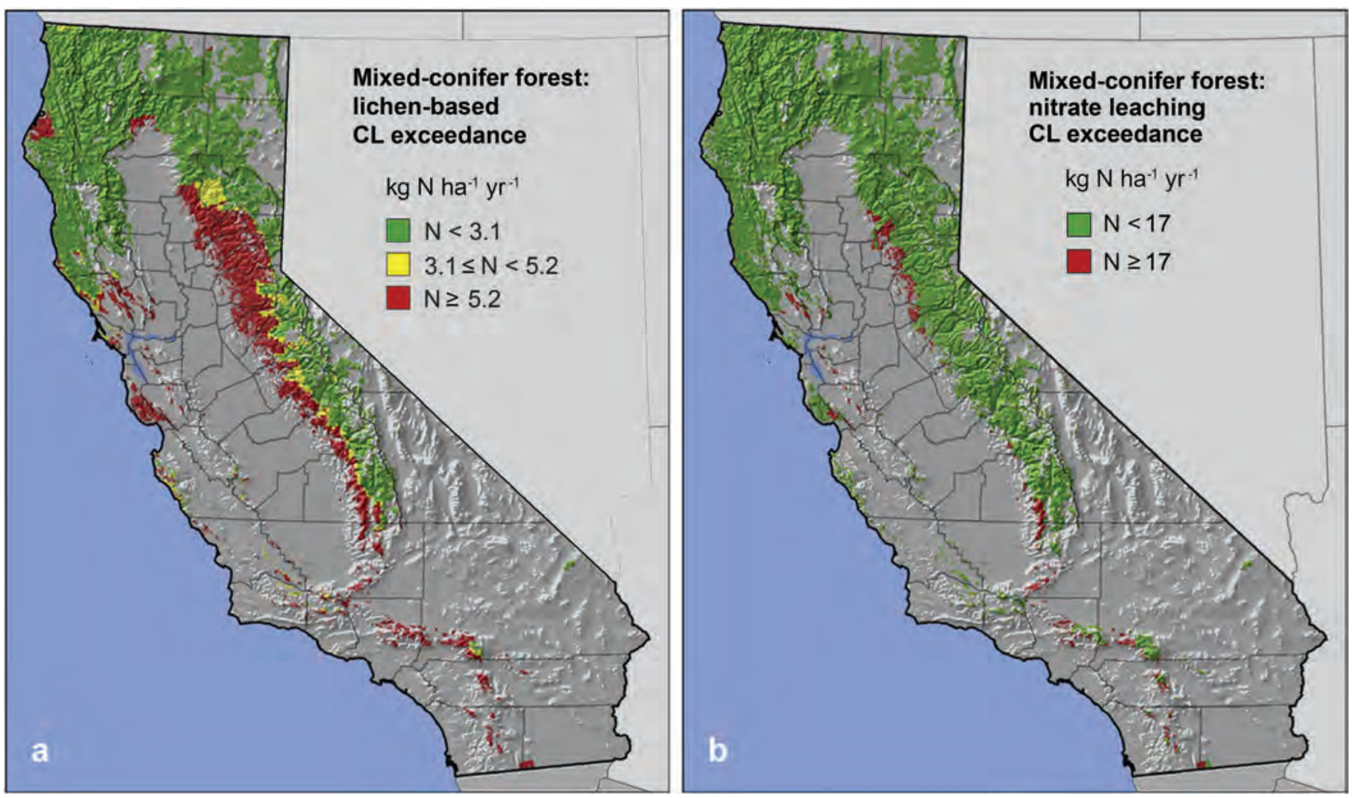

Figure 6—Critical load (CL) exceedance map for mixed-conifer forests based on (a) lichen community effects and (b) nitrate leaching. Reprinted from Fenn et al. (2010) with permission from Elsevier.

Interactive Effects of Ozone, Nitrogen Deposition, and Climate Change

A warmer climate in the Western United States will affect the Sierra Nevada forests directly through soil moisture stress and indirectly through increased extent and severity of various disturbances. **Stress complexes**, a combination of biotic and abiotic stressors, will compromise vigor and, ultimately, the sustainability of forest ecosystems. Increased water deficit will accelerate normal stress complexes, which typically involve various combinations of long-term droughts, insects, and fire (McKenzie et al. 2008). In that general context, the combination of elevated ozone concentrations and nitrogen enrichment has already produced pronounced (and mostly negative) effects on California mixed-conifer forest ecosystems (Takemoto et al. 2001). These pollutants interact with other environmental stressors, especially drought, to predispose forests to impacts of pests and diseases. Through studies of nitrogen additions, researchers have found that nitrogen enrichment enhances mortality of ponderosa pines caused by bark beetles, as does ozone stress. Grulke et al. (2010) highlighted the San Bernardino Mountains as a case study in which multiple stressors, including ozone exposure, nitrogen deposition, and fire suppression, have predisposed forests to injury and mortality from bark beetles, drought, and fire. Although air pollution effects have been less severe in the Sierra Nevada than in the San Bernardino Mountains, chronic ozone exposure and nitrogen deposition are expected to become more prevalent, particularly in the southern part of the region (Fenn et al. 2003b, Takemoto et al. 2001). Furthermore, studies have shown synergistic effects of air pollution with other stressors; for example, in the southern Sierra Nevada, the negative effects of ozone on tree growth may be partially offset by nitrogen deposition, but the combined effects of ozone and chronic nitrogen deposition may lead to severe perturbation of tree physiology and ecosystem sustainability (Fenn et al. 2003b). Additionally, air pollutants may interact with climate change in complex ways that significantly differ from the sum of their separate effects (Bytnerowicz et al. 2007).

Further research is needed to evaluate how nitrogen deposition and ozone affect carbon sequestration both aboveground and in the soil (Bytnerowicz et al. 2007). This information will be critical to climate change mitigation efforts in the region. Recent assessments suggest that many ecosystem and environmental responses to nitrogen deposition could lead to a net cooling effect, primarily as a result of enhanced carbon sequestration in woody biomass and increased haze and particles formed from nitrogen air pollution (Erisman et al. 2011), although there are many uncertainties in these evaluations. Many studies show that nitrogen enrichment and ozone exposure can lead to reduced carbon allocation belowground, resulting in greater carbon in aboveground detritus (Fenn et al. 2003b). Likewise, numerous studies confirm that long-term decomposition of litter slows when nitrogen concentrations in litter are elevated; this may result in greater carbon storage in litter, especially during long fire-free periods (Whittinghill et al. 2012). However, when these polluted forests experience fire, more carbon may be released from burning litter.

Impacts of Other Pollutants

Other pollutants of concern include black carbon, PM, pesticides, and heavy metals. Black carbon and dust particles pose a threat to water resources by promoting earlier melting of snowpack (Hadley et al. 2010). Although levels of methylmercury are relatively low in fish from Sierra Nevada lakes (Davis et al. 2009), mercury levels reported from sediments in Lake Tahoe are surprisingly high for alpine regions (Heyvaert et al. 2000). There is concern of long-range transport of semivolatile organic compounds (SOCs), such as pesticides, polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs), in high-elevation aquatic and terrestrial ecosystems of the Sierra Nevada. Measurements have been performed within the Western Airborne Contaminants Assessment Project at the Emerald Lake and Pearl Lake area of Sequoia and Kings Canyon National Parks, showing contamination of snowpack, lake sediments, vegetation, and fish. Sequoia–Kings Canyon had the highest concentrations of current-use pesticides compared with other Western national parks (Landers et al. 2008). Sources of these pollutants include wildfires, vehicles, urban and agricultural areas west of the Sierra Nevada, and, increasingly, long-distance transport from Asia (Hadley et al. 2010, Heyvaert et al. 2000). Wildfires have significant potential to mobilize heavy metals, including mercury, in ways that pose threats to human health (Goldammer et al. 2008) (see chapter 4.3, "Post-Wildfire Management"). More research and monitoring of air, snow, vegetation, and lakes throughout the Sierra Nevada are needed to better understand spatial and temporal distribution of biologically important heavy metal and organic contaminants and their potential threats to ecosystems.

Forest Management Strategies to Address Pollutant Effects

In addition to direct pollutant load reduction, a prudent strategy to reduce the impacts of air pollution on forests would include treatments to reduce accumulated nitrogen in the forest by reducing stand stocking and fuel loads (Fenn et al. 2003b). To treat the problem of nitrogen saturation in highly polluted forests, such as the mixed-conifer forests of southern California, several papers have recommended the use of prescribed burning (Fenn et al. 2010, Gimeno et al. 2009). Although the conditions in the Sierra Nevada are generally less severe than in the mountains of southern California, frequent prescribed burning could help mitigate nitrogen inputs in forests experiencing elevated deposition. However, because prescribed fire has limited ability to reduce nitrogen in the mineral soil, Fenn et al. (2010) also suggest testing the potential of thinning to stimulate vegetation growth. Both thinning and prescribed fire can be used to proactively reduce the amount of plant matter available for combustion and reduce potential emissions of nitrogenous pollutants. However, long-term ecosystem protection and sustainability will ultimately depend on reductions in nitrogen deposition, and this is the only strategy that will protect epiphytic lichen communities. Measures to reduce nitrogen deposition through more stringent control of emissions caused by combustions of fossil fuels as well as those from the largely uncontrolled agricultural sector are needed. The CL analyses and maps of CL exceedances are useful management tools for quantifying the severity of the pollution problem and identifying areas at risk from chronic nitrogen deposition. Also, there is a clear need for further decreases in ozone generation, and this can be accomplished through control of emissions of ozone precursors (nitrogen oxides and volatile organic compounds). Strict compliance with the federal and state ozone air pollution standards is needed. New measures, such as federally imposed improved mileage standards for motor vehicles, could greatly help in reducing emissions of ozone precursors and lowering ambient ozone concentrations. If this is accomplished, future forests would be less stressed by direct phytotoxic ozone effects as well as secondary effects, such as increased susceptibility to drought and bark beetle attacks. Furthermore, the impacts of long-range mercury transport on Sierra Nevada aquatic ecosystems (especially high-elevation lakes) is still not well understood, and findings from the national mercury monitoring network administered by the National Atmospheric Deposition Program should be evaluated and monitoring efforts intensified if needed. Additional monitoring efforts and research on potential impacts of long-range transport of pesticides and other potentially toxic organic compounds are needed to assess potential threats. If such threats are found, recommendations for stricter control of their use for agricultural production in the California Central Valley should be made.

Fires, Smoke, and Air Quality

Prescribed fire and managed wildfire use entail a short-term impact to human communities to restore ecological processes and avoid the potential impacts of undesirably severe and poorly controlled wildfires. Fires release pollutants of concern, including fine particulate matter (PM2.5), coarse particulate matter (PM10), ammonia, carbon monoxide, carbon dioxide, nitrogen oxides, sulfur dioxide, and various volatile organic compounds (VOCs) (Cisneros et al. 2012, Urbanski et al. 2008). Use of prescribed fire as a management tool is constrained by state and federal air quality regulations for human health and visibility (Quinn-Davidson and Varner 2012), and potential smoke impacts to human populations (see chapter 9.3, "Sociocultural Perspectives on Threats, Risks, and Health").

A study of historical fire regimes and associated smoke emissions in California concluded that fires historically burned over extensive areas, and that smoke emissions were substantial, especially from the large areas of mixed-conifer forests that experienced frequent fire prior to the 19th century (Stephens et al. 2007). A long history of fire suppression has encouraged residents and visitors to the Sierra Nevada to expect exceptional visibility and smoke-free conditions during the summer and fall, but this may not be a realistic expectation for the area, especially given that a changing climate is projected to increase the likelihood of large, severe wildfires (Westerling et al. 2006). Many decades of altered fire regimes have also led to a large buildup of living and dead biomass in the understory and forest floor; in the Lake Tahoe basin, these accumulations represent a significant store of potential pollutants, whether through high nutrient levels in runoff (Miller et al. 2010) or through emissions during combustion.

Pacific Southwest Research Station researchers have worked with Region 5 Air Resources managers to study effects of wildland and prescribed fires on air quality in the context of state and national air quality standards. During severe fires, accumulated nitrogen in vegetation, litter, and surface soils may also be released as ammonia and nitrogen oxides (Urbanski et al. 2008), and these emissions could cause nitrogen deposition problems downwind of the fires (Goldammer et al. 2008). However, the potential of prescribed fires to generate enough ozone to exceed federal or state air quality standards is limited owing to their low thermal intensity and geographic scale as well as their application during periods of low potential for photochemical ozone formation (Bytnerowicz et al. 2010). Better understanding of the impacts of wildland and prescribed fires on ambient ozone and nitrogenous pollutants is needed because of their potential effects on human health and the sustainability of forest ecosystems (Bytnerowicz et al. 2008). For instance, Preisler et al. (2010) detected a small but significant effect of wildfires on ambient ozone concentrations using the Blue Sky smoke dispersion model (O'Neill et al. 2008); however, these authors also pointed out serious weaknesses in monitoring and modeling approaches related to both wildland and prescribed fires. These are mainly related to the difficulty in distinguishing between fire-related ozone precursor emissions and emissions from nonfire anthropogenic sources, as well as complicated impacts of meteorology and complex mountain topography on ambient ozone concentrations (Preisler et al. 2010).

Effects of Management Strategies

A number of factors influence the amount and quality of emissions from burning, including fuel moisture, amount, and quality; these factors in turn are influenced heavily by weather and season. For example, burning material with higher moisture generally produces more carbon monoxide and ammonia, whereas burning drier fuels results in more complete combustion and greater release of smoke, carbon dioxide, and nitrogen oxides (Chen et al. 2010). The impacts of burning the forest in a prescribed burn are different from intense wildfire in important ways. First, intense wildfire often occurs in the summer under dry and windy conditions that facilitate smoke dispersal and lofting into the upper atmosphere (Cahill et al. 1996); however, dispersal depends upon local topography and weather conditions and is not assured. Even wildfires that occur under favorable ventilation conditions are still likely to cause emissions that exceed health and visibility standards (Gertler et al. 2010). Because wildfires have been relatively infrequent, their long-term average impact on respirable PM has often been relatively small (Cahill et al. 1996); however, a worsening of poor air quality days in the Lake Tahoe basin has been linked to wildfires (fig. 7) (Green et al. 2012).

In contrast, managers can generally time and control prescribed burns to alter smoke production and transport in response to conditions on a daily basis. Prescribed burns in many parts of the synthesis area, including the Lake Tahoe basin, predominantly occur later in the fall when smoke tends to dissipate less readily. As a result, models of prescribed burning under typical fall conditions indicate potential to violate air quality standards (Gertler et al. 2010) (see box 8.1-2). However, the modest amount of burning during the fall and winter, combined with protective measures to limit smoke, typically result in low contributions to PM10 loading in inhabited areas (Cahill et al. 1996, Gertler et al. 2010).

A comparison of expected emissions from prescribed burning and wildfire would have to consider cumulative effects of prescribed burning. A recent modeling study found that prescribed burning would release less carbon dioxide than wildfire in frequent-fire forest types of the Western United States, but it assumed that the prescribed burning was so mild that it killed no trees and was conducted only once (Wiedinmyer and Hurteau 2010). These assumptions underestimate the severity and

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Figure 7—Smoke obscured visibility at Lake Tahoe on June 28, 2008. During that time, much of northern California was blanketed in smoke from large wildfires that reduced visibility, caused hazardous levels of air pollution including particulate matter, and forced cancellation of outdoor recreation events such as the Western States 100-mile endurance run.

frequency of prescribed burning needed as a restorative practice in the synthesis area. The authors of that study indicated that cumulative prescribed fire emissions of carbon dioxide would likely be higher than wildfire emissions in cases where reestablishment of trees was relatively fast. However, treatments that prevent severe tree mortality from wildfire would likely have an emissions benefit (Wiedinmyer and Hurteau 2010).

Research Needs

There is a need to integrate research and management planning to evaluate trade-offs between wildfires and treatments that include prescribed burning. Sound management of forests, fuels, and air quality will require the scientific community to fill a number of research needs (Bytnerowicz et al. 2009). The most pertinent of those needs to this synthesis are (1) better characterization of the spatial distribution of fuels as well as their physical and chemical properties; (2) improved weather forecasting of changing climate/atmospheric circulations at local to regional scales; (3) more accurate empirical and statistical downscaling tools for assessing the impacts of climate change on fire behavior and emissions; (4) improved characterization

Box 8.1-2

Comparisons of Wildfires and Prescribed Fire Effects in the Lake Tahoe Basin

The air quality effects of smoke under different scenarios have been compared in the Lake Tahoe basin. The Lake Tahoe Air Model is a heuristic, cell-based predictive model that was developed to analyze the effects of prescribed fires and wildfires on fine particle mass (PM2.5) and visibility (Gertler et al. 2010). The model was used to compare impacts from a hypothesized regime of small, non-crowning wildfires burning 30 ac per day in the summer, a scenario intended to represent conditions prior to the mid-19th century. The results indicated that a regime of these "natural" wildfires would generate "spotty but persistent smoke in relatively low concentrations around the basin" that would not violate state and federal air quality standards, and have little impact on lake clarity (Gertler et al. 2010: 71). The model analyses of prescribed burns of 50 and 100 ha in the fall season resulted in much higher smoke levels that violated state and federal standards for 2 to 3 days (Gertler et al. 2010). The model was also used to examine effects from a moderately sized August wildfire (1500 ha); it predicted that smoke from this type of fire would completely fill the basin with smoke and exceed air quality standards for 4 to 5 days (Cliff and Cahill 1999). These analyses supported the finding that severe wildfires in the Lake Tahoe basin have greater potential than low-intensity prescribed burns to contribute to violations of air quality standards, obscure visibility across the lake, promote algal blooms, and reduce lake clarity (Gertler et al. 2010). Researchers have concluded that the reduction in visibility needed to accommodate increases in prescribed burning would be counterbalanced by reducing the air quality impacts of potential major wildfires (Gertler et al. 2010).

of emissions of air pollutants and greenhouse gases during fire events; (5) detailed identification and chemical characterization of VOCs to develop markers (gaseous and aerosol tracers to distinguish smoke from prescribed vs. wildland fires); (6) real-time monitoring of ambient air quality during forest fires; (7) improved regional air quality models that include realistic wildland fire emissions; (8) fire behavior models coupled with meteorological and chemical models for improved understanding of pollution transport; (9) better understanding of ozone and nitrogen deposition effects, as well as interactions among various pollutants, drought, and pests on composition, structure, and function of forests and other ecosystems; and (10) models aimed at better understanding of the effects of air pollution and climate change on forests at the landscape scale.

Management Implications

- Emissions from wildfires and prescribed fires have potential to exceed air quality standards; however, prescribed burning can be managed more easily to mitigate air quality impacts to people. Additionally, because of the relatively low probability of wildfire in any given area, expected emissions from a regime of prescribed burning may often exceed those from wildfire.
- There are sound ecological reasons to promote greater tolerance and application of prescribed fires, and shifting smoke production from uncontrolled wildfires to managed fires can help reduce the overall impacts of burning. Acceptance of fire as a management tool will also require better large-scale monitoring of smoke emissions (including ground level and remotely sensed) and development of models that are able to predict spatial and temporal distribution of toxic pollutants resulting from fires.
- A variety of tools are being employed and developed to allow better predictions and monitoring about burn activities, including the BlueSky smoke modeling framework, which provides real-time predictions of smoke impacts from prescribed and wildland fires; and the Fuel Characterization and Classification System, First Order Fire Effects Model, and Consume for describing fuel loading and predicting emissions.
- These tools will help managers and the larger public evaluate tradeoffs about how to reduce the debt of accumulated fuels and allow the return of a more natural fire regime where the impacts can be tolerated.

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