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Chapter 20

Interactive Effects of Climate and Wildland Fires on Forests and other Ecosystems—Section III Synthesis

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The chapters in Section III of this book provide an overview of how components of climate change, including air pollution, are likely to interact with fire in modifying key ecosystem processes, whether those processes were demographic, successional, or elemental cycling. These chapters primarily discuss increased temperature, reduced available soil moisture, and pollutant deposition or exposure as the key climate change attributes. Most of the chapters suggest that changes in frequency and intensity of disturbance regimes, such as wildfire and insect infestation, will likely be the instigators of ecosystem change.

McKenzie et al. (this volume) provide a broader biogeographic context for the subsequent chapters, which all focus on response of the mixed-conifer forest or chaparral in the Sierra Nevada, the Transverse Range in southern California, or the Peninsular Range of southern California and northern Baja California. Minnich and Franco-Vizcaíno (this volume) contrast how management policies in California and Mexico have altered fire size, interval, frequency, and its intensity in the landscape, thus causing vegetation susceptibility to fire in California or resilience to fire in Mexico. In a case study for the mixed-conifer zone in the Transverse Range of southern California, Grulke et al. (this volume) describe the role of air pollution—ozone (O_3) and nitrogen (N) deposition—as a causative stressor in increasing forest susceptibility to wildfire. Johnson, Fenn, Miller, and Hunsaker (this volume) describe partitioned losses of carbon (C) and N as atmospheric emissions and catchment runoff and net accretion of calcium after fire in the mixed-conifer forest. They describe the facilitation by N-fixing fire successional species in incorporating N back into an N-limited ecosystem. In the last chapter, Gimeno et al. (this

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volume) simulate the effect of different frequencies of prescribed fire management in combination with reduced N deposition on mitigating long-term effects of excess N deposition in this ecosystem. All chapters present conceptual models or use simulation models to illustrate likely interactions between components of climate change and fire on forest structure and function.

McKenzie et al. (this volume) propose conceptual models for ecosystem response to climate change and wildfire in four regions: southwestern pinyon pine-juniper woodlands, Sierra Nevada mixed-conifer forests, Rocky Mountain lodgepole pine, and the interior boreal forests of Alaska. By all climatic projections, these four regions are very likely to have a more negative water balance than under current conditions. Warmer climate, soil moisture stress, plant drought stress, bark beetle epidemics, and wildfire comprise a disturbance complex that is predicted to have region-specific effects and different trajectories for the affected ecosystems. The authors suggest that the synergy amongst disturbances will invoke new fire regimes, new species complexes, and broad-scale changes.

Except for interior Alaskan forests underlain by permafrost, all other forest types discussed in this chapter had similar sequences of disturbances; namely, global warming is likely to increase drought- and insect-induced tree mortality, result in excessive fuel accumulation, and will in turn increase forest susceptibility to extensive, intense fires. The authors present four models in which the first for pinyon pine-juniper woodlands could be considered the base model of climate-mediated ecosystem response. For interior continental lodgepole pine forests, the base model is modified by an initial stand-replacing fire regime, which is typical of this species' ecology. For Sierra Nevada mixed-conifer forests, tropospheric O_3 exposure is an additional synergistic stressor with drought, bark beetles, and defoliators contributing to tree mortality. The authors suggest that severe extended droughts could directly induce intense fires in the mixed-conifer forests, without the precursor of bark beetle, as presented in the base model. In all three lower latitude forest types, the change in fire frequency and severity will likely precipitate changes in species composition, including exotics. Although higher temperatures and drought alone could alter species composition in the mixed-conifer and interior lodgepole pine forests, these climatic factors did not directly alter species composition in pinyon pine-juniper woodlands: the ecosystem is relatively simple floristically, and already highly water-limited.

The sequence of disturbance vectors in Alaskan interior forests on permafrost-free soils was similar to that of continental coniferous forests.

However, the increased temperature directly affected beetle fecundity in Alaska, rather than a drought-mediated increase in tree susceptibility to beetle infestation, as predicted for lower latitude forests. For interior forests underlain by permafrost soils, global warming mediated permafrost degradation. In low topographic areas, permafrost degradation would likely lead to a type conversion from deciduous forests to wetlands, fens, and bogs. In upland interior forests underlain by permafrost, the loss of permafrost would likely increase drought stress and forest susceptibility to wildfires, and increase deciduousness in the resulting forest. Overall, the authors suggest that the interaction between climate, vegetation, and resulting fire creates a "disturbance synergy" that drives ecosystem change via new fire regimes on a decadal basis and habitat change over a multi-century time period.

Minnich and Franco-Vizcaíno (this volume) contrast the resulting vegetation patterns in forest and chaparral under highly suppressed (southern California) and largely unmanaged (Mexico) fires. Based on historical accounts (>100 years ago), wildfire was known to burn at low levels over months in the chaparral surrounding Los Angeles. Under current conditions in Mexico, such fires are common and of low intensity. Because of their frequency, fuel accumulation is generally not excessive, and burning may be discontinuous within a stand, resulting in patchiness in the resulting age structure and remaining fuels. In southern California, fire suppression began in the early 20th century, and fuels have inexorably accumulated since. Since then, when fire occurred (and occurs), fires are intense and extensive, and burn out only when insufficient fuels support them (e.g., previously burned areas), or they are extinguished. Fires occurring in early summer or small fires (<0.4 ha) are relatively easily suppressed. Fires occurring in late summer under Santa Ana conditions (dry, hot, offshore winds) burn through areas of high fuel accumulation, cannot be suppressed, burn intensely, and are carried through or across previously burned areas that under different conditions would not likely burn. These conditions result in much larger areas that are intensely burned.

The authors detail the role of differences in fire weather conditions between southern California and northern Baja California. On the one hand, offshore, hot, dry Santa Ana winds propagate fire across large areas in southern California. In northern Baja California, onshore moist winds in early summer and more moist monsoonal storms in late summer are less effective in promoting large fires. Despite these climatic differences, one could argue that a finer vegetation mosaic might have been in place or could develop in southern California if fuel loading were lower (e.g., under current conditions could be mechanically removed or via a low-intensity prescribed fire), and less intense early summer fires were allowed to burn (the very ones we can successfully control)—if not freely, then more extensively. However, reducing fire suppression within the context of current land use is untenable due to the large number of mountain communities and private landowners adjacent or within at-risk forests and chaparral in southern California without a fire-defensible space. Perhaps the best way to defend communities is with consolidated land use, and a well-defined, reduced fuels, defensible zone bordering the wildlands.

Minnich and Franco-Vizcaíno (this volume) present a conceptual model to help explain fire-generated and maintained mosaics of multi-age stands. Their model shows that as carbohydrate (or carbon, energy, or biomass) builds up on a site, plant available water declines as more leaf area is translated to higher transpirational losses. When there is little vegetative regrowth immediately after the fire, and the ratio of available water to plant biomass on the site is high, the probability of fire is low. Similarly, as the carrying capacity for biomass on the land base increases, the plant available water declines. With ignition, fires are carried when the energy of accumulated biomass exceeds the heat capacity of plant water content (Rothermel, 1972). This best explains the fire patterns in old stands of chaparral as they are generally completely consumed in fires. Old-growth forests may persist if the fires were early enough in the growing season, sufficient site water was available, and thus ratio of water available to stand biomass were high.

The same conceptual model can be applied to forest susceptibility to flammability within a given growing season or across different slope aspects in the landscape. In the case of aging chaparral with maximized biomass, less water is available per unit biomass, which hastens the onset and duration of drought stress, and consequently, susceptibility to flammability within a growing season. Interestingly, this difference in the ‘‘window of susceptibility to flammability’’ for different aged and types of vegetation is the mechanism by which a multi-aged mosaic is established and perpetuated. With sufficient fire suppression, even multi-aged mosaics develop sufficient biomass for extensive fires when it does occur, leading to intense fires, which disrupt the very vegetation structure that provides some measure of resistance to such fires. The initial point of ignition is stochastic, but flammability is a function of the rate of ignition from all sources, patch size, and vegetation fuel threshold (a function of biomass accumulation since the last fire). That ‘‘self-organized patch emplacement’’ develops across the landscape is not surprising, considering the underlying relationship between biomass accumulation and plant available water, which are very much influenced by elevation, topographic position, aspect, and both short- and long-term changes in climate.

Grulke et al. (this volume) present a conceptual model of a single location of pine-dominated mixed-conifer forest in the western San Bernardino Mountains (eastern Transverse Range) experiencing the highest pollution deposition in North America. They show that the combination of historical changes (human settlement, timber utilization to recreation, human attitudes towards fire safety), increase in stand density, pollution deposition (high O_3 exposure and N deposition), episodic drought stress, bark beetle epidemics, tree mortality, and anomalously high litter accretion results in forest susceptibility to wildfire. The authors show that although we have inherited a ‘‘tinderbox’’ from historical fire suppression policies (see Minnich and Franco-Vizcaíno, this volume), the main thesis of the chapter is that air pollution is more than an additional stressor; it is causative to increased forest susceptibility to wildfire. The primary evidence includes the following: (1) air pollution (both O_3 exposure and N deposition) increases older needle and lower branch loss, increasing litter accumulation; (2) air pollution decreases long-term litter decomposition of litter by altering litter chemistry, further promoting litter accumulation; (3) air pollution decreases root mass, increasing individual tree susceptibility to drought; (4) high O_3 exposure increases, not decreases, canopy transpiration, further increasing individual tree susceptibility to drought; (5) pollution-induced changes in within-tree allocation of resources are such that bole carbohydrate is increased, and bole protein may be increased due to drought stress, increasing tissue quality for bark beetles; (6) drought is common in Mediterranean climates, and ponderosa pine experiences moderate or severe drought about half of the time based on a 125-year regional precipitation record; (7) bark beetle epidemics are known to occur after multi-year droughts (increased tree susceptibility to successful bark beetle attack), followed by a year of above average precipitation (increased numbers of generations of beetles); and (8) tree mortality under both drought and bark beetle attack is high. Air pollution modifies many ecosystem components in ways that increase susceptibility to wildfire.

The case study was illustrated using a temporal sequence of aerial imagery beginning with the point of bark beetle infection after three years of chronic drought, followed by the expansion of bark beetles with chronic and one year of acute drought, and then full beetle outbreak in a wet year (promoting survival), following the chronic and acute drought. It is no surprise that wildfire is then easily transmitted through a forest with high standing dead biomass (40% mortality). Air pollution increases standing live and dead biomass and reduces plant available water within a stand. Both phenomenological and experimental evidence is presented to support air pollution as cause, rather than a contributing stressor. Using aerial photographs from the pre-drought to post-drought periods for sites across the San Bernardino Mountains with a range of pollutant deposition and stand densities, a relationship between pre-drought canopy cover or tree density and post-drought tree mortality was demonstrated. Stands in the eastern San Bernardino Mountains, despite less water availability, had lower initial stand density and lower mortality rates. In the central and western San Bernardino Mountains, stands had higher initial stand density and much greater mortality rates. The relationship offers a quantitative risk assessment: stand cover $<45\%$ yielded the lowest mortality rates ($<20\%$) with the concurrent stressors of air pollution, drought stress, and bark beetle infestation.

Similar to the first two chapters of Section III (McKenzie et al., this volume; Minnich and Franco-Vizcaíno, this volume), Johnson et al. (this volume) present a series of studies on the effect of fire on different vegetation types (forest and chaparral, mesic and xeric forests). They describe nutrient losses during fire due to emissions, mineralization, and leaching, as well as post-fire nutrient accretions of ecosystem carbon, N, and calcium over immediate, medium, and long-term time periods. A simple, effective accounting model was used to illustrate net ecosystem changes in these partitions with wildfire versus prescribed fire at two return rates in mixed-conifer forest. In mixed-conifer forests, soil carbon pools may not recover until the vegetation returns to the original pre-fire state. In contrast, ecosystem N losses by fire can be recouped within two decades by N-fixing, successional species. A watershed-scale experiment was presented that elucidated how different initial ecosystem partitioning in chaparral alters carbon and N loss after prescribed fire and wildfire. In chaparral catchments, prescribed burning could not mitigate excess atmospheric N loading and did not significantly modify high nitrate leaching from the ecosystem. In mesic forests, N losses from fire far exceed N leaching and result in a net loss of ecosystem N except for the few forests that are known to be N-saturated.

Johnson et al. (this volume) compare an unburned site and a site that had been burned 20 years prior to the study in the eastern Sierra Nevada mixed-conifer forest. Immediately after fire, there was an increase in mineral N leaching, which declined to near control levels within three years. The total loss of nitrate due to leaching was a fraction of that lost to volatilization during the fire. Soil solution concentrations of NH_4^+ and NO_3^- increased 100-fold during the first year after fire, but declined significantly after the second year. Although aboveground carbon and N is largely lost in wildfires, belowground carbon pools are often unaffected by the fire itself, but have low-level, long-term losses from decomposition of roots and residual soil organic material. Carbon pools were not expected to recover until the vegetation itself returned to pre-fire conditions. In this ecosystem, the short-term pulse of fire-mediated release and mobilization of plant available N is followed by prolonged N accretion over decades by secondary successional, N-fixing plants after fire that largely recoup N lost to volatilization (during combustion) and short-term leaching (several years). Results of a simple accounting model demonstrated greater total N losses from prescribed fires at 10- and 20-year intervals over 100 years than for all-consumptive wildfires occurring once in 100 years. Of interest is the shift of the hydrophobic layer after severe fires, from near-surface to 8–10 cm in the mineral soil horizon. This had significant limitations on percolation of nitrate-rich leachate to deeper soil horizons, and increased the volume of soil susceptible to erosion. The depth to the hydrophobic layer may also have an effect on seedling survival after fire, because conifers that were able to penetrate this layer were more likely to survive to 15 years (Grulke, unpublished data).

The authors describe no net differences in ecosystem phosphorus, potassium, or sulfur between burned and unburned areas, but potassium and calcium were significantly greater in burned areas. Exchangeable potassium, calcium, and magnesium were greater in shrub-dominated (burned) than the forest site. Calcium levels were unaccounted for by pre-fire stand content. The authors posit that either post-fire vegetation readily takes up and redeposits these elements or they were released from extreme heating of soil minerals *in situ*. An increase in plant available calcium would increase soil pH and base saturation, mitigating acidification of N-saturated conifer forests, but may have little affect in chaparral or forests with low N deposition. The largest ion increases in soil solution was SO_4^{2-}, probably resulting from oxidation of soil organic material, but also possibly from soil pH increases previously mentioned.

The clarity of Lake Tahoe has declined since the late 1960s, due in large part to stream water N inputs such that phosphorus is considered limiting. Interestingly, accumulated N deposition in litter layers, unburned from fire suppression policies and not percolating through mineral horizons due to shallow hydrophobic soil layers, may have contributed to increased N pulses into Lake Tahoe. Thus, wildfires and fire suppression in the Lake Tahoe Basin, are expected to continue to threaten water quality.

In southern California, pollution has been transported into the foothills and mountains over the past 50 years, resulting in excessive N content of litter and soils. In the reviewed study by Johnson et al., soil and stream water chemistry were monitored in chaparral-dominated watersheds with experimental manipulations conducted to test whether prescribed fire could mitigate N accumulation in chaparral soils. Because 80% of the chaparral ecosystem N is stored belowground, prescribed fire did not mitigate high soil N nor stream water nitrate effluxes over time. The authors suggested that prescribed fire alone could not reduce excess N in the chaparral unless atmospheric inputs were also decreased. They hypothesized that prescribed fire in N-saturated mixed-conifer forests may be more effective because more of ecosystem N is aboveground and combusted during fires. This hypothesis was tested independently in the chapter by Gimeno et al. using a simulation model.

Gimeno et al. (this volume) performed simulations to test the effectiveness of prescribed burns in mixed-conifer forests on reducing stream water nitrate and soil N emissions within the context of low to high N loading using a biogeochemical model (DAYCENT; Parton et al., 1998). Different N loads (5–70 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$) were applied to drive different ecosystem allocation of carbon and N, especially to fuel loading and its N content, and allowed to equilibrate over 100 years. Then 0–100% reductions in atmospheric N deposition were imposed for the following 200 years of simulations, with or without concurrent prescribed fires at three intervals (15, 30, and 60 years), assuming that two 100-year wildfires would occur regardless of prescribed fire. The simulation produced N losses in stream water and as trace gas emissions from soil, total fuel load, N content in fuel load, and air pollution emissions (linking the biogeochemical model to the First Order Fire Effects Model [FOFEM]), which simulates pollution emissions from wildfire events. Stream water nitrate is an excellent indicator of ecosystem N saturation (Fenn et al., 2003), with critical loads already identified for this ecosystem. Simulations were validated using field data of stream water nitrate in catchments of different N loading.

The simulated N deposition increased fuel mass by 120% between the lowest (5 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$) and the highest (70 $\mathrm{ha^{-1}\,yr^{-1}}$) deposition rate. The effect of the highest N deposition was mitigated to the lowest N deposition level by applying prescribed fire at either 15- or 30-year intervals. Nitrogen content in litter increased with simulated N deposition, but allocation of N to foliage did not increase past the N deposition rate of 25 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$, nor were prescribed fire treatments effective in reducing foliar N levels at N deposition rates of the same value.

In Gimeno et al. (this volume) simulations, wildfire emissions increased with N deposition, because of its effect on total litter produced.

Atmospheric emissions from wildfires were 470% greater for the highest versus the lowest N deposition loading scenario, although NO_x emissions were as much as 210% higher at the highest N deposition level. Simulated N deposition had a significant effect on stream water nitrate export when N deposition was 25 kg ha^{-1} yr^{-1} or greater. If N deposition were reduced by 100%, nitrate export returned to background levels in eight years, after approximately 50 years with 50% reduced N deposition and prescribed fire. Prescribed fire alone did not reduce stream water nitrate to background levels, possibly because prescribed fire itself increases total ecosystem nitrate losses, especially in the short term, and because fire does not remove the large organic N stores in soil that provide a large pool of N to be mineralized and nitrified (see Johnson et al., this volume). However, the combined application of prescribed fire (at 15-year return rates), and a 75% reduction in N deposition, permitted ecosystem nitrate exposure to reach near background levels. Reducing N deposition by 50% in combination with prescribed fire also caused major decreases in stream water N export, although not to background levels. Prescribed fire and stricter air quality regulations also reduced nitrate export after sporadic wildfire.

Using the biogeochemical model, soil N emissions increased with increased N deposition, which was greater than that N lost to stream water. Because Johnson et al. (this volume) estimations "set" soil emissions and tracked soil nitrate outputs, the results are not comparable. In Gimeno et al. simulations, soil N emissions were high at equilibrium, and could not be controlled with prescribed fire (15-year return) in the 25 kg N ha^{-1} yr^{-1} atmospheric N deposition scenario unless deposition were eliminated. Under these conditions, background levels of soil N emissions were reached in about 80 years.

In their simulations, significant reductions (50–100%) in anthropogenic N deposition were required in combination with short rotation prescribed fire (15–30 years) to return nitrate leaching or soil N emissions to near baseline levels, or at least to levels below those associated with critical N loading. Although complete reductions in N deposition are unlikely to occur in order to improve water quality and restore forest health, the simulations presented in Gimeno et al. highlight the potential for prescribed fire in mitigating ecosystem N losses after wildfire. Their simulations elucidate the important interrelationships among N deposition, fuel loading and litter N content, nitrate losses to stream water, and soil N emissions. Even a 25–50% reduction in N deposition in combination with prescribed fire of any interval resulted in major progress towards reducing chronic N losses from mixed-conifer forests.

Prescribed fire has rarely been permitted in inhabited wildlands, due to the narrow band of time annually when such fires can be set safely and air pollution effects on human health. However, because it is clear that much of the N loading is found in forest floor litter, mechanical removal of litter could mitigate both total nitrate losses and soil N emissions when a wildfire does occur. Mechanical removal combined with a reduction in understory biomass, implemented in a noncontiguous mosaic, may help slow and redirect wildfire in forests. In chaparral ecosystems, reestablishment of mosaics of different aged stands as fire breaks, whether by mechanical or prescribed burns, would do much to mitigate fire risk to the many homes and structures in close proximity to wildlands, although this is unlikely to mitigate N saturation unless N deposition is also greatly reduced.

The chapters in Section III of this book provide insight into potential interactive perturbation of climate change (drought, air pollution) and fire in western North American forest ecosystems. There are several reasons why these perturbations are important. A recent increase in fire frequency and intensity is of academic interest because of the effects such emissions may have as a direct, positive feedback to global warming. At the regional scale, a change in climate and fire regimes will disrupt ecosystem structure and processes and reduce the capacity of current ecosystems to resist other, lesser perturbations (invasive species, insect epidemics), but different forest structure and processes will emerge. Anticipating that ecosystems are likely to change, as well as the magnitude and location of change, will help us plan for it. Conceptual models of how ecosystems might change are the first step towards planning for change.

Perturbations to forest health reduce the quantity and quality of ecosystem processes. That fire suppression reduces forest health through increased stand density is not a new phenomenon, but that fire suppression disrupts maintenance of a mosaic of stand age classes in the landscape, the characteristic that could reduce the risk of extensive and intensive wildfire spread, adjusts our perception of the "cost" of fire suppression. Likewise, that air pollution could impair forest health is not a new idea, but that high air pollution *instigates* increased canopy transpiration, exacerbates tree drought stress, and increases tree susceptibility to insect attack and success adjusts our perception of the "cost" of air quality regulation. In addition, we know that fire causes short-term reductions in air and water quality, but that frequent prescribed fire, at return rates known to improve attributes of forest health, increases the total nitrate lost from the ecosystem relative to a single, large wildfire every 100 years questions our perceptions of the benefits of prescription. Last, because the current high levels of atmospheric N inputs into the landscapes surrounding large urban areas cannot be mitigated by prescribed fire alone, better air quality regulations must be implemented along with societal changes in energy use. However, not all mitigation strategies have been investigated. Implied in these assessments is that mechanical removal and disposal (or green use) of excess biomass, especially the N-enriched litter in forests affected by high air pollution, is untenable at the landscape level. Other mitigative strategies need to be incorporated into biogeochemical models to assess their relative effects on air and water quality, and on subsequent risk for the occurrence of catastrophic wildfire. Although biogeochemical and economic models have been linked to understand global responses to climate change, there is a pressing need to link these models to help solve regional dilemmas as well.

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