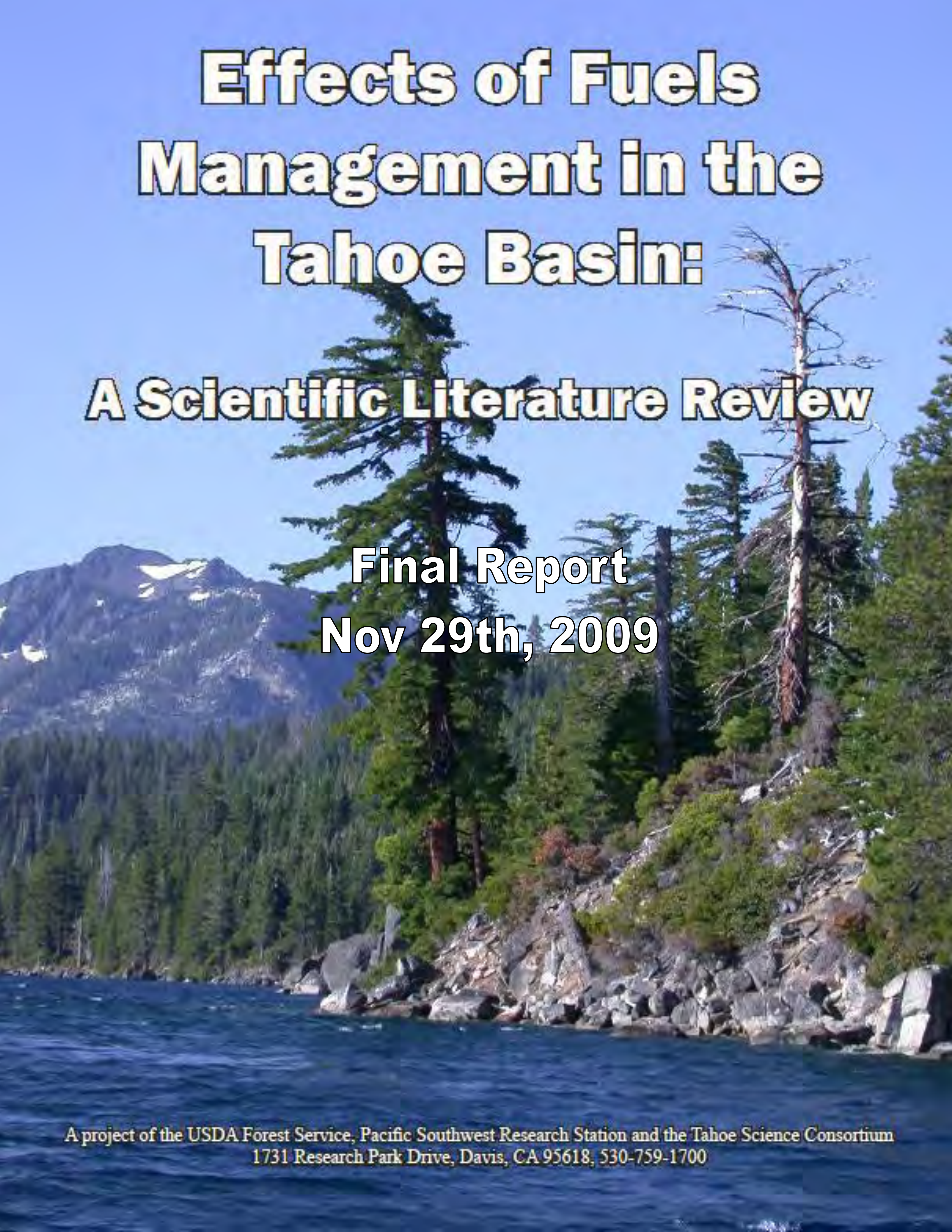
Effects of Fuels Management in the Tahoe Basin:

A Scientific Literature Review



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1731 Research Park Drive, Davis, CA 95618, 530-759-1700

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Executive Summary:

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Introduction

Decision makers and the public in the Tahoe basin are engaged in important debates regarding the tradeoffs between reducing the risk of severe wildfire, protecting and restoring ecological values, and wisely using economic resources. Efforts to reduce fuel hazards and restore natural ecological processes involve risks to resource values, but inaction carries the risk of severe wildfire in highly altered forest stands. Scientific investigation has an important role to play in helping to evaluate the tradeoffs involved in fuels management. To address this issue, the Pacific Southwest Research Station commissioned literature reviews on the effects of fuels treatments in the Tahoe basin on air quality, water quality, soils, vegetation, and wildlife. The resulting papers and an associated on-line searchable database of publications address previous calls to make scientific information more available to guide decisions. The review papers considered the general effects of prescribed burning and mechanical harvest, as well as some specific treatment methods being applied or considered in the basin, including hand thinning, cut-to-length (CTL) treatment, whole tree removal (WTR), broadcast or understory burning, pile burning, chipping and mastication. Appendix A identifies many of the current research projects in the basin that will help to answer key questions about treatment effects.

Setting for Fuel Treatments

Distinctive Ecological Factors Affecting Fuel Treatments in the Basin

- The proximity of the wildland-urban interface to an ultra-oligotrophic lake compounds the inherent complexity of evaluating the effects of land management activities. The basin's steep bowl-shape traps air and water pollutants and renders watersheds more vulnerable to soil erosion and severe wildfire behavior.
- Forest conditions have been dramatically altered by past harvests, subsequent regrowth, and reduction of natural fires. The forests closest to the lake and urban areas are also the most highly altered.
- The lake's exceptional clarity has generated distinctive concerns about loading of very fine inorganic particles (clay and very small silt particles) and nutrients. More fine-textured, volcanic soils pose greater concerns than granitic soils.
- An objective of minimizing loading of fine particulates and nutrients to the lake has potential to conflict with efforts to reestablish a more natural fire regime, since treatments can mobilize fine sediments and nutrients. However, reestablishing forest conditions and a fire regime within the range of historic variability should, over the long-term, reduce influxes of sediment and nutrients that can result from severe wildfires, as well as nutrient release from forest floors.
- Because of weather constraints and limited treatment options, the operating season for forest treatments is relatively short, and opportunities for over-the-snow harvest are limited to small-scale, intermittent operations. Opportunities for such logging are particularly limited on the east side of the basin where there is less snow and poorer road access.

Institutional Factors Affecting Fuel Treatments in the Basin

- Institutions in the basin appear to support both wildfire hazard reduction and ecological restoration, but tensions between are particularly prominent in policies regarding treatment of steep slopes and wetland areas referred to as Stream Environment Zones (SEZs). Specialized practices and equipment requirements have been required for treatments in these sensitive areas, as well as to conduct treatments in urbanized areas.

- Typical costs for mechanical fuel treatments in the basin are several times higher than for areas elsewhere in the Western U.S., reflecting various factors including relatively less infrastructure for removing and processes forest products. However, benefits of fuels treatments in terms of avoided ecological impacts and property losses may counterbalance the exceptionally high treatment costs.
- Prescribed burning following hand treatments has been applied on steep slopes where mechanical treatment is not feasible due to mechanical limitations or concerns about soil disturbance by heavy equipment. While hand crews have been a preferred treatment in sensitive areas such as steep slopes and SEZs, this treatment is restricted to small diameter trees due to issues of safety and logistics. Hand treatment also creates large numbers of piles that have to cure for long periods before being burned. A recent study of the Angora fire attributed some areas of high severity burns to an insufficient level of fuel reduction, which may have resulted from limitations on mechanical treatments on steep slopes. Because of these concerns, agencies are interested in other equipment options that could improve access to remote areas, lower treatment costs, allow for greater reduction in fuels, and reduce the backlog of burn piles. There is a knowledge gap concerning the use of mechanical equipment on steep slopes in the basin.

Effects of Treatments on Resource Values

- Wildfires in areas with high fuel loads can burn at moderate to high severities, which can increase nutrient availability, expose bare soils, form persistent hydrophobic soil layers, and export sediment and nutrients downstream and into the air, which in turn threaten lake clarity and human health.
- Fuel reduction treatments, particularly mechanical treatments, can reduce crown fire potential by reducing ladder fuels. Treatments can also reduce potential wildfire severity by reducing surface fuels. If treatments result in high amounts of surface fuels that are not followed by removal or burning, subsequent wildfires could result in more severe impacts to soils and vegetation.
- There is a particular lack of knowledge about the effects of fire in SEZs within the basin. Better understanding of the thresholds at which fire enters or is retarded by SEZ condition is needed to predict fire behavior and effects in riparian areas. The natural fire regime in many riparian areas is not well-established, although there is ongoing research in the Tahoe Basin to address that knowledge gap (see *Restoration and fuel treatment of riparian forests* in Appendix A).
- There is a need to assess the optimal amount of organic matter present to balance the risks of erosion and formation of water repellent layers. Research is presently underway to determine optimal targets for reducing fire hazard while minimizing erosion rates (see *Balancing fuel reduction, soil exposure, and erosion potential* and *Integrated decision support for cost effective fuel treatments under multiple resource goals* in Appendix A).
- The WEPP model, which estimates both erosion and deposition on hillslopes, requires parameterization and validation for the Tahoe Basin; such efforts are currently in progress (see *Sources and transport of fine sediment (WEPP modeling)* and *Predicting nutrient and sediment loading from prescribed fire using WEPP* in Appendix A).

Prescribed Broadcast and Understory Burning

The papers recommend expanded use of prescribed fire for purposes of ecological restoration and fuel reduction, particularly in sensitive areas such as steep slopes and SEZs.

Soil and Water Quality

- Prescribed burns are typically designed to burn at low severity. Low temperature prescribed fire is not likely to result in significant nutrient or sediment runoff over unburned conditions. Effects of prescribed fire on soil structure are likely to be minimal given the low temperatures typically achieved. Prescribed fire can affect soil biota and chemistry but it is not likely that effects are detrimental to ecosystem functioning. Water repellency produced by low or moderate severity fires is usually less persistent than that produced by high severity fires. Promoting patchy burns should reduce potential for runoff by avoiding creation of continuous hydrophobic layers.
- There is a knowledge gap regarding nutrient release and hydrophobicity in undisturbed soils versus soils subjected to prescribed fire practices in the basin. Research projects are currently underway to investigate these soil processes (see *Nutrient emissions from prescribed fire* in Appendix A).

Vegetation and Wildlife Habitat

- Because prescribed fire typically kills fewer large trees than thinning, it has more limited effects on fuel loads, transmittance of light to the understory, and key attributes of wildlife habitat. However, prescribed fire may result in a more substantial and longer-lasting reduction in cover of some shrubs than does thinning.
- Prescribed fire tends to have neutral or positive effects on herbaceous cover, growth of shade-intolerant species and species that depend on fire to germinate, early seral and ground-associated bird species and total small mammal biomass.
- Prescribed fire reduces density of larger diameter snags and also results in a substantial reduction (45 to 80%) in volume of down logs. Reduction of large snags and logs by prescribed fire could impact species that depend on those legacy forest features, such as woodpeckers. Maintaining unburned areas near burned areas or creating a burn mosaic is likely to help maintain forest legacy elements and reduce impacts to amphibian and reptile populations.

Air Quality

- Understory burns typically generate high levels of particulates close to the ground that persist locally, particularly during the fall season. Prescribed burns in the late spring and early summer could generate relatively less air quality problems due to increased ventilation during those periods; however, the higher risk of fire spread associated with spring burning needs to be considered. Burning during dry conditions and timing burns to occur before anticipated rains can mitigate smoke emissions from prescribed burning.

Pile Burning

- Burning of slash piles raises more concerns about potential impacts, since piles can generate high temperatures that locally impact soil chemical and physical properties (including causing hydrophobicity) and can impact soil biota (including seeds, fauna, and mycorrhizae). If undesirable impacts occur, they can be mitigated through various amendments and treatments to promote regrowth of native vegetation.

- Knowledge gaps include the effects of pile burning on soils in SEZs and the effects of pile burning on water quality at a watershed scale. However, there are research efforts underway to evaluate the effects of different size piles on soils and water quality in SEZs and non-SEZ areas (see *Effects of pile burning in the Tahoe basin on soil and water quality* and *Predicting nutrient and sediment loading from prescribed fire using WEPP* in Appendix A).
- Prior to burning, fresh piles can attract bark beetles during the late spring to mid-summer when beetles are active. Methods to reduce threats from bark beetles include generating slash materials during the late summer through mid-winter, covering slash piles with plastic, locating slash in open areas away from trees, and promoting desiccation of slash by spreading it in sunny areas.
- Because piles can burn at high intensity, they tend to generate less local smoke than understory burns but also can loft particulates higher, creating regional impacts. Methods to mitigate smoke emissions include burning during dry conditions, covering piles with a tarp, timing burns to occur before anticipated rains, and burning under a tree canopy.
- More extensive data on smoke emissions from burning (including vertical data, particle size, and chemical composition at sites across the basin) is needed to refine and validate the LTAM model so that it can generate accurate predictions of the effects of wildfire and prescribed burning.

Mechanical Harvest

Soil and Water Quality

- Studies and monitoring reports indicate that mechanical treatments of fuels in the Tahoe Basin are not causing significant impacts to soil and water quality. Studies of mastication equipment have concluded that soil compaction is well distributed so as to prevent detrimental effects.
- Mechanical thinning is likely to have little net impact on soil biota. Mechanical harvesting can impact soil biota though changes in soil physical properties but it is unclear if changes in soil biota are detrimental.
- Effects of mechanical harvest on bulk density, compaction and soil strength are likely to be minimal but may occur on skid trails and landing areas that receive heavy traffic, particularly in finer-textured and wet soils.
- Roads used for fuel treatments may significantly contribute to erosion, depending on their location, condition, and hydrologic connectivity to streams; however, road BMPs can be effective in preventing transport of road pollutants to aquatic environments.
- Operating mechanical equipment on slash materials can reduce the impact of traffic on bulk density, however, leaving these materials can affect fire hazard and removing them can be costly.
- Conducting mechanical harvests when soils are dry will limit the risk of compaction. CTL and mastication equipment can be used when soil moisture is sufficiently low and infiltration rates are sufficiently high.
- In riparian areas, high moisture levels could increase the impact of mechanical treatments on physical properties. If soils are relatively dry and safeguards are carefully followed,

mechanical equipment can operate in SEZs without causing detrimental impacts to soil and water quality. Further research is needed to determine threshold values of soil moisture for operation in SEZs.

Vegetation and Wildlife Habitat

- Thinning has variable effects on understory herb and shrub richness and cover, depending on initial community composition. Mechanical fuels treatments in general will:
    - increase regeneration opportunities for many canopy tree species;
    - stimulate short-lived plants such as herbaceous forbs and grasses;
    - increase opportunities for invasive plant species;
    - increase vigor and abundance of leguminous species;
    - negatively affect shrubs in the short term, although many shrubs have the ability to resprout, affording them resilience to disturbance following an initial decline, and;
    - cause decline of saprophytes (non-photosynthesizing plants).
- Thinning alone tends to have a neutral or positive effect on coarse woody debris volume and cover. However, thinning may reduce density of larger diameter snags and downed logs, which are used by wildlife.
- Leaving slash materials on the ground may adversely affect plant regeneration depending on the size and depth of the resulting materials.

Effects of Combined Prescribed Burning and Thinning

- The combination of prescribed burning and thinning is likely to be more effective than either treatment alone in reducing fuel loads and restoring ecological functions. The combination is likely to have a minimal impact on soil chemical, physical and biological properties, and it may enhance understory response due to increased, locally patchy consumption of duff layers.
- Species that are likely to be particularly sensitive to changes resulting from fuels reduction treatments include bird species associated with mature forests, northern flying squirrels, and mammalian carnivores such as the American marten. Northern flying squirrels are particularly vulnerable to habitat changes occurring as a result of treatment, given their dependence on old forest conditions, high canopy closure and truffles, since prescribed fire and thinning can reduce the frequency and diversity of that food source even decades after treatment.
- Studies of effects on wildlife are largely limited to a few years before and after treatment or retrospective studies without pre-treatment data, but studies of longer-term responses and cumulative effects of treatments across landscapes over time are lacking. Studies also need to consider the interactive effects of forest management and urbanization. Such research could help to develop tools to predict changes in habitat, populations, and communities caused by fuels management activities. Experimental studies of wildlife responses to fuels treatments are in progress within the basin (see *Effectiveness of upland fuel reduction treatments* and *Silvicultural prescriptions to restore forest health* in Appendix A).
- Another knowledge gap is the desirable distribution and abundance of various vegetative conditions and structural features including large logs, large snags, and decadent trees

and techniques for avoiding losses of these features during both thinning and prescribed burning treatments.

Tradeoffs between Reducing Erosion/Emissions and Reducing Fire Risk

- There are important tradeoffs between erosion risk and fire risk because of their relationships to harvest residues and bare soils. Potential for runoff and erosion generally increases with disturbance to the surface organic material or litter, which protects the mineral soil below it. However, soil disturbance and exposure to light may be needed to meet vegetation objectives in particular areas, such as recruitment of pines and understory plants. In addition, while cover by harvest residues may limit erosion potential, it may increase the risk of higher burn severity.
- When followed by burning, whole tree removal and cut-to-length harvest may result in similar total reductions in forest fuels. If residual materials following CTL treatment are left on-site, then subsequent burns would result in greater emissions. Collecting and removing materials leftover from CTL treatments imposes costs. The LTBMU reports that it has sometimes removed the residual materials, but more typically has followed CTL treatment by mastication.
- Removal of fine fuels could potentially decrease nitrogen runoff by reducing organic matter pools. However, current nitrogen stocks are higher than in historical forests so a loss of nitrogen capital in itself may not be detrimental to ecosystem functioning. Well-developed organic horizons in fire-suppressed forests may be contributing significant amounts of nutrients to Lake Tahoe.
- Biomass removal and off-site disposal simplifies subsequent prescribed burning and helps to reduce air quality impacts. However, it may forgo ecological benefits associated with on-site burning, such as potential for increased nutrient availability and promotion of shade-intolerant and fire-dependent plants.
- Several research projects are underway to better quantify the tradeoffs involved in removing or burning fine fuels, but more work will be needed to examine tradeoffs in a variety of ecological contexts. Additional research is needed to refine fuel loading models for masticated and chipped fuel beds.

Conclusion

- The review papers collectively suggest that current treatment practices in the basin can achieve fuel reduction and ecological restoration goals without negatively impacting important values, while recognizing the need to balance the costs and benefits associated with leaving, removing, or burning forest fuels. There are numerous research efforts underway that will help management practices to continue to adapt as the problem of fuels reduction evolves. However, there remain important issues to be examined through carefully monitored treatments and experiments, particularly concerning stream environment zones, mechanical treatments on steep slopes, treatment effects on wildlife, and burning effects on air quality.

Introduction to the

Effects of Fuels Management in the Tahoe Basin

Jonathan W. Long[1]

[1] Sierra Nevada Research Center, Pacific Southwest Research Station, U.S. Forest Service, 291 Country Club Blvd, Incline Village, NV 89451, email: jwlong@fs.fed.us, 775-881-7560 x. 7482 (ph)

Abstract

Decision makers and the public in the Tahoe basin are engaged in important debates regarding the tradeoffs between reducing the risk of severe wildfire, protecting and restoring ecological values, and wisely using economic resources. Efforts to reduce fuel hazards and restore natural ecological processes involve risks to resource values, but inaction carries the risk of severe wildfire in highly altered forest stands. Scientific investigation has an important role to play in helping to evaluate the tradeoffs involved in fuel treatments. The Pacific Southwest Research Station commissioned literature reviews on the effects of fuels treatments in the Tahoe basin on air quality, water quality, soils, vegetation, and wildlife. This paper prefaces those reviews by outlining policy issues regarding fuel management in the Tahoe basin, explaining how distinctive qualities of the basin affect fuel management, summarizing the main options being considered to treat the basin's forests, and reviewing past efforts to assess the science of fuel reduction treatments in the basin. The synthesis papers and an associated on-line searchable database of publications address previous calls to make scientific information more available to guide decisions. These products should inform the adaptive decision-making and learning systems that guide fuel reduction while protecting resource values.

Keywords: fuels management; Lake Tahoe; synthesis; treatment effects; adaptive management

1 Introduction

The management of forests and fire in the Tahoe basin has been a subject of policy debates and investigations for well over a century (Lindstrom et al., 2000). However, the Angora wildfire of 2007, which burned over 200 houses and 1210 ha (3000 acres) of forest, (USDA Forest Service et al., 2007), provided a dramatic reminder of the importance of reducing wildfire hazards in an area with an extensive wildland-urban interface. The governors of Nevada and

California jointly convened a Tahoe Fire Commission after the Angora fire to review forest management policies in the basin, with a goal of recommending –improvements and changes that will reduce the Tahoe Basin's wildfire vulnerability while protecting the environment." Fuel reduction treatments are important for protecting life and property as well as for restoring and conserving forest ecosystems. However, fuels treatments have potential to impact water quality, soils, wildlife habitat, and air quality, all of which have special standards and regulations set to protect them within the basin (Patten, 2004; Cobourn, 2006).

Distinctive qualities of the basin, such as the proximity of its wildland-urban interface to an ultra-oligotrophic lake, compound the inherent complexity of evaluating the effects of land management activities. The basin has been described as a complex environmental commons that is defined by –a complex organizational network responsible for rule-making", –a high level of diversity of perceptions of the value and appropriate use of the resource being managed," and –multiple, interrelated resources requiring intervention in order to address the problems facing a principle resource of interest" (Kauneckis and Imperial 2007, p. 508). Many researchers agree that forest fuel reduction in general fits the description of a –wicked problem," in that people tend to disagree on both the problem and proposed solutions (Salwasser, 2004; Carroll et al., 2007). Proposed solutions do not yield a stable solution, but instead give rise to new problems, particularly as social preferences shift. For example, burning logging slash in piles has been a preferred method for cost-effectively reducing forest fuels, but the Fire Commission Report (p. 99) suggested that that preference needs to shift as concerns rise about greenhouse gases and other emissions.

Science can contribute to formulating solutions to wicked problems by elucidating the likely consequences of management alternatives (Salwasser, 2004). In the fall of 2007, at the request of the Lake Tahoe Basin Management Unit (LTBMU) and in collaboration with the Tahoe Science Consortium (TSC), the Pacific Southwest Research Station initiated a literature review on effects of fuels treatments, with particular focus on air quality, water quality, soils, vegetation, and wildlife. The review summarizes what has been learned from studies and monitoring within the basin, and from studies that are transferable to the basin based on comparable ecological conditions. This introduction describes the basic issues regarding fuel management in the Tahoe basin, explains how distinctive qualities of the basin affect these issues, summarizes the main treatment options being considered to treat the basin's forests and some of their associated tradeoffs, and reviews past efforts that have assessed the science of fuel reduction treatments in the basin.

1.1 Special Conditions in the Tahoe Basin

The surface of Lake Tahoe lies at an average elevation of 1897 m (6225 ft), straddling the border between California and Nevada within the Sierra Nevada mountain range. The upland areas of the Tahoe basin are covered by coniferous forests, montane chaparral, meadows, deciduous woodlands, and barren areas (Manley et al., 2000). The lake has remarkably high clarity and low fertility due to a combination of exceptional depth (501 m or 1645 ft), an unusually low ratio of watershed area (1300 km^2 or 500 mi^2) to lake area (497 km^2 or 192 mi^2), and predominantly granitic geology (Gertler et al., 2006). However, eutrophication due to increased nutrient inputs in combination with increased fine sediment loads have caused the lake clarity to decrease by one third, as measured by a decline in Secchi depth from 31 m (102 ft) in 1968 to 21 m (69 ft) in 2005 (Swift et al., 2006).

Although bedrock in the Tahoe basin is composed chiefly of granitic rock (typically granodiorite), volcanic rocks (typically andesitic lahar) also occur in many areas (USDA Natural

Resources Conservation Service, 2007). The volcanic rocks tend to weather into finer, phosphorus-laden particles, which pose a greater risk to lake clarity as they are eroded. Much of the basin contains steeply sloped terrain. The combination of steep slopes and shallow, erodible soils results in relatively high erosion hazards over large areas of the basin (Shelton, 1992: USDA Natural Resources Conservation Service, 2007). Due to a combination of geology and land use, the streams contributing the most fine sediment and phosphorus are located on the California side of the lake (Hatch, 1999; Simon, 2008).

The Tahoe basin is a distinctive environment for addressing forest fuel management, in part because it is deeply bowl-shaped. The steep elevation and moisture gradients in the basin contribute to a high diversity of animals and plants but may also impede movement of these populations in response to changes in their habitats (Manley et al., 2000). The basin forms a natural sink, as local air pollutants are frequently trapped by inversions, and wind and water carry very fine inorganic and organic particles into the huge lake, where they remain suspended for years and reduce lake clarity (Swift et al., 2006). The smallest particles are among the most important concerns because of their long residence time, their effects on clarity, and their capacity to transport phosphorus, a key nutrient controlling algal growth. As a result, water quality management in Lake Tahoe focuses on loading of clay and very small silt particles. By contrast, watershed management in many other parts of the Western U.S. often focuses on larger silt and sand particles and their effects on in-stream habitat for fish (e.g., Reid, 1998).

Other characteristics of the basin complicate efforts to reduce forest fuel loads. Development around the lake has created large areas of wildland-urban interface in which there is high potential for human health effects from fire. The proximity of forest fuels to residences, infrastructure and other property increases the risks associated with prescribed burning.

Fluctuating temperatures and snow cover during the winter season at Tahoe complicate efforts to conduct winter mechanical treatment, which requires frozen soils, skid trails, and roads (Douglas, 2002). Consequently, opportunities for over-the-snow operations in the basin are typically limited to areas accessed by paved or graveled roads and having colder and more stable microclimates (which are more common on the west shore of the lake than on the Nevada side); therefore, such harvest operations are likely to be small and intermittent, which demands flexibility and patience from operators (T. Sasaki, California State Parks, and R. Shaw, Nevada Division of Forestry, pers. communications, 3/18/2009).

Both natural and social factors result in relatively high costs for fuel treatments in the basin. Costs for mechanical treatments are estimated at $2470-$8660/ha ($1000-$3500/acre), but one contractor estimated that costs could exceed $24,700/ha ($10,000/acre) in some urban lots (USDA Forest Service et al., 2007). Elsewhere in the Western U.S., typical costs range from $250-$1850/ha ($100-$750/acre) for mechanical cutting, piling, and burning (Rummer et al., 2003). A current lack of merchantable product further reduces opportunities for offsetting costs (Dave Fournier, LTBMU, pers. communication 8/13/2009). The current structure of Tahoe forests has been an important factor, as treatments targeting small diameter trees typically cost more than ones that can recoup revenues from large sawlogs (Hartsough, 2003). A recent panel examining vegetation treatments in the basin (Miller et al., 2008**)** reported several other explanations for these high costs, which included:

- specialized practices and equipment requirements for treatments in urban lots and sensitive SEZ habitats (pp. 21-22);
- relatively short (often 3-4 month) field season (p. 22);
- lack of local mills and other processing facilities (p. 22);

- high administrative costs (p. 23); and
- limited access via road networks (p. 23)

The basin faces another special challenge in the form of high numbers of tourists, outdoor recreationists, and second-home owners that visit or reside in forested areas (Imperial and Kauneckis, 2003). Treatment in areas of high development or use typically imposes higher costs as a result of interactions with people and mitigation to avoid conflicts (Dave Fournier, LTBMU, pers. communication 8/13/2009). The large numbers of part-time residents in the basin may diminish support for fuel treatments, since as such residents can be less motivated to reduce wildfire hazard than long-term, full-time residents (Collins, 2009). However, with property values exceeding $1.5 million/ha ($600,000/acre), the benefits of fuels treatments in terms of avoided property losses serve to counterbalance the exceptionally high treatment costs (USDA Forest Service et al., 2007, p. 29). Therefore, while the issues affecting fuel management at Lake Tahoe are not unique, tensions between competing values are particularly prominent in land use decisions (Forney et al., 2001).

Forest management in the basin is also complicated by the array of institutions that have responsibility for land management and regulation, including parallel sets of California and Nevada agencies. As a result, entities wanting to treat forests have to navigate a complex regulatory environment, including standards that often vary across political boundaries, despite the presence of the transboundary Tahoe Regional Planning Agency (TRPA). However, particularly since the Angora wildfire, regulatory agencies have taken steps to streamline permitting procedures.

1.2 Departures from Historical Conditions

Historical data collected from remnant stumps, photographs, and surveys provide evidence that the mixed conifer forests in the Tahoe basin, like those in the rest of the Sierra Nevada, were shaped by frequent fires prior to Euro-American settlement (Manley et al., 2000). During pre-settlement times, the low elevation montane forests (<2133 m or 7000 ft) were more open and were dominated by species adapted to frequent fire, such as Jeffrey pine, ponderosa pine, and sugar pine; however, species that tolerated more shade, such as white fir and incense cedar, were also a component of these forests (Manley et al., 2000; Taylor, 2004). A study of Jeffrey pine-white fir from stands on the east shore found a mean fire return interval of 11.4 years for the period from 1450 to 1850, with no fires recorded after 1871 (Taylor, 2004). Another study of old-growth mixed conifer stands in the General Creek watershed on the west shore found that fires burned with low to moderate severity on a 9-17 year average until about 1880 (Taylor and Beaty, 2007). Smoke levels from such fires likely exceeded modern standards during the summer and fall (Stephens et al., 2007; Lindstrom et al., 2000).

Unregulated timber harvest during the 19th century Comstock mining era was followed by extensive growth of even-aged and densely-stocked stands that included less fire-tolerant species (Manley et al., 2000; Taylor, 2004). As a consequence of the fire exclusion of the 20th century, thick layers of pine needles, duff, and dead biomass have accumulated, and shrubs and small trees have grown under the canopy of larger trees, increasing the potential for stand-replacing crown fires. By the late 20th century, second growth conifer stands constituted about 95% of the total area of forest in the basin (Lindstrom et al., 2000) and composition had shifted towards more shade-tolerant species (Manley et al., 2000).

Tree densities have increased greatly in the basin's forests as large trees have been replaced with many more small trees. Within the lower montane zone, a recent study of Jeffrey pine-white fir stands on the east shore reported an increase from a mean of 68 trees/ha (28 trees/acre) prior to 1850 to 343 trees/ha (139 trees/acre) (Taylor et al., 2006). In the General Creek watershed, on the more productive west shore, a study of old-growth mixed conifer stands reported tree densities averaging 616 trees/ha (249 trees/acre) (Beaty and Taylor, 2007). In higher elevation montane forests (2133-2590 m, 7000-8500 ft), red fir and western white pine are dominant, but white fir in particular has increased in density (Manley et al., 2000; Taylor, 2004; Scholl and Taylor, 2006). Within one east shore stand, tree density has increased from 162 to 538 trees/ha (66 to 218 trees/acre) since pre-settlement times (Taylor et al., 2006). Lodgepole pine, a pioneer species easily killed by fire, has invaded moist meadow areas and second-growth forests in upper montane areas (Taylor, 2004). That species has also become 3-4 times denser in stands where it was dominant in pre-settlement times (Taylor, 2006). Pre-Comstock high-elevation (>2590 m or 8000 ft) subalpine forests experienced wildfire much more infrequently than low-elevation Jeffrey pine-white fir forests and as a result, these stands have been least altered by historical changes in fire regime (Manley et al., 2000).

These changes in structure and composition, combined with extensive tree mortality from insect outbreaks and droughts associated with a changing climate, have increased the potential for large or severe wildfires that can destroy property and cause major environmental impacts (Manley et al., 2000). This potential corresponds to an increased occurrence of large, severe forest fires across the western U.S. that has been linked to increased fuel loading due to fire suppression and historical forest management, as well as to climate change (Westerling et al., 2006). Another contributing factor is human-caused ignitions, which often cause fires that escape and burn under dry, windy, and hot conditions; as a result, human-set fires have become the source of most of the areas burned by wildland fire in the Tahoe basin (Manley et al., 2000).

1.3 Goals of Fuel Treatments and Ecological Restoration

Wildfire risk reduction and ecological restoration are regarded as mutually compatible, if not inseparable, goals in guiding language of the Healthy Forests Restoration Act and other policy statements (e.g., Bosworth, 2006). A Community Wildfire Protection Plan prepared by Steve Holl Consulting and Wildland Rx for the Tahoe basin affirmed the goal of “protect[-ing] values at risk by reducing fuel hazards and restore ecosystem health by mimicking the results of historic disturbance regimes using cost effective vegetation treatments” (2007, p. 3-2). The recently adopted multi-agency strategy for fuel reduction in the basin (“Strategy”) states that achieving the desired condition “means reducing vegetation in proposed project areas toward historic levels (Low [I] condition class) resulting in fire behavior characteristics associated with surface fires,” (USDA Forest Service et al., 2007, p. 39). The California-Nevada Tahoe Basin Fire Commission (2008, p. 7) shared that sentiment in articulating the need for “(a)ll agencies to make restoration of the basin’s forests to a more natural and fire-resistant condition as [sic] a common and primary goal”. A pre-eminent environmental group in the basin has expressed support for this goal, expressing “hope that the forest fuels can be reduced to the point at which controlled low-intensity understory burns can be set to mimic the historic fire regime” (League to Save Lake Tahoe, 2009). Therefore, among key stakeholders in the Tahoe basin, wildfire hazard reduction and ecological restoration appear aligned at the level of general principles.

Proponents of ecological restoration also agree on the importance of reintroducing fire, reducing density and basal area of smaller diameter trees, and establishing a more random distribution of remaining trees (Taylor, 2004; North et al., 2007). A recommended strategy is to “thin from below,” by removing smaller trees from the understory while retaining many large overstory trees (Stephens and Moghaddas, 2005b; North et al., 2007). The 10 year basin Strategy and its affiliated Community Wildfire Protection Plans emphasize the thin from below prescription to reduce accumulations of fuels that are beyond the range of natural variability. The Strategy outlines a plan to treat 27,500 ha high-condition-class acres (68,000 acres) over the next 10 years, including 19,800 ha (49,000 acres) of first-entry vegetative fuel treatments and 7700 ha (19,000 acres) of maintenance treatments. The areas to be treated encompass a large percentage of the 19,300 ha (47,800 acres) of lower montane forests that surround the lake. While these treatments are extensive, they are not intended to alter forest structure and composition to the degree needed to restore the mosaic of seral stages that existed prior to the extensive regrowth after the Comstock era logging (D. Fournier, pers. communication, 1-05-2009).

1.4 Key Issues

Despite apparent congruence at the level of overall goals and strategies, tensions often emerge when trying to achieve multiple objectives on the ground. Given this potential, basin managers want to know whether the effects of fuels treatment on resources are at an acceptable level given potential trade-offs. Accordingly, the LTBMU, which has primary management responsibilities over 80% of forests within the basin (Bosworth, 2006), requested a review of the effects of various treatments on different resource values, including water quality, soils, air quality, and sensitive wildlife populations (Table 1). The wide array of potential ecological effects makes it difficult to conduct such comprehensive analyses (Mason et al., 2006). Moreover, evaluation of treatment impacts requires consideration of not only the direct costs and benefits of the treatments, but also their effects on the anticipated frequency and severity of wildfires (Kline, 2004; Agee and Skinner, 2005). Benefits in terms of diminished wildfire suppression costs could be substantial, as those costs were $11,100 per ha ($4500/acre) and $9400 per ha ($3800/acre) for the 2002 Gondola Fire and for the 2007 Angora Fire, respectively (USDA Forest Service et al., 2007, p. 22).

Table 1: LTBMU staff requested review of effects of treatment activities on particular resource values

Treatment Activities	Resource Values
Chipping and mastication	Fire behavior and effects on the residual overstory Understory growth Water quality (nutrient release and transport)
Pile burning	Soil quality
Prescribed burning	Nutrient transport; smoke impacts and release of particles and nutrients to the air
Silvicultural and burning treatments	Wildlife habitat and populations at various trophic levels
Mechanical operations in SEZs	Water quality and soil conservation
Untreated SEZs impacted by wildfires	Fire behavior and effects
Fuel reduction in steeply sloped areas	Water quality and soil conservation

An important subset of issues focuses on treatment of sensitive areas including wetlands or Stream Environment Zones (SEZs) (Cobourn, 2006) and steep slopes, which federal and basin regulatory agencies have long considered to be areas greater than 30% in slope based on the Bailey Land Capability System developed for the basin (Bailey, 1974). SEZs represent about 7300 ha (18,000 acres), or roughly 10% of the land area in the basin (Miller et al., 2008), while forested areas in need of fuels reduction on steep slopes may constitute about 11,700 ha (29,000 acres) (Coburn and Segale 2005: 1). Regulatory agencies have established higher standards of environmental protections within these areas because research has shown them to have generally heightened potential for sediment and nutrient delivery to Lake Tahoe (e.g., Byron and Goldman, 1989). However, both steep slopes and SEZs may also have greater need for fuel reduction treatments. Forest thinning on steep slopes needs to be more extensive to achieve a similar fire hazard reduction as on gentle slopes (Safford, 2009). For these reasons, decisions about treatment of SEZs and steeply sloped areas have significant implications for efforts to reduce wildfire hazards.

2 Types of Treatments

This section provides an overview of primary options being considered within the basin. The strategic plan for fuel treatments in the basin identifies several types of treatments that will be used to reduce excess fuel loads, including understory burning, pile burning, hand thinning, mechanical thinning, aerial thinning, mastication and chipping (USDA Forest Service et al., 2007, p. 14). Current management practices, as reported by the LTBMU (USDA Forest Service 2008) are focused upon a combination of:

1) initial thinning using either hand crews, cut-to-length treatment with mechanical equipment, or whole tree removal with mechanical equipment;

2) mastication to grind small trees and shrubs not processed by mechanical equipment;

3) pile burning of large materials that remain on-site, usually after two years of curing, and sometimes managed to encourage fire creep into surrounding areas; and

4) eventually, maintenance burning of the understory.

2.1 Understory Burning

Understory burning is viewed as the closest substitute for the pre-settlement fire regime in which fires frequently swept through the forest understory, cleaning up the accumulation of litter, woody debris, and small trees (Lindstrom et al., 2000). Consequently, understory burning can help to reduce excessive accumulations of litter that may be a long-term source of biologically available nutrients (Miller et al., 2005; Moghaddas and Stephens, 2007). By generating smoke and heat, burning has ecological effects that are not replicated by thinning (Manley et al., 2000). Furthermore, fire modeling and field experiments have demonstrated that some form of prescribed burning is often necessary to reduce wildfire hazards (Stephens 1998; Stephens and Moghaddas, 2005a). Although prescribed burning generates no durable product that can offset its costs, it may be a preferred treatment in remote areas and areas that do not have dense ladder fuels and high accumulation of surface fuels, including old-growth stands and previously treated areas (Manley et al., 2000; Stephens and Moghaddas 2005a). Typical prescribed burn treatments in the Sierra Nevada occur in the late spring and late fall to early winter periods, when air quality conditions allow more burning and fires are easier to contain; however, the relatively mild burns during such periods may not be severe enough to consume the surface fuels and small trees needed to restore desired conditions (North et al., 2007). Moreover, air quality concerns and weather constraints severely limit the windows for prescribed burns.

Managers have considered current fuel loadings in many areas to be too high for extensive understory burning without initial fuel reductions. Understory prescribed burning in the basin has been reported as quite limited, as little as 50-100 ha (125-250 acres) of lower montane forests per year (Stephens et al., 2004). However, its use appears to be on an upward trajectory as agencies shift into ―maintenance" burning in previously thinned areas (Dave Fournier, LTBMU, pers. communication 8/13/2009). Accordingly, forest managers in the basin have adopted plans to burn many times that area each year over the next decade, and they express a desire to burn even more. Not accounting for pile burning, the LTBMU has a goal of burning 160-200 ha/yr (400-500 acres/yr) (D. Marlow, pers. communication 3/20/2009), although that figure may include considerable amounts of meadow burning. In addition, the LTBMU burns piles on 200-800 ha/yr (1500-2000 acres/year), and encourages fires to creep out between the piles to consume a larger portion of the treated area (D. Marlow, pers. communication 3/20/2009). Meanwhile, the Nevada Division of Forestry is hoping to treat at least 40 ha/yr (100 acres/yr) (R. Shaw, pers. communication 3/20/2009), and the North Lake Tahoe Fire Protection District has adopted a plan to burn nearly 200 ha/yr (500 acres/yr) after initial cutting and pile burning (RCI, 2004). Considering plans from multiple jurisdictions, approximately 1980 ha/yr (4900 acres) would be burned annually if initial and maintenance treatments were completed as scheduled (Steve Holl Consulting and Wildland Rx, 2007). That estimate, while perhaps optimistic given the regulatory and social constraints on burning, lies within the range of 850-3225 ha (2109-7975 acres) that Manley et al. (2000, p. 470) estimated to have burned annually in pre-settlement times.

2.2 Thinning

Thinning removes the smaller understory trees and shrubs called ladder fuels that contribute to wildfire hazards by conveying surface fire to the crowns. Larger trees may also be removed as part of a treatment prescription to help achieve forest resource goals, offset costs, change species composition, or achieve other silvicultural objectives for a stand. Approximately 800 ha (2000 acres) of mechanical thinning are projected to occur annually in the basin during the next ten years (Steve Holl Consulting and Wildland Rx, 2007). The three major harvesting methods in the Tahoe basin are hand crews, cut-to-length (CTL), and whole tree removal (WTR). Hand crews are highly mobile, but are limited to processing relatively small trees; consequently, such treatment is considered insufficient for reducing high fuel loads in many areas in the basin (Steve Holl Consulting and Wildland Rx, 2007). Cut-to-length (CTL) reduces soil disturbance by preventing stems from being dragged on the ground and by creating mats of slash on which equipment can operate. Because of this advantage, CTL has been the preferred mechanical harvest system in the basin (USDA Forest Service et al., 2007, p.19), although it may cost about $1240/ha ($500/acre) more than WTR (Steve Holl Consulting and Wildland Rx 2007, p. 7-1).

There is strong interest in expanding the range of possible tools for application in sensitive areas such as steep slopes and wetlands. The current strategy indicates that aerial-based mechanical thinning using helicopter or cable-based systems would be needed where slopes exceeded 30% (USDA Forest Service et al., 2007, p. 14). High-lead and skyline systems remove logs from the forest by suspending one or both ends from a cable attached to a yarder that is held in place by guylines. These cable methods typically require a ridge-top road network to which logs can be pulled uphill. Another variety of cable-based system suspends the cut trees from a yoader, which is a fully mobile piece of heavy equipment that both yards and loads, and which can move into a harvesting unit without roads. Removing logs with a helicopter is another option that can minimize impacts to soils. This option has been used in the basin to remove trees cut by hand crews where access by equipment was limited around private residences in Tahoe; however, such treatments are very expensive, with operating rates of $7,000 per hour (RCI, 2004). As a result, helicopter logging is often considered a treatment of last resort, typically considered when removing pockets of larger, high value trees from areas with restricted access (Han et al., 2004).

2.3 Removal of Residual Biomass

Several approaches have been proposed as alternatives to understory burning as a means of removing the smaller woody materials generated by forest treatments, which is a critical component of effective fuel reduction treatments (Stephens, 1998). These slash materials can be placed into piles that are subsequently burned. Within the basin, pile burning is used on steep slopes where machines are prohibited and adjacent to developed areas and to SEZs. The number of approved days for burning due to air quality concerns restricts pile burning, and deep snow during winter makes it difficult to burn piles when atmospheric conditions would safely permit burning. Pile burning concentrates impacts to soils and plant communities where the piles are burned, although there are techniques to mitigate those impacts (Korb et al., 2004). The proximity of SEZs to streams has led regulatory agencies to be conservative in permitting fuel reduction activities that might result in the mobilization of nutrients or sediment. However, others contend that wetland systems are generally more resilient and are therefore able to accommodate disturbance resulting from pile burning. Pile burning within SEZs has been a largely understudied issue, but several research projects are currently underway in the basin.

Mastication and chipping have been commonly employed within the basin as alternatives to pile burning. Mastication reconfigures forest vegetation in the stand by using a rapidly rotating grinding head to shred and chop small trees, shrubs, and downed woody debris. Self-leveling tracked machines and modified walking excavators can be used for mastication on steep slopes, while low ground pressure tracked machines can be used in SEZs to minimize disturbance of soft soils (USDA Forest Service, 2004). The treatment does not immediately reduce fuel loads, but it can reduce fire effects by lowering the height of forest fuels, converting fuels into finer, faster-burning materials; and accelerating decomposition (USDA Forest Service, 2004).

Chipping is similar to mastication, except that it cuts the residual materials into small chips. Chippers may be wheeled vehicles that must be hauled by another vehicle, or which can limit the ability to bring them into some areas; the largest chippers are truck-mounted. Many chippers project chips through a chute which can be aimed to pile chips in designated areas or to transfer them to a truck-mounted container. If the chips are removed off-site, then chipping reduces fuel loads. Chipping can also achieve changes in fuelbed structure and moisture levels that reduce fire severity (Glitzenstein et al., 2006). However, the resulting compact layer of debris can insulate soils, alter soil moisture, reduce nitrogen availability to plants, slow decomposition, depress understory growth, and attract bark beetles in ways that depart from natural conditions, although information regarding these effects is still rather limited (Fettig et al., 2006; Resh et al., 2007). Finally, the loud noise from chipping operations is a concern due to the explicit noise thresholds in the basin.

2.4 Tradeoffs between Treatments

Table 2 summarizes advantages and disadvantages of primary fuel treatment options, which are usually applied in various combinations. Preferred options in the basin have been cut-to-length treatment and hand crews because of their potential for avoiding soil disturbance (USDA Forest Service et al., 2007, p. 19).

Table 2: Summary of costs, advantages and disadvantages of treatment options

Treatment	Cost Estimates of Treatments	Advantages	Disadvantages
Underburning or broadcast burning	\$990-\$3700/ha (\$400–\$1500/acre)[1,2]	Reintroduces a fundamental ecosystem process into forests; only burning actively reduces duff and litter layers Can use in areas with poor road access	Smoke production Risk of fire escaping prescribed boundaries Needs frequent follow-up treatments Seasonal constraints
Pile burning	\$740-\$1,730/ha (\$300–\$700/acre)[1,2]	Generally easier to implement than understory burning, especially in steeply sloped areas, developed areas, and SEZs	Air quality and weather constrains number of days to permit burning Concentrated impacts to soils and plants at pile locations
Hand thinning	\$1610-\$8660/ha (\$650-\$2,500/acre)[2] (pile burning is often required as an additional expense)	Reduced impacts to soils and vegetation facilitates operation in sensitive areas such as steep slopes, SEZs and developed areas Effective in areas with poor road access	Limited to removing small diameter trees (<35 cm or 14 inches dbh, Safford et al., 2009) Often more expensive than mechanical methods (Keatley, 2000) Significant safety and other labor concerns
Whole tree removal	\$2,470-\$8,650/ha (\$1000 - \$3,500/acre	Removing tree tops and limbs reduces	Similar potential to conventional ground-based

	)[1] $3,410-$7,410/ha ($1500 - $3,000/acre)[2]	fire hazard Typically less expensive than CTL (Adebayo, 2006)	tractor operations for compacting and displacing soils
Cut-to-length (CTL)	$2,470-$8,650/ha ($1000 - $3,500 /acre)[1] $4,940-$8,650/ha ($2,000 - $3,500/acre)[2]	Reduces impacts to soils and residual vegetation through use of slash mats and by reducing the number of trips and extent of landings (Keatley, 2000).	CTL harvester leaves slash and/or masticated material within the stands which either requires costly removal or increases fire hazard Requires a large investment in the specialized harvester/processor and forwarder
High lead and skyline systems, including variants such as the tong-tosser and the mobile yoader	Typical costs not determined for basin because treatments have been largely experimental; however, costs for cable-based systems can be three times the cost of ground-based harvest systems (Windell and Bradshaw, 2000: 15; Han et al., 2004)	Reduces impacts to soils by partially or fully suspending logs from an aerial cable	High costs, highly specialized equipment and personnel Requires suitable road networks to remove materials Clearing of cable corridors can have visual impact as well as potential erosion hazards if not carefully designed and implemented (this issue is less significant for the more mobile yoader)
Helicopter systems	Costs not generally determined for basin due to limited use, but costs can be several times higher than for ground-based systems, particularly if logs are small (Han et al., 2004)	Reduces impacts to soils by fully suspending logs Effective in urban areas with limited access	Very expensive Noise and safety concerns, particularly near residential areas and major roadways Requires large landings and suitable road networks for piling and removing the logs Not efficient for removing smaller trees and shrubs that may contribute more to fire hazards (Stephens, 1998)
Mastication	$1,730-$3,710/ha ($700–$1,500/acre)[1]	Highly mobile equipment offers improved access	Converts ladder fuels into surface fuels, but does not directly reduce fuel loads

Chipping	$500-$1,730/ha ($200 - $700/acre)[1]	Can transform fuels into less hazardous forms Chips can protect soils from erosion and compaction by equipment	Chip layers (particularly deep ones) effect nutrients, soil moisture, temperature, and understory plants in ways that differ from natural forest conditions Equipment is noisy Chipping during the spring can attract bark beetles (Fettig et al., 2006)

[1]USDA Forest Service et al., 2007, p.19
[2]Steve Holl Consulting and Wildland Rx, 2007, p. 7-1

There are several fundamental tradeoffs that govern the choice of how to rid the basin of excessive amounts of woody materials while maintaining natural disturbance processes above a highly sensitive body of water. First, methods that directly remove more of the fuel loads, such as whole tree removal, typically entail a higher risk of impact to soils and residual vegetation than CTL harvest and aerial methods (Walker et al., 2006). When followed by burning, whole tree removal and cut-to-length harvest may result in similar total reductions in forest fuels, but the whole tree removal takes the resources off-site, while cut-to-length often leaves the harvest residues on-site (Walker et al., 2006). Consequently, cut-to-length treatments could result in greater emissions during subsequent burns. An alternative of removing the residual materials following CTL harvest has significant costs; in the case of the Heavenly Valley SEZ demonstration project, up to half of the $7000/acre ($17,300/ha) treatment costs went towards removal of the slash mats on which the equipment was operated (Norman et al., 2008).

As a general rule, special efforts to minimize either ecological impacts or residual fuel loads increase treatment costs. The relative efficiency of different methods often depends on physical qualities of the stands being treated, such as stand density and ground slope (Hartsough, 1997). The effects of mechanical harvest techniques can also be mitigated through use of low-pressure tires, long booms, designated trails, reliance on highly skilled operators, and other management practices (Miller et al., 2008). The Tahoe Fire Commission report and the expert panel report by Miller et al. (2008) indicated that regulatory policies in the basin have prohibited or restricted some types of equipment and required specialized treatments such as aerial methods or over-the-snow logging. Because mitigations and specialized methods increase costs relative to conventional, ground-based harvest and skidding, such requirements prompt debates about cost-effectiveness (Han, 2007).

In addition to the complexity introduced by economic considerations, the ecological interactions of multiple disturbances are complex. For example, the soil disturbance caused by mechanical treatments can mediate the effects of subsequent fires (Moghaddas and Stephens, 2007). Furthermore, fuel reduction treatments, including prescribed fire, can attract insect pests that can kill trees and thereby increase hazardous fuels (Bradley and Tueller, 2000). Another basic tradeoff is that many fuel reduction treatments reduce crown fire potential, but they can create more surface fuels which in turn could increase the severity and spread of ground fires (Stephens, 1998; Resh, et al., 2007). Practices that minimize soil disturbance (e.g., over-the-snow logging) serve to minimize the likelihood of impacts to water quality but can fail to promote recruitment of young pines and understory plants that is needed to meet vegetation objectives. Most importantly, an objective of minimizing particulate loading to the lake (through both aerial emissions and surface runoff) constrains efforts to reestablish a more natural fire regime. These examples demonstrate that the various treatment options entail complex ecological and economic tradeoffs that need to be well understood. In addition, these impacts need to be evaluated from appropriate spatial and temporal perspectives to account for the likelihood that small areas may be impacted without necessarily resulting in detectable changes at some distance downstream, across a wide landscape, or at some future time.

3 Reviews of Science to Support Fuels Management in the Basin

Calls for scientific research to guide forest management in the basin have become prominent within the past two decades. The Lake Tahoe Restoration Act of 2000 (www.fs.fed.us/r5/ltbmu/documents/snplma/lake_tahoe-restoration_act_106_506.pdf) called upon the Secretary of Agriculture to ―consult with and seek advice and recommendations regarding the coordination of scientific resources and data, for the purpose of obtaining the best available science as a basis for decision-making on an ongoing basis.” Subsequently, the USDA Forest Service and the state of Nevada requested a review of the LTBMU’s fuels and vegetation management program and its relationship to the fuels objectives of the Lake Tahoe Restoration Act, with a particular focus on ―integration of scientific findings into the LTBMU's program” (USDA Forest Service, 2002). In 2007, the bi-state Tahoe Fire Commission was convened to ―perform a comprehensive review of the laws, policies, and practices that affect the vulnerability of the Tahoe basin to wildfires and/or that pertain to fire prevention and fuels management in the basin” (http://resources.ca.gov/TahoeFireCommission/). In February 2008, a workshop was held to discuss vegetation management in sensitive areas. An expert panel provided findings and recommendations concerning how to better align management and science in the basin to address these issues (http://www.tahoescience.org/tsc_products/Products.aspx). Both the expert panel and the Fire Commission called for the compilation and synthesis of scientific literature evaluating the effects of fuel treatments on resources of concern in the Tahoe basin. This current synthesis effort resulted in the compilation of an on-line searchable database of publications regarding fuel treatment efforts relevant to the Tahoe basin, which is currently housed on the Tahoe Integrated Information Management System (TIIIMS) website (www.tiims.org).

Two major synthesis initiatives have previously been directed by Congress: the Sierra Nevada Ecosystem Project (with a final report submitted to Congress in 1996) and the Lake

Tahoe Watershed Assessment (Murphy et al., 2000). The latter report asserted that ―little information exists in the basin or elsewhere in the western states on the ecological impacts of mechanical treatments or their effectiveness in reducing fire hazard compared to burning" (Manley et al., 2000 p. 473). During the following decade, significant new information has been obtained in the basin and across the Western U.S. Monitoring of treatments conducted by the LTBMU and other management agencies are an important source of recent information from within the basin. Meanwhile, Fire and Fire Surrogates (FFS) studies sponsored by the Joint Fire Science Program (Bigelow and Manley, this volume) have helped to understand how alternative treatments affect fire behavior, vegetation, soils, wildlife, and water quality in forests comparable to those in the Tahoe basin. Despite such progress, the Tahoe Science Plan, developed from 2006-2009 (Hymanson and Collopy, 2009), posed a range of questions concerning the effects of current and future treatments on fire hazard, scenic and recreational amenities, water quality, soil erosion, terrestrial and aquatic wildlife habitat.

Within the Tahoe basin, relatively few controlled experiments have compared treatments within and across different ecological types, although several such investigations are currently underway using funds from the Southern Nevada Public Lands Management Act. As an alternative to controlled experiments, various modeling tools have been employed in an effort to evaluate the effects of fuel treatments at project, landscape and basin scales. Applications of several such tools, including the Lake Tahoe Atmospheric Model, the Lake Tahoe Total Maximum Daily Load (TMDL), and the Water Erosion Prediction Project (WEPP), are addressed in subsequent papers. Modeling is a useful tool in evaluating tradeoffs between treatments and the increased wildfire risk associated with no treatment, but carefully designed manipulative experiments remain a preferred approach for advancing scientific understanding and reducing uncertainty (Gertler et al., 2006).

4 Next Steps for Synthesis Efforts

Complex institutional relationships that have evolved within the basin influence forest management strategies, and they may complicate efforts to reach consensus on standards and goals (Imperial and Kauneckis, 2003). Attempts to seek better scientific models often fail to produce a solution to wicked problems, ―because the science is uncertain and because the problem is as much political as technical” (Balint et al., 2006, p. 25). Efforts to solve wicked problems such as fuels reduction generate consequences that take time to evaluate and may give rise to new problems. As a result, institutional changes are often recommended to promote long-term learning networks and decision-making processes that can adapt as the problem evolves (Rauscher, 1999; Borchers, 2005; Carroll et al., 2007). Institutional changes in the basin have resulted from recent collaborative efforts among agencies, such as the Pathway 2007 process (http://www.pathway2007.org/), the development of the 10-year Strategy (USDA Forest Service et al., 2007), and the California Nevada Bi-state Fire Commission. The efforts have secured funding for multiple partners and led to the formation of a Multi-Agency Coordinating group (MAC), the Tahoe Fire and Fuels Team (TFFT), and a Fire Public Information Team (Fire PIT). These institutions have helped agencies to share information on contracting criteria and environmental guidelines, to share equipment across fire districts, and to inform the public regarding defensible space and treatment of urban lots (Dave Fournier, LTBMU, pers. communication 8/13/2009).

Institutional support for scientific research has increased due to funding from the Southern Nevada Public Lands Management and activities of the Tahoe Science Consortium

(TSC). Funds have supported several research projects that have been selected and designed with input from management agencies, as well as science integration efforts such as the Tahoe Science Plan and the chapters in this literature review. Continued efforts are needed to integrate scientific knowledge in ways that can be readily applied to the Tahoe landscape; for example, the recent expert panel on vegetation management specifically recommended a basin-wide analysis of costs, environmental effects, and effects on wildfire behavior of various treatments (Miller et al., 2008). Creating maps based on such analyses can help decision makers identify the relative benefits and risks of treatments designed for ecological restoration and/or fuel reduction (Prather et al., 2008). In that vein, a subtheme in the Tahoe SNPLMA science program called for developing tools to quantify and compare treatment effects on various resource values across the basin landscape. These current and prospective research efforts should help management practices to continue to adapt as the problem of fuels reduction evolves.

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Vegetation Response to Fuels Management in the Lake Tahoe Basin

Seth W. Bigelow, Ph.D. and Patricia N. Manley, Ph.D.[1]

1: Sierra Nevada Research Center, Pacific Southwest Research Station,
USDA Forest Service; 1731 Research Park Drive, Davis, CA 95618. 530-759-1700

Abstract

Fuels treatments are the primary response to the urgent priority of dealing with wildfire in mixed-conifer forests of the Lake Tahoe Basin. Compared to mid-19th century, these forests are characterized by dense concentrations of small shade-tolerant trees, a dominant even-age cohort of overstory trees, shaded and floristically depauperate understories, and thick soil surface layers high in organic matter. Studies in other frequent-fire forests of the West bear on how fuels treatments can help to restore forest health and biodiversity while achieving their main purpose of changing fire behavior. Studies of short-term responses to fuels treatment indicate that some groups of plants increase in density and cover (e.g., short-lived plants, invasive weeds, and legumes), and others decrease (shrubs and saprophytes). Factors triggering germination of seeds – e.g. light intensity and quality – vary by species group, and low-intensity fire probably has a vital role in germination of smoke- or heat-triggered species groups (e.g., legumes). Thinning prescription and biomass disposal method interact to determine effect on vegetation; for example, prescribed burning of the large debris items produced in a crown thinning can promote understory diversity by increasing consumption of organic soil horizons. It is not known whether burning small piles of debris may enhance ecosystem health by mimicking this effect. Broadcast spreading of chipped biomass can suppress understory growth and complicate prescribed burning. No single fuels treatment will maximize forest health and stand-level plant diversity because treatments select for different plant species and groups.

Key words: fuels reduction treatments; understory plants; Sierra Nevada; forest thinning; prescribed fire.

I. Introduction

Fuels reduction treatments affect forest structure and species composition in the short term by the selective removal of certain tree diameter classes and species, and in the long-term through altering growth resources (e.g., light, bare mineral soil, moisture) and fire behavior. More is known about the short-term effects of treatments than the long-term ones. Understory plants are the main contributors to floral diversity in the Lake Tahoe basin (Manley et al., 2000), and they provide many ecosystem services, such as scenic beauty, erosion control, nutrient retention, food resources for animals, and control over tree regeneration (Grime, 1998; George and Bazzaz, 1999). The aim of this review is to summarize information on short and longer-term effects of fuels treatments on forest structure and understory diversity in the Lake Tahoe basin.

The past two decades have seen a change in priorities for management of public lands administered by the U.S. Forest Service in the Lake Tahoe Basin. Wildfire was not among the top issues of concern in the 1988 Land and Resource Management Plan, (Harris and Barker, 1988), and was listed as only the third of five problem areas in the 2001 amendment to the plan (Powell and Blackwell, 2001). By 2004, however, wildfire risk had become the foremost Sierra-wide priority, as reflected in the opening sentences of the 2004 plan amendment, "This decision adopts an integrated strategy for vegetation management that is aggressive enough to reduce the risk of wildfire to communities in the urban-wildland interface while modifying fire behavior over the broader landscape" (Blackwell and Troyer, 2004).

Managers in the Lake Tahoe basin must reduce the risk of wildfire while advancing other objectives common to many publicly owned forests, and some Tahoe-specific ones such as maintaining the clarity of Lake Tahoe. Forest Service staff refer to their task as "*reducing surface and ladder fuels and thinning forest stands to improve vigor"* while *"integrating ... wildlife habitat, scenic quality, and soil and water quality (objectives)"* (Lake Tahoe Basin Management Unit communication, October 2008). Fuels reduction treatments are commonly seen as the first step to restoring forest health in areas that were adversely affected by the logging of the Comstock Era (1880 – 1920) and by the disruption of normal disturbance processes of the fire suppression era (~1920 – 1990; Stephens and Ruth, 2005). Reinhardt et al. (2008) caution, however, that fuel treatments are primarily designed to make wildfire less disruptive, and that the expectation they will achieve other objectives (restore ecosystem health, pre-European conditions, or historic range of variability) may lead to misunderstandings.

Most forests at lower elevations in the Lake Tahoe basin are currently outside their natural range of variability in species composition, forest structure, and fire frequency and intensity (e.g., Hammer et al., 2007). For example, reconstructions of Jeffrey pine/white fir forests in the Carson range indicate a former basal area of ~23 m^2 ha^{-1} (100 ft^2 $acre^{-1}$), but current basal area is approximately twice that (Taylor, 2004). Historically, stands generally were characterized by large-diameter trees and open understories (Barbour et al., 2002; Taylor, 2004), but today, forest stands have high densities of small-diameter trees, high tree mortality from drought stress and insect damage, and high densities of snags and downed logs. Shade-tolerant tree species such as white fir (*Abies concolor*) have become more prevalent at the expense of intolerant species like Jeffrey pine (*Pinus jeffreyi*). Thinning alone may never fully restore historic function, structure, or resilience, but it is important to understand how fuels treatments contribute to forest restoration by mimicking historic, endogenous disturbances.

Our review focuses at the scale of the stand and understory rather than the landscape, but it is important to note that landscape pattern may have been changed by logging in the late 19th century and fire suppression in the 20th century. The clearcutting of the Comstock Era would have eliminated much natural variation in stand structure, and many of the current large trees grew back soon afterwards, leaving landscape pattern more homogeneous than it was prior to the 1850's. The historic role of high-intensity fires is unresolved but it may have helped to create landscape heterogeneity, both by creating a mosaic of different forest age classes and structural conditions, and creating montane chaparral shrub-fields (Lieberg, 1902; Russell et al., 1998; Nagel and Taylor, 2005). Historically, wildfires would have burned more frequently and intensely on dry southwest facing slopes, but fire suppression has attenuated the natural heterogeneity that would result from the interaction among microclimate, fire, and vegetation (Taylor and Skinner, 1998; Heyerdahl et al., 2001; Taylor and Skinner, 2003; Hessburg et al., 2005). Displacement of Washoe tribal groups from ancestral grounds also eliminated the pattern of burning resulting from their activities (Lindstrom et al., 2000).

In the first section of this review we describe a group of experimental studies from the Sierra Nevada and Cascades ranges. Most of the studies involved thinning and burning, and report the effects of these treatments on forest stand structure. Although prescribed burning alone is not a widespread current practice of the Lake Tahoe Basin Management Unit (LTBMU), we report findings from burn-only experiments because management practices sometimes change rapidly. The experimental studies we examine occurred in areas that differed widely in precipitation, which provides a context for the varied treatment responses expected in the basin depending on the location (the more mesic west shore or more xeric east shore; Table 1).

The second and third sections examine the responses of understory plants found in the Lake Tahoe basin and plant germination responses, respectively, to fuels reduction treatments. We review the physiology of seed response to major resources (e.g., light) and disturbances (e.g., fire). An understanding of seed persistence in the soil is central to many aspects of practical land management for conservation (Thompson et al., 1993), and the same is likely true of plant response to fuels treatments. With knowledge of the general types of germination response to disturbance, informed predictions about treatment responses can be made even in the absence of species-specific studies. Often, mechanisms of plant response to disturbance arise in a taxonomic ancestor and are conserved within a plant family (Keeley and Fotheringham, 2000), so we emphasize plant families within this review. The fourth section reviews responses to particular treatment combinations, and we conclude with management implications.

2. Experimental fuels treatment studies

The Teakettle Experimental Forest project on the Stanislaus National Forest compared understory and overstory thinning with and without prescribed burning (North et al., 2007). The understory thin followed California spotted owl report guidelines by removing all trees between 25 and 76 cm (10 and 30 in) DBH while retaining ≥40% canopy cover (Verner et al., 1992), and the overstory thin was a shelterwood that removed all but 22 large (>75 cm or 30 in DBH) trees ha^{-1} (~2 acres). A reconstruction of historic stand composition was also carried out. None of the treatments effectively restored the high basal area and low stem count characteristic of the historic stands: treatments that removed sufficient numbers of trees reduced basal area excessively, and treatments that retained high basal area did not sufficiently reduce stem count (Table 2).

Within the Lake Tahoe Basin, historical reconstruction has been conducted on the east side of the lake in the Carson range near Daggett Pass and Glendale, NV, in an area that has annual long-term precipitation of ~500 mm (20 in) (Table 1). In this Jeffrey pine/white fir forest, estimates of presettlement stem density (trees > 10 cm or 4 in DBH) were 68 stems ha^{-1} (~2 acres), and basal area was 26 m^2 ha^{-1} (113 ft^2 $acre^{-1}$) (Taylor, 2004). Current stem density is 343 stems ha^{-1} (~2 acres), and basal area is 46 m^2 ha^{-1} (200 m^2 ha^{-1}).

A study of fuels reduction treatments took place at the nearby Blodgett Experimental Forest in Georgetown, California. Blodgett Experimental Forest is <80 km (50 mi) from the Lake Tahoe Basin at a similar latitude, but at a lower elevation on the west side of the Sierra crest with higher precipitation, in mixed conifer and mixed conifer-hardwood vegetation types (Sawyer and Keeler-Wolf, 1995). Treatments were mechanical (crown thinning then mastication of small diameter [<25 cm or 10 in DBH] understory trees), prescribed fire alone, or mechanical plus prescribed fire (Stephens and Moghaddas, 2005). Burning reduced the stem count by half, but had little effect on basal area, indicating that most trees killed were of small diameter. Mechanical thinning with burning did not decrease basal area more than thinning alone, but it had a greater effect on the stem count, reducing it by 75%.

Table 1. Elevation and average annual precipitation (P) within the Lake Tahoe basin and at Sierran and southern Cascades sites where experimental fuels treatments have taken place.

Station Location	Elevation (m)	P (mm)	Reporting period or source
Squaw Valley lodge, CA[1]	1902	1295	1955 – 1975
Tahoe City, CA	1899	800	1903 – 2007
Echo Summit, CA	2240	1267	1944 – 1994
Meyers Inspection Stn., CA	1934	1039	1955 – 1969
Heavenly Valley, CA	2616	876	1979 – 2005
Daggett Pass, NV	2240	556	1988 – 2007
Glenbrook, NV	1900	462	1901 – 2007
Teakettle Forest	1900	1250	(North et al., 2007)
Blodgett Forest	1315	1600	(Stephens and Moghaddas, 2005)
Sequoia	2000	1170	(Stohlgren and Parsons, 1987)
Goosenest	1523	800	(Ritchie, 2005)
Blacks Mountain	1900	460	(Zhang et al., 2008)

[1] Lake Tahoe data are from the Desert Research Institute's Western Regional Climate Center website (www.wrcc.dri.edu/Climsum.html).

The Sequoia study was located in mixed conifer forest in the southern Sierra Nevada. This study contrasted early-season (spring) and late-season (fall) burns in the absence of mechanical thinning (Knapp et al., 2005). The reduction in basal area was similar between early and late season burns (from 65 down to 55 m^2 ha^{-1} , 32 to 27 yd^2 $acre^{-1}$) but the late burns were more effective at reducing stem count, as would be expected under the drier conditions of late summer and early fall. Coarse woody debris volume was significantly reduced, with late season burns causing greater declines (86%) than early season burns (59%). Where fire passed over the forest floor, late season burns consumed five times as much litter and duff as early season burns.

Two other studies in California address short- and long-term ecological effects of forest treatments although neither was designed to address fuels reduction. The Blacks Mountain Ecological Research Project examines the role of stand structural complexity in maintaining forest health. Blacks Mountain Experimental Forest consists of interior ponderosa pine forest in the southern Cascade range (Oliver, 2000). Mean annual precipitation is 457 mm (18 in), comparable to the driest areas of the Lake Tahoe basin (Table 1), and pre-treatment basal area was correspondingly low, ~30-35 m^2 ha^{-1} (16-17 yd^2 $acre^{-1}$). Treatments included a heterogeneous thin which retained large trees ("high complexity") and a homogeneous thin ("low complexity"), with and without prescribed fire (Ritchie et al., 2008; Zhang et al., 2008). The low-complexity treatment reduced basal area and stem-count much more than the high-complexity treatment; prescribed burning had no measurable effect on either variable (Table 2).

The Goosenest Adaptive Management Project was designed to test methods for accelerating development of late-successional forest properties (Ritchie, 2005). It is located at Goosenest Experimental Forest in the Klamath Mountains of California, 340 km to the north of Lake Tahoe Basin. The forest is dominated by ponderosa pine and white fir; it receives higher annual precipitation than Blacks Mountain but has porous volcanic ash soils which limit water availability. Control site basal area was 19 m^2 ha^{-1} (9 yd^2 $acre^{-1}$), lower than any of the other experimental studies (Ritchie and Harcksen, 1999). Three treatments comprised pine emphasis (thinning small-diameter shade-tolerant trees and regenerating ponderosa pine in small clear-cut openings), pine plus fire (the same treatment followed by prescribed fire); and large tree (thinning small trees without regard to species). Both pine and large-tree treatments decreased basal area from ~19 m^2 ha^{-1} (9 yd^2 $acre^{-1}$) to ~10 m^2 ha^{-1} (5 yd^2 $acre^{-1}$), and reduced stem count considerably. Fire did not affect stem count.

Table 2. Effects of experimental manipulations on structural attributes of forests near the Lake Tahoe Basin.

Study	Treatment	Canopy cover (%)		Basal area (m^2)		Stem density	
		Pre	Post	Pre	Post	Pre	Post
Teakettle[a]	1865 reconstruction			52		67	
	Low thin	81	73	56	41	469	240
	High thin	“	63	“	23	“	150
	Burn	“	80	“	54	“	354
	Low thin + burn	“	71	“	38	“	143
	High thin + burn	“	60	“	17	“	94

Blodgett[b]	Control	69	75	55	56	1101	1110
	Thin	66	58	52	41	972	429
	Burn	68	65	49	48	850	452
	Thin + burn	63	51	55	39	823	239
Sequoia[c]	Control	~	~	59	61	320	319
	Early burn	~	~	65	55	407	254
	Late burn	~	~	65	54	325	146
Blacks[e]	Lo diversity	~	~	34	9	972	285
	Hi diversity	~	~	31	24	681	522
	Lo + burn	~	~	30	10	838	280
	Hi + burn	~	~	35	25	994	503
Goosenest[e]	Control	~	~	~	19	623	823
	Pine	~	~	~	11	535	168
	Large tree	~	~	~	9	623	193
	Pine + burn	~	~	~	10	530	175

[a] (North et al., 2007).

[b] (Stephens and Moghaddas, 2005); trees > 2.5 cm DBH.

[c] (Schwilk et al., 2006); trees > 10 cm DBH.

[d] (Zhang et al., 2008); trees > 0.3 m height.

[e] (Ritchie and Harcksen, 1999); trees > 10 cm DBH.

(~ = information not available).

3. Responses of plant functional groups to fuels treatments

To understand the effects of fuels treatments in fire-suppressed conifer forests on the plant community, it is helpful to classify plants into functional groups. The most basic classification is growth form: tree, shrub, graminoid (grass-like plant), or forb (an herbaceous plant that is not grass-like). Other useful functional characteristics are the lifespan of graminoids and forbs (annual or biennial versus perennial), whether a plant can fix nitrogen (i.e., capture gaseous nitrogen from the atmosphere and convert it to a nutritive form), whether a plant is a saprophyte (captures energy from the roots of other plants), and if the plant is an invasive exotic. This section describes treatment responses that are characteristic of one or more functional groups.

3.1. Fuels treatments may improve conditions for the regeneration of canopy trees.

Regeneration may or may not be a goal of fuels treatments in the Lake Tahoe basin given current stages of forest development, but insofar as fuels treatments open the overstory canopy and expose bare mineral soil, they improve conditions for regeneration. Bare mineral soil is the best seedbed substrate for most conifers because leaf litter and organic soil horizons dry out readily (Kozlowski et al., 1991). Seeds of white fir and ponderosa pine may germinate better on an ash substrate than on bare mineral soil (and much better than on an organic horizon; Fisher, 1935; Bailey and Covington, 2002). Rototilling was slightly better than burning as a seedbed treatment for ponderosa pine (Schultz and Biswell, 1959). White fir can germinate and survive in deeper leaf litter layers than sugar pine (Stark, 1963).

Fuels treatments may enhance tree regeneration by decreasing competition from understory plants, shrubs in particular. Jeffrey pine and ponderosa pine compete poorly against encroaching understory vegetation (Jenkinson, 1990; Oliver and Ryker, 1990). Sugar pine is intermediate in competitive ability between ponderosa pine and white fir(Baker, 1949; Oliver and Dolph, 1992): the latter species competes strongly against shrubs and can emerge from dense shrub-fields where the other two species are likely to fail (Dunning, 1923; Conard and Radosevich, 1982). Shrub removal during fuels treatments is likely to enhance the establishment of Jeffrey pine more than white fir.

Canopy-thinning fuels treatments increase light to the forest understory, but the impact on tree regeneration is a function of the canopy strata removed and the spacing of residual trees. Fuels treatments are often applied with the goal of maximizing space between residual trees, and this procedure may not create gaps that are large enough to foster growth of shade-intolerant species (Moghaddas et al., 2008; Zald et al., 2008). Jeffrey pine is an extreme shade-intolerant species, requiring large canopy gaps or very open stands to achieve rapid growth (Jenkinson, 1990; Stephens and Fry, 2005). White fir, in contrast, is highly shade-tolerant, and it approaches peak growth rates at relatively low light intensities (Conard and Radosevich, 1981), such that opening the canopy should not result in large increases in growth. Sugar pine is intermediate in tolerance and may be reported as shade intolerant (Ansley and Battles, 1998) or shade tolerant (McDonald and Abbott, 1994). Its ability to utilize light appears to depend on its size, because it grows slowly when small (Fowells and Schubert, 1956; York et al., 2004) but accelerates in growth later.

3.2 Short-lived plants are stimulated by most fuels treatments.

When forest understories are disturbed by fuels treatments, there is often a community of short-lived (e.g.., annual or biennial) plants ready to respond (Table 2). Short-lived plants do not have to build the root structures necessary for long-term survival, so they can put all their energy into growth and respond to short-term opportunities. Several studies report native annual forbs to be the strongest responders after fuels treatments (Huisinga et al., 2005; Moore et al., 2006; Perchemlides et al., 2008). Another study detected a strong positive response of short-lived native and exotic forbs to prescribed burns in the fall but not in the spring (Kerns et al., 2006). The stimulatory effect of the fall burns was attributed to both the increased heat (because fuels were dry after the summer) and the larger openings (due to greater overstory tree mortality in the hot burns). Communities of short-lived plants are likely to eventually lose out to competition from longer-lived plants as part of natural succession, but such communities can be moderately persistent. For example, annual plants were still abundant in plots sampled 4 to 7 years after treatment (Perchemlides et al., 2008)

3.3 Fuels treatments create opportunities for invasive plants.

The invasive plant species of frequent-fire pine forests of the Sierra Nevada are high-resource specialists: they do poorly in the understory of fire-suppressed forests but can grow rapidly when the canopy becomes more open and the mineral soils are exposed. Many researchers have noted increases in the cover of invasive plant species after fuels treatments (Griffis et al., 2001; Kerns et al., 2001; Keeley et al., 2003); however, in most of these cases invasive plants were established prior to treatment. The Lake Tahoe basin is fortunate in that most of the forests are not at present heavily invaded by exotic plants (Stanton and Daily, 2007; Heckmann et al., 2008), owing in part to their isolation from lower-elevation source populations.

3.4 Shrubs are negatively affected in the short term by fuels treatments.

Shrubs are often negatively affected during fuels treatments, either because they are directly targeted by hand-thinning, mastication, or prescribed fire (Perchemlides et al., 2008), or due to incidental damage from being run over by equipment (Table 2). Shrubs are often resilient, though, and may recover by resprouting from below-ground structures or by fire-stimulated germination from a seedbank (Keeley and Zedler, 1978; Kauffman and Martin, 1990), depending on species. Mechanical fuels treatments not followed by prescribed fire will not induce germination of species with fire-triggered germination. Most fuels treatment studies have too brief a duration to provide information on time required for shrub communities to recover their former dominance after thinning. One longer-term study showed that fuels treatment impacts can be severe; an experimental underburn stimulated germination but weakened mature individuals of antelope bitterbrush (*Purshia tridentata*) (Busse et al., 2000). A second burn 11 years later eliminated virtually the entire bitterbrush population because the young plants had not yet become reproductive (Busse and Riegel, 2009).

3.5 Saprophytes decline under all fuels treatments.

Saprophytes are one of the few understory plant groups that thrives in fire-suppressed forests, perhaps because they are able to avoid the problem of lack of light by deriving sustenance from the roots of trees. Populations of these plants are consistently found to decline when fuels treatments are implemented (Table 3).

3.6 Legumes and other nitrogen-fixing plants may benefit from treatments.

Nitrogen fixation requires high inputs of light, so nitrogen-fixing plants may respond positively to fuels treatments where shading from neighboring plants is reduced (Moore et al., 2006). Prescribed fire may reduce soil nitrogen, providing a further advantage to N-fixing plants (Newland and DeLuca, 2000), but some researchers caution about generalizing too broadly about the beneficial effects of fire on N-fixing plants (Hiers and Mitchell, 2007).

Highlights

- Mechanical fuels treatments, in general, have predictable effects by plant functional group:
  - increased regeneration opportunities for canopy trees
  - increased regeneration of short-lived plants such as herbaceous forbs and grasses
  - increased opportunities for invasive plant species
  - decreased shrub cover
  - decreased abundance of saprophytes (non-photosynthesizing plants)
  - increased vigor and abundance of leguminous species

Table 3. Responses of plant species occurring in the Lake Tahoe Basin to experimental fuels reductions conducted in western ecosystems.

Species	LH	Family	Common name	Thin[a]	Burn	Thin+ Burn
Graminoids						
Bromus orcuttianus	P	Grass			↓[2]	
Elymus elymoides	P	Grass	squirrel-tail	↑[4]↑[5]		↑[4]↑[5]
Achnatherum occidentale	P	Grass	western needlegrass[b]		↓[6]↓[2]↑[2]	↓[6]
Forbs						
Adenocaulon bicolor	P	Sunflower	trail plant		↓[2]	
Allophylum integrifolium	A	Phlox	White allophylum		↑[2]	↑[1]
Collinsia torreyi	A	Snapdragon	blue-eyed Mary		↑[1]	↑[1]
Cryptantha simulans	A	Borage	cryptantha		↑[1]↑[3]	↑[1]
Galium triflorum	P	Madder	bedstraw		↓[2]	
Hieracium albiflorum	P	Sunflower	White hawkweed		↓[1]Ø[2]	↓[1]
Osmorhiza chilensis	P	Celery	Sweet cicely		↓[2]	
Phacelia hastata	P	Waterleaf	silverleaf phacelia			↑[1]
Pteridium aquilinum	P	Bracken fern	bracken fern		Ø[2]	
Viola purpurea	P	Violet	mountain violet		Ø[2]	
Shrubs						
Arctostaphylos patula	P	Heath	greenleaf manzanita	↓[1]		↓[1]
Ceanothus cordulatus	P	Buckthorn	mountain whitethorn[c]	↓/↑[1]		↓/↑[1]
Ceanothus spp.	P	Buckthorn			↑[2]	

Chimaphila menziesii	P	Heath	little prince's pine		↓[2]	
Chrysolepis sempervirens	P	Oak	bush chinquapin	↓[1]		↓[1]
Prunus emarginata	P	Rose	Bitter cherry	↓[1]		↓[1]
Purshia tridentata	P	Rose	antelope bitterbrush		↓[7]	
Ribes roezlii	P	Gooseberry	Sierra gooseberry	Ø[3]	Ø[3]	↓/↑[1]↑[3]
Ribes sp.	P	Gooseberry				
Symphoricarpos mollis	P	Honeysuckle	creeping snowberry	↓[3]	↓[3]↓[2]	↓[3]
Saprophytes						
Corallorhiza maculata	P	Orchid	spotted coralroot	↓[1]	↓[1]	↓[1]
Goodyera oblongifolia	P	Orchid	rattlesnake plantain	↓[3]	↓[3]	↓[3]
Pterospora andromedea	P	Heath	pinedrops	↓[1]	↓[1]	↓[1]
Pyrola picta	P	Heath	wintergreen	↓[3]	↓[1]↓[2]↓[3]	↓[1]↓[3]
Invasive exotics						
Cirsium vulgare	B	Sunflower	bull thistle	↑[3]	↑[3]	↑[3]

[a] Reference key: (1) Wayman and North 2007, (2) Knapp et al. 2007, (3) Collins et al. 2007, (4) Moore et al. 2006, (5) Griffis et al. 2001, (6) Metlen et al. 2005, (7) Busse et al. 2000.

[b] Response dependent on early versus late burn. Western needlegrass did poorly in spring burns but well in fall burns.

[c] Life history: P = perennial, A = annual, B = biennial.

4. Mechanisms of plant response to fuels treatments

Knowledge of the underlying mechanisms of seed and plant response to disturbance is useful in predicting how fuels treatments may affect plant species and communities. Mixed-conifer forests have been characterized as having few species that form persistent soil seed banks, and as such require resprouting from vegetative structures or recolonization from source populations to facilitate the recovery of most understory plant species after fire disturbance (Keeley et al., 2003).

4.1. Light quantity and quality affect plant recovery following disturbance.

Understory plants respond to the vertical distribution spectral quality of light. Fuels treatments alter light by removing some overstory vegetation and disturbing the soil, which may result in illumination of buried seeds (Pons, 2000). Plant leaves filter red light effectively but allow much far-red radiation to pass, so that the ratio of red light to far-red is low in dense plant canopies (Jones, 1992). In full sunlight, the ratio of red- to far-red light (R:FR) is ~1:1, but in coniferous evergreen woodland R:FR is often in the range of 1:2 to 1:5 (Kozlowski et al., 1991). Seeds at or near the soil surface may have their dormancy broken by the increase in R:FR that occurs with removal of overstory canopy (Pons, 2000).

A requirement of light to break dormancy in certain plant species allows formation of a persistent seed bank in the soil, and prevents seeds from germinating too deep in the soil to reach the surface. Light will only penetrate a few millimeters into most soils, although it may penetrate more than a centimeter into sandy soils. Most seeds with a light-requirement for germination are small, and when soil is disturbed these seeds can sense very brief, weak pulses of light in a wide range of wavelengths (Shinomura, 1997), which break their dormancy. Plant genera occurring in Tahoe with light-broken dormancy include *Rumex* (dock; Totterdel and Roberts, 1980), *Cirsium* (thistle; Pons, 1984), and *Lepidium* (pepperweed; Toole et al., 1955), all of which are invasive exotic plants.

4.2. Fire can stimulate germination

Prescribed burning of the forest understory can promote germination by either heat-shock stimulation or smoke and charred-wood stimulation. Seeds whose dormancy is broken by heat, often referred to as "hard-seeded", have dense tissue beneath the outer seed coat that prevents them from taking in water. Fire disrupts the water-impermeable tissues, allowing seeds to take in water and germinate (Keeley and Fotheringham, 2000). Hard-seeded species differ in the intensity and duration of heat required to stimulate recruitment. Heat-shock stimulated germination tends to be most common within particular plant families, such as many legume species and a number of species in genera of the buckthorn (particularly *Ceanothus*; e.g. Kauffman and Martin, 1991) and mallow (e.g., *Sidalcea*) families.

Germination of a number of species is stimulated through by-products of biomass combustion such as smoke or charred wood (Keeley and Fotheringham, 1997). Evidence suggests that oxides of nitrogen are the chemical triggers, but a receptor has not yet been isolated. Combustion products are transferred through the seed coat as vapor or liquid. Plant families occurring in the Lake Tahoe basin with smoke-stimulated germination include Hydrophyllaceae (the water-leaf family), Papaveraceae (the poppy family), Polemnoniaceae (the phlox family), and the Scrophulariaceae (the figwort family). Dormant, soil-stored seed banks triggered to germinate by smoke or charred wood, or heat shock, are common in annuals and shrubby perennials, uncommon in trees, and rare in herbaceous perennials (Keeley and Fotheringham, 2000).

4.3. Sprouting species have enhanced recovery rates

Resprouting of established perennial plants after fire or mechanical disturbance is an effective mechanism for recovery after fuels treatments (Keeley et al., 2003). Plants need surviving meristems (growing tips) and stored reserves (often as starches stored in roots; Bond and Midgley, 2000) to sprout after an injury. Allocation of resources to storage means that the resources cannot be used to support growth or reproduction; thus, species that sprout effectively after disturbance may devote limited resources to seed production. Species vary greatly in their allocation to resprouting versus seeding strategies; the ability to resprout vigorously is of particular value under unpredictable and/or frequent fire regimes; non-sprouting species may be eliminated completely under a very short fire cycle (Keeley and Zedler, 1978).

Highlights

- Many seed-bank forming species have light-sensing proteins in their seed coat, and will germinate when light increases after thinning, or when they are exposed to light when soil is disturbed during forest management operations.
- Germination of some species requires stimulation by fire; the mechanism can be either disruption of seed coat by heat shock or detection of chemicals associated with charred wood and smoke.
- Fuels treatments that do not include prescribed burning are unlikely to elicit germination of species with fire-dependent germination.

5. Vegetation and Fuels Management Treatment Methods on the LTBMU

Vegetation and fuels management treatment methods currently in use on the US Forest Service Lake Tahoe Basin Management Unit can be broadly classified in hand- or mechanical-thinning categories. The choice of a method usually implies a set sequence of subsequent methods for disposal of biomass, although there is always some flexibility. The hand method comprises hand-thinning of shrubs and small-diameter (up to 14” or 36 cm DBH) trees followed by piling and burning. It is usually reserved for sensitive areas such as steep slopes and stream zones. Mechanical methods can be either cut-to-length or whole-tree harvesting. With both methods, tree boles and much biomass are removed to landings. Mechanical mastication is then applied to small-diameter trees and shrubs. Management plans call also call for follow-up prescribed underburns but to date this treatment has only been applied to a very limited area.

5.1 Hand-thin and pile-burn.

Removal of shrubs and small-diameter trees does not cause large increases in understory light (Wayman and North, 2007), and so has limited potential to enhance representation of light-loving plant species. Because of the lack of involvement of tracked or wheeled equipment, there is minimal mechanical soil disturbance involved with this method. Pile burning is the most ecologically significant aspect of the packet of practices associated with this method. Impacts associated with pile burns are usually thought of as being deleterious, but there are reasons to expect some direct ecological benefits associated with pile burns. As practiced in the Lake Tahoe basin, fires are sometimes allow to creep out away from burning piles, thus providing a limited-scale prescribed underburn.

There can be long-lasting adverse impacts to soil directly under burn piles. Slash-pile burning can sterilize the soil by eliminating viable seeds and the mycorrhizal spores that plants require for properly functioning root systems (Korb et al., 2004; Wolfson et al., 2005). Some exotic invasive plants are more capable of colonizing burn-pile scars than native plants (e.g., the Tahoe invader diffuse knapweed, *Centaurea diffusa* (Scherer et al., 2000)). Burn-pile scar invasion by exotic plants can be reduced by the addition of native plant seed and mycorrhizal inoculate shortly after piles are burned (Korb et al., 2004).

Disturbance of organic soil horizons (e.g., duff) built up by fire suppression is a double-edged sword. Thick organic horizons present a challenge to establishment of many plants, and disturbance to or scarification of the organic horizon to provide bare mineral soil for rooting is crucial to regeneration of canopy trees (Helms and Tappeiner, 1996) and many understory plants. In the Teakettle study, treatments that enhanced fire intensity by adding logging slash to the soil had more vigorous understory response than treatments involving prescribed fire alone (Wayman and North, 2007). A greater amount of logging slash resulted in hotter fires, greater organic horizon consumption, and better germination of understory plant species. Burning thinned areas resulted in an increase in bare mineral soil (>50% bare mineral soil in thinned and burned stands compared with ~20% in control stands): burning in thinned stands had a much larger impact on understory plant response than thinning intensity. Prescribed fires alone were not particularly favorable to understory plant response, perhaps because they were ignited under cool, damp conditions. Thus, prescribed burning of scattered logging slash can result in hot burns that consume large patches of the organic horizon. The Teakettle study did not involve pile burning, but it is possible that small burn piles could provide some ecological benefits that are analogous to those from burning slash from overstory thinning observed in the Teakettle study.

Pile burning allows burns to occur outside the usual burning seasons, and sometimes it is even possible to ignite piles after snow has fallen. Under such circumstances, of course, fires would not creep away from burn piles. Studies on season-of-burn (e.g. spring vs. fall) have shown that some understory species respond positively, or at least resiliently, to burning regardless of season, but several species are sensitive. For example, western needlegrass (*Achnatherum occidentale*), a species present in the Lake Tahoe basin, declines after spring burns but is stimulated by fall burns (Metlen and Fiedler, 2006; Knapp et al., 2007). Overstory tree mortality may be higher after fall burns (Thies et al., 2005; but see Harrington, 1993), as may be the ground cover of invasive downy cheatgrass (*Bromus tectorum*) and bull thistle (*Cirsium vulgare*; Kerns et al., 2006). These studies are most relevant to broadcast burning, but may also be relevant to pile burn + creep.

5.2 Mechanical Thinning + Mastication

Mechanical treatments aimed at removing understory and overstory trees allow increased light transmission to the understory, which can increase understory productivity and species richness (Metlen and Fiedler, 2006). Treatments aimed at decreasing crown fire risk by increasing spacing among residual trees are likely to allow less light transmission to the understory than patchier more heterogenous treatments, which may be better for plant species diversity. The degree of increase in understory light after thinning operations will depend on the canopy stratum and/or tree diameter class targeted: an overstory, crown-reduction canopy thinning is likely to result in large increases in average understory light levels, whereas thinning of only small-diameter trees will result in smaller (often immeasurably small) changes in understory light (Wayman and North, 2007).

The addition of woody material, a high-carbon substrate, to a soil surface has many effects on ecosystem properties that are addressed in detail in other papers in this volume (Moody et al. *this issue*, Verburg et al. *this issue*). Briefly, the addition of woody material can cause short-term immobilization of nitrogen and alter availability of mycorrhizal inoculate that plant roots require. The size of the woody particles dispersed on the soil is important (Wolk and Rocca, 2009). Small wood particles, (i.e., <10 cm or 4 in. in any dimension) spread evenly on the soil surface, may cause some of the same problems associated with the organic soil horizon typical of forests subject to fire-suppression (Landhaeusser et al., 2007) . Although chipping and spreading was a feature of some earlier fuels reduction projects in the Lake Tahoe basin, it no longer features in LTBMU management plans. Mechanical mastication of trees and shrubs results in larger wood particles, which are less likely than chips to create an impenetrable surface layer.

A study of fuels-reduction and mastication in southern Oregon oak woodlands showed that there was sufficient space between masticated particles to allow many plants to grow back after treatment (Perchemlides et al., 2008): average proportion of ground surface covered by woody debris was 16%. Collins et al. (2007) did not report proportion of ground surface cover by woody debris after mastication, but they observed substantial regrowth of many species (Table 2). For Perchemlides *et al.* (2008), depth of particles and the extent of impacts were related to the amount of woody debris mastication in a given area. In many areas, a vigorous community of native annual forbs and exotic annual grasses was established 4 to 7 years after fuels reduction.

There can be increased rates of bark beetle infestation with chipping (Fettig et al., 2006). Thinning is recognized as an effective measure to reduce bark beetle-caused mortality, but several species of beetles are attracted to slash created during thinning (Furniss and Carolin, 1977). Fettig *et al.* (2006) confirmed that bark beetle attacks are exacerbated by chipping in ponderosa pine forests of California and Arizona, with 3-fold increases in attacks occurring on sites where slash was chipped versus scattered whole. Chipping in the fall rather than the spring caused lower infestation rates, and raking chips away from the bases of trees may further reduce infestations. Alternatively, bark beetle attacks can be beneficial for wildlife, providing food and nesting for woodpeckers and other cavity-using species (Saab and Powell, 2005).

6. Conclusions

Climatic gradients in the Lake Tahoe basin are steep, with attendant changes in vegetation. Historical reconstructions and studies from outside the Lake Tahoe basin can serve as target or reference ecosystems, but owing to the variability within the basin, some objective criteria (e.g., long-term average annual rainfall) should be used to determine relevance of a particular study. No single fuels treatment will maximize forest health and stand-level plant diversity because treatments select for different plant groups.

Fuels treatments have the potential to increase plant diversity at the landscape scale, but their effects are contingent on they are applied. The outcome is determined in part by how far the canopy is opened, how biomass disposal is accomplished, and how or if prescribed fire is applied. Mechanical treatments are likely to adversely affect shrubs and understory plants that thrive in low light (e.g., saprophytes). The duration of the adverse impact on shrubs is not well known, and may depend in part on the frequency of treatments. A number of shrub genera that are prevalent in the Lake Tahoe Basin resprout only weakly, and managing for their persistence may be challenging in the absence of prescribed burning. Fuels treatments that open the overstory canopy can stimulate germination of short-lived (annual and biennial) species.

Fuels treatments involving overstory canopy thinning often strive for regular spacing of residual trees in order to minimize propagation of fire. Even spacing does not mimic historical stand structures, and may not provide sufficient light for regeneration of the shade-intolerant pine species, if desired. Heterogeneous thinning that produces variable gaps will maximize stand-level biodiversity. Method of disposal of biomass may be as important as the thinning treatment in its effects on vegetation response. Pile-burning (with creep) offers one of the best current opportunities to reintroduce fire, albeit in a limited way, to the forested landscape of Lake Tahoe. Pile-burning has aspects that are potentially harmful, but may provide the benefit of reducing the soil organic horizons and providing a source of ash and charred wood that can stimulate species requiring fire-related cues to germinate. Some taxa, however, require heat-shock cues for which there is no non-fire analogue. The lack of prescribed fire is likely to reduce the presence of species with heat-based germination cues, which includes ecologically important plant functional groups such as nitrogen fixers.

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Effects of Fuels Management on Future Wildfires in the Lake Tahoe Basin

Tadashi J. Moody, Scott L. Stephens, Max A. Moritz*[1]

1: Division of Ecosystem Science, Department of Environmental Science, Policy and Management, University of California Berkeley, 137 Mulford Hall, Berkeley, CA 94720-3114, USA
*Corresponding Author

Abstract

Fuel treatments have become an accepted means of mitigating the risk of high severity fires in the dry forests of the western US, and our current understanding of how fuel treatments affect wildfire relies on a variety of sources. Here we review what is known from research that is directly relevant to the Lake Tahoe Basin (LTB). Despite current scientific research across the western US and much general scientific study within the LTB, there is surprisingly little direct research on fuels management practices here. Fuel treatments can include various forms of thinning and/or prescribed burning, designed to reduce volume and continuity of fuels and subsequently decrease the risk of uncharacteristic fire effects. Of particular interest in the LTB are the effects of thinning treatments performed in conjunction with mastication – the chipping, crushing, or shredding of non-merchantable woody biomass (small trees and shrubs). Masticated fuel beds are difficult to study because current methods of fuel load estimation may not perform well, and adequate fuel models do not exist for them. Experimental and observational evidence suggests that masticated fuel beds may perform like activity fuels and increase severity of effects in post-treatment fires. Mastication followed by a surface fuel treatment such as prescribed fire may reduce tree mortality in future wildfire. Riparian areas are also of concern in the LTB because current management policy in the Sierra Nevada greatly restricts fuel management options and within these zones. Variation in fuel moisture, vegetation composition, and stream order may result in complex patterns of fire frequency, severity, and behavior within and between riparian areas. Prescribed fire has successfully been employed in riparian areas in the Sierra Nevada with minimal short-term effects on several biotic and abiotic characteristics, and water quality in LTB may also relatively unaffected by prescribed fire. Prescribed fire alone may not achieve management goals, depending on whether they are for fire hazard reduction or ecological restoration. Similar to riparian areas, options for fuel treatments on steep slopes are limited. Prescribed fire and/or jackpot burning, while difficult to implement in the LTB, may be the best option for these areas. Evaluation of treatment effectiveness depends on fire behavior and effects models, which have not been directly tested in the LTB. Model output could be improved

with better fuel models for treated stands (e.g. masticated fuel beds), or by improving inputs such as species bark thickness equations. Regardless of the models used, better fire weather information is needed for use in fire planning and management. Solutions to fire management problems in LTB are hampered by a lack of scientific research and a means for assessing tradeoffs between competing human and natural values.

Introduction

Although there is increasing uncertainty over how much of prehistoric forest landscapes burned in predictable low-intensity surface fires (e.g., Russell et al., 1998; Schoennagel et al., 2004; Hessburg et al., 2007), it is generally accepted that dry forest types of the western United States have been altered through over a century of novel conditions, particularly those that once experienced frequent, low-moderate intensity fire regimes (Agee and Skinner, 2005). Because these changes involve various land management practices – most notably fire suppression, but also logging, grazing, and urban development – simple time-since-fire metrics do not always predict areas that will burn at high severities (Franklin and Agee, 2003; Stephens and Ruth, 2005; Odion and Hansen, 2006). In contrast, patterns of extreme fire weather occurrence can act as consistent drivers of fire size and severity patterns, but we have limited knowledge of fire weather events in space and time. Regardless, many forests which experienced low-moderate or mixed severity fires prior to Euro-American settlement are now at greater risk of high severity, stand replacing crown fires that are often difficult to contain or suppress. This is a serious concern for the increasingly populated Lake Tahoe Basin (LTB).

Uncharacteristically severe fires are due in large part to changes in the structure of live and dead vegetation (fuels), such as increases in the volume and continuity of dead woody material on the forest floor (primarily surface fuels), decreases in forest canopy base height (increased ladder fuels), and increased density of forest canopies. These alterations can result in increased surface fire intensity (heat output), increased ability of fire to reach forest canopies, and increased capacity for fire to spread through the canopy. The net outcome is more severe fire effects on forest resources and greater difficulty for firefighters in protecting life, property, and values at risk, particularly where human development on fire-prone landscapes has created a complex wildland-urban interface (WUI) problem. Alteration of vegetation structure and continuity of fuels has become an accepted means of mitigating the risk of high severity fires (Grahm et al., 2004). Fuel treatments can include various forms of thinning and/or prescribed burning designed to reduce volume and continuity of fuels, and subsequently reduce the risk of uncharacteristic fire effects. Retaining the largest trees in forest stands also increases the resistance to high severity wildfire (Agee and Skinner, 2005; Stephens and Moghaddas, 2005a).

Policy and Management Context

The general goals of fuels treatments – to reduce fire hazard, restore ecosystem health, or both – are generally agreed upon. However, specific application of fuel treatments by skilled fire and fuels managers requires careful consideration of many issues, such as where and when to apply limited resources to vast areas of forests that may be in need of fuel treatment. What types of fuel treatments to apply can be a difficult problem, given that different treatments in different locations have varying effects, not only on potential fire behavior but on other forest resources as well. Fuel treatment decisions have potential ramifications in terms of air quality, water quality, wildlife habitat, soil resources, vegetation communities, and many other ecosystem elements (Collins et al., 2007; Kobziar et al., 2007; Amacher et al., 2008; Moghaddas and Stephens, 2008), issues covered by other papers in this volume. Additionally, fuel treatments should be considered in the context of larger land management goals and policies.

The Lake Tahoe area stands out not only for its natural beauty but also as a striking example of the complexity of managing fire and fuels in the altered forests of the western United States. Since its sighting in 1844 and subsequent displacement of the native Washoe, over 150 years of Euro-American settlement and varying land uses (e.g., recreation, timber production, commercial fishing, grazing and urban development) have altered the terrestrial ecosystems of the LTB dramatically from pre-settlement conditions (Elliott-Fisk et al., 1996). Much of the forested land of the LTB today is relatively young, densely stocked, and generally homogenous, owing to intensive logging efforts in support of Comstock Era mining. Urban development within many areas of the LTB has created extensive WUI areas in which the necessities of fire-safety and structure protection become intermixed with goals of resource protection and overall forest health. Recreation and tourism, the primary industry in the LTB today, depends greatly on the quality and health of the Lake Tahoe ecosystems (Elliott-Fisk et al., 1996). Changes in ecosystem elements such as water quality, air quality, wildlife habitat, soil resources, and plant communities affect both the residents living in the WUI and people visiting for the beauty and vast recreational opportunities. Both groups depend in direct and indirect ways on forests that are not only fire-safe but also ecologically resilient.

Fire planning and fuel treatment efforts around the basin have begun to address this situation, but land management and planning in the LTB is complex. The Tahoe Regional Planning Agency (TRPA) regulates land use in the basin involving federal agencies, two states, local governments, private landowners and non-profit and collaborative groups with stakes or responsibilities in the LTB. National forests collectively cover 78% of the land in the basin and are managed as the Lake Tahoe Basin Management Unit (LTBMU). Fire and fuel management by these groups occurs in the context of many environmental and social issues within the basin. Effects of land use decisions on lake clarity, water quality, air quality, soil erosion, sensitive species, the recreation industry, and economic development are all critical considerations. Past efforts, such as the Sierra Nevada Ecosystem Project (Elliott-Fisk et al., 1996) and the Lake Tahoe Watershed Assessment (Murphy and Knopp, 2000), and current ones, such as the

Comprehensive Science Plan for the Lake Tahoe Basin, have attempted to synthesize knowledge and identify key questions relating to the health and future of the LTB environment.

Ecological and Scientific Context

Wildland fire operates on many different spatial and temporal scales. In an annual and stand-level context, the process of combustion of live and dead vegetation serves to reduce above-ground biomass that has built up over some period of time. Forests can increase or decrease in fire hazard (Johnson and Gutsell, 1994) as fuels build up on the ground and in the vegetation canopy. Depending on how often a region is exposed to extreme fire weather conditions, fire hazard may be less constrained by time since the last fire and fuel accumulation (Moritz, 2003). A relevant example in the LTB may be the region near South Lake Tahoe, which experiences relatively severe fire weather episodes and has a long history of severe fire events (Russell et al., 1998; Murphy et al., 2007).

First order fire effects are those that occur as a direct or immediate result of the combustion process. Examples include plant mortality, either by combustion or by exposure to lethal temperatures for sufficient durations, atmospheric emissions, and reduction of fuel biomass. On landscape and multi-annual scales, fire serves in many systems as a natural form of ecological disturbance. The frequency, seasonality, size, intensity, severity, spatial complexity, and type of fires that typify a particular landscape define its fire regime (Gill, 1975). Alteration of fire regimes outside their natural range of variability, such as those changes resulting from historical land management practices or from current fuel treatments, can have consequences for fire behavior, and subsequent first order or secondary effects. Defining desired future conditions or trends for a landscape and methods for achieving those conditions should consider these consequences.

Our current understanding of how fuel treatments may alter fire behavior and effects in western forests relies on several sources: our scientific understanding of fire ecology in various forest types, anecdotal and direct observational evidence of wildfire in treated and untreated areas, pre- and post- wildfire vegetation monitoring studies, fuel treatment experiments, and our ability to predict fire behavior and effects through models. Current models in use include models for surface fire behavior (Rothermel, 1972), crown fire initiation and spread (Van Wagner, 1977), fuel beds (Anderson, 1982; Scott and Burgan 2005), fire effects (Ryan and Reinhardt, 1988), and those that integrate multiple aspects of fire behavior and effects (Finney, 1998; Carlton, 2004). Most experimental or monitoring studies necessarily use fire models, as studying wildfire under the conditions that fuel treatments are intended to address is often impossible. In a few instances, areas that had been treated in the recent past have burned in wildfires, providing opportunity for study (Stephens et al., 2008a).

Several goals guide the implementation of fuel treatments in forested ecosystems, including reducing fire size and spread rate, keeping fire out of the canopy, and decreasing fire intensity. Protecting lives, structures, and values at risk, improving effectiveness of firefighting efforts, and creating safety zones and avenues for firefighter egress are also key considerations. In terms of resiliency and forest health, fuels treatments can be designed so that during a hypothetical ―problem fire" (e.g. near-worst case scenario) some proportion of the forest trees will survive. Locating treatments on the landscape to achieve the above goals is a topic of current research and debate. Defensible fuel profile zones (DFPZs) (Agee et al., 2000) and strategically placed landscape area treatments (SPLATs) (Finney, 2001) are two current models for this.

While a substantial general literature exists for many ecosystem elements in the LTB, our understanding of pre-settlement vegetation structure and condition, pre-historical fire regimes, and other topics that can inform fire and fuels managers is still developing. Recent work (Taylor, 2004; Taylor and Beaty; 2005; Beaty and Taylor, 2007) has helped to forward our understanding in LTB of contemporary old-growth and pre-settlement stand structure, fire regimes, and exogenous factors contributing to fires patterns on the landscape (e.g. climate). Taylor (2004) established reference conditions for Jeffrey pine-white fir (Pinus jeffreyi Grev. & Balf. – Abies concolor (Gordon & Glend.) Lindley), red fir-western white pine (Abies magnifica Andr. Murray – Pinus monticola Douglas), and lodgepole pine (Pinus contorta ssp. murrayana (Grev. & Balf.) Critchf.) forests on the eastern shore of Lake Tahoe. Comparison to current conditions showed that contemporary Jeffrey pine-white fir forests are denser and more homogenous than presettlement, while current red fir-western white pine forests are also denser but have more lodgepole pine than their presettlement counterparts. Taylor (2004) and Taylor and Beaty (2005) also established fire regime characteristics for these forests, showing years of widespread presettlement fire to be closely associated with drought. Beaty and Taylor (2007) estimated fire regime parameters for old-growth mixed conifer forests on the West Shore, showing fire return intervals of 9-17 years for 0.5 ha (~ 1 acre) plots. Previous work in remnant old-growth forests in the LTB (Barbour et al., 2002), in addition to relatively intact Jeffrey pine-mixed conifer forests in northern Baja California (Stephens and Gill 2005, Stephens et al. 2008b), can assist in our understanding of forest dynamics in the LTB. Studies within the Sierra Nevada and in similar coniferous forest types in the western United States may also help to further our understanding of forest dynamics, potential fire behavior, and ecological effects.

Key Questions

Despite current scientific research efforts regarding fire and fuels management in the western United States and much general scientific study within the LTB, there is a surprising dearth of direct research on fuels management practices in the LTB. This paper is part of a larger effort by the U.S. Forest Service Pacific Southwest Research Station and the Tahoe Science Consortium to review available scientific literature relevant to fuel treatments and their effects on ecosystems in the Lake Tahoe Basin, as an aid to land and fire managers in the LTBMU. The specific goal of this paper is to synthesize scientific information that may facilitate an understanding of the effects of varying potential fuel treatment methods on future wildfire behavior and first order effects in the LTB. The LTBMU staff has identified specific questions of concern to be addressed in this review:

1. What fire behavior and effects can be expected during a wildfire in chipped and masticated treatment units where biomass is left on site?
2. What is known about wildfire in unmanaged stream environment zones (SEZs)?
3. What evidence is there for treatment effectiveness on steep (i.e. >30%) slopes, which constitutes much of the LTB?
4. How well do current fire effects models work in the LTB?

Fire and Masticated Fuel Beds

Thinning treatments to reduce ladder or crown fuel volume or continuity are increasingly being performed in conjunction with mastication – the chipping, crushing, or shredding of non-merchantable woody biomass (small trees and shrubs) – with the goals of reducing crown fire activity (by removing ladder fuels), surface fire intensity (by reducing fuel bed depth), and subsequent tree mortality. Masticated materials from these operations are often left on site, under the premise that this shorter, more compact fuel bed will meet these goals. Total fuel load is not reduced immediately unless biomass is removed from the site, or mastication is followed by a surface fuel treatment such as prescribed fire. Mastication does change fuel bed characteristics such as depth, bulk density, moisture absorption and packing ratio, as well as fuel particle characteristics such as shape and surface area to volume ratio (Kreye and Varner, 2007; Kane, 2007), and thus presumably changes fire behavior. While flaming front surface fire intensity may be reduced or increased, the more dense fuel bed may result in longer flaming or smoldering combustion, and subsequently longer heat pulses to the forest floor and vegetation, possibly causing higher levels of mortality. These potential changes in future fire behavior and effects have not been well quantified. They are difficult to study because current forms of fuel load estimation (e.g. Brown, 1974) may not perform well for masticated fuel beds, where materials are of different shape and sizes than natural fuels (Hood and Wu, 2006; Kane, 2007). Additionally, adequate generic fuel models for use with the Rothermel (1972) fire spread model (e.g. Anderson, 1982; Scott and Burgan, 2005) do not currently exist for chipped or masticated fuel beds (Kane, 2007).

To date no published work specifically on fire behavior or fire effects in masticated fuel beds exists for the Lake Tahoe region. Performance of masticated fuel beds has been addressed experimentally in several studies by either: 1) measuring pre- and post-treatment fuel beds and estimating potential fire behavior and effects through standard or modified-standard fuel models, or 2) directly measuring fire behavior and effects during prescribed fire. In a replicated experimental study examining fire and fire surrogate treatment effects in the Blodgett Experimental Forest (north-central Sierra Nevada, approximately 35k west of the LTB), Stephens and Moghaddas (2005b) found that fuel beds resulting from prescribed fire treatments and mechanical treatments (thinning and mastication) followed by prescribed fire, performed the best in terms of predicted fire behavior and tree mortality. Mechanical treatments alone also reduced predicted fire behavior and mortality as compared to controls, but still resulted in high mortality under severe fire weather conditions. They conclude that mastication is effective at reducing ladder fuels, but also increases surface fuel depth and continuity, which can result in more severe fire effects. In a study of mastication and spring prescribed fire in mixed shrub woodlands in the Whiskeytown National Recreation Area of northern California (Bradley et al., 2006), masticated fuel beds subjected to prescribed fire resulted in greater heat outputs and mortality of overstory and pole-sized oaks and conifers, when compared to non-masticated treatment units. Busse et al. (2005) found that lethal soil temperatures (>60 deg. C or 140 deg. F) could be reached with burning of masticated shrub fuels, particularly in dry soils with masticated fuel beds > 7.5cm (3 in.) in depth. Prescribed fire in masticated fuel beds in sites in the northern Sierra Nevada and southern Cascades (Knapp et al., 2006) resulted in higher than expected overstory crown scorch, and subsequent tree mortality.

The ultimate test of fuel treatment effectiveness is performance under real wildfire conditions. Examples of this are obviously rare, and analysis of treatment performance is usually either observational/anecdotal (fire behavior) or post hoc (fire effects). In a study of four wildfires in the Sierra Nevada, Hansen and Odion (2006) found that fire-induced mortality was greater in 5 of 6 thinned sites when compared to unthinned sites. The remaining site had been masticated months prior to the wildfire, and showed lower mortality when compared to unthinned site. Empirical evidence for fuel treatment effects and effectiveness during several large fires (Hayfork, Tyee, Megram, Hayman, and Cone) was summarized by Agee and Skinner

(2005). They conclude that important considerations include treatment of residual treatment/activity fuels, scale of treatment units, and age of treatment units. The Biscuit fire afforded a rare opportunity for study, when it burned through previously treated forest stands. Though residual surface fuels were not masticated, thinning-only treatments resulted in higher surface fuel loads, and subsequently higher surface fire intensity and greater mortality from the Biscuit fire than those treated with a thinning followed by prescribed fire (Raymond and Peterson, 2005). Similar results were found after the Cone Fire burned through pre-fire treatments at Blacks Mountain Experimental Forest in Northern California. Ritchie et al. (2007) found that probability of tree survival after the Cone Fire was greatest for areas treated with thinning and prescribed fire, whereas in thin-only units it was substantially less, but still much better than the untreated forest. Though the latter two examples don‘t deal directly with mastication, they serve to underscore the point that increases in surface fuels from treatments can have adverse effects on fire behavior and tree mortality.

The Angora Fire, one of the highest profile fires in the west in 2007, is the closest and most recent example of fuel treatment effectiveness in the LTB. There were 194 ha (480 acres) of treated US Forest Service land burned in the fire, of which only 30 ha (75 acres) burned as crown fire (Murphy et al., 2007). While fuel treatments did not include mastication, they did consist of pre-commercial and commercial thinning, followed by hand thinning, piling and burning (Murphy et al., 2007). Several efforts are underway to evaluate the efficacy of the fuel treatments, as well as effects of the fire on other forest ecosystem elements (Safford pers. comm.).

Highlights

- Current forms of fuel load estimation may not perform well in masticated fuel beds since masticated materials are of different shapes and sizes than natural fuels.
- Adequate generic fuel models for use with the Rothermel fire spread model do not currently exist for chipped or masticated fuel beds.
- To date no published work specifically on fire behavior or fire effects in masticated fuel beds exists for the Lake Tahoe region.
- Important considerations for masticated fuel beds may include treatment of residual fuels, scale of treatment units, and age of treatment units.

Fire and riparian environments

Historical logging did not tend to discriminate between upland and riparian forests, yet current management policy of riparian environments in the Sierra Nevada – often called stream environment zones (SEZs) – greatly restricts fuel management options and activity within these zones. This raises questions about the degree to which fire suppression has altered natural fire frequencies and severities in SEZs. Observations of wildfires and additional anecdotal evidence suggest that "unmanaged" or unaltered SEZs may, under certain conditions, exhibit rapid rates of fire spread. Deciding whether or not to leave SEZs in their current state, however, will require a possible tradeoff in competing risks and values (e.g., water quality, habitat, and fire hazard), and acceptance of compromise is likely in LTB. To address this issue, it is also necessary to have some understanding of the prehistoric conditions within SEZs, an assessment of the fire behavior and expected effects if left unaltered, and a clear definition of desired future outcomes and related inherent tradeoffs.

Although there are several recent papers reviewing different aspects of wildfire in riparian areas (e.g., Bisson et al., 2003; Dwire and Kauffman, 2003; Reeves et al., 2006; Pettit and Naiman, 2007), there is general agreement about a lack of knowledge concerning fire in these environments. There is no published work on wildfires and SEZs in LTB. It is widely held that fires burned prehistorically in many SEZs, but less often than in upland areas, due to higher moisture levels in live and dead fuels closer to watercourses. Wind speeds may be lower than in surrounding uplands, which can lower fire intensities in riparian areas, although channeling of winds in steeper riparian areas could occur. Some have noted that fire frequencies in drier environments may be similar between riparian and upland areas (e.g., Dwire and Kauffman, 2003); others report similar average fire intervals but higher variation in riparian areas (Skinner 2003). In general, variation in fuel moisture, vegetation composition, and stream order may result in complex patterns of fire frequency, severity, and behavior within and between SEZs. Depending on conditions during a given fire, some riparian areas are therefore likely to act as barriers to spread, while others might burn more readily (Taylor and Skinner, 2003; Pettit and Naiman, 2007).

Given the lack of reference conditions for these areas and the heterogeneity of fire behaviors to be expected in SEZs, it is still unclear what constitutes ―uncharacteristically severe” fire in riparian areas. Although the recent Angora Fire in LTB was catastrophic in human terms, was the high severity riparian burning that occurred during extreme weather conditions outside the natural range of variability? Due to higher biomass productivity in SEZs, some sections will naturally capable of carrying higher severity fires during periods of drought and dieback or during episodes of extreme fire weather (Agee, 1998). Accommodation of a range of natural disturbance severities, both due to fire and other physical processes, is actually necessary to maintain riparian habitats and biodiversity (Bisson et al., 2003). Some degree of high severity burning is therefore to be expected in SEZs, similar to mixed severity fire regimes of higher elevation coniferous forests.

In terms of fire regime restoration alone, SEZs have been classified as relatively low priorities for fuel treatments. Where concerns over fire hazard are considered of paramount importance, riparian areas are still viewed as sensitive to mechanical fuel reduction techniques, and prescribed fire is seen as the most appropriate tool (Weatherspoon and Skinner, 1996; Brown et al., 2004). Prescribed fire has successfully been employed in riparian areas with minimal short-term effects on several biotic and abiotic characteristics (e.g., Beche et al., 2005), and water quality in LTB may also relatively unaffected by prescribed fire (e.g., Stephens et al., 2004). There is some evidence for shifts in species composition in riparian areas due to fire suppression, such as conifer encroachment (Kobziar and McBride, 2006). The lack of fire and the relatively high site productivity in and near riparian areas has resulted in the production of many large trees in the past 100 years. In one study, high intensity prescribed fire was applied to reduce fuel loads and increase the light for deciduous plants near streams, but it was not successful in reducing tree density in mixed conifer forests in the Sierra Nevada (Beche et al., 2005). Reduction of tree encroachment in riparian areas may therefore require the use of mechanical methods, since trees have become large enough to be very difficult to kill by prescribed fire. If mechanical methods are deemed necessary for habitat restoration in riparian zones, approaches would need to be designed to limit soil disturbance, compaction, and erosion.

Due to higher moisture levels, riparian zones in Sierra Nevada forests normally should not act as ―fuses" to carry fire across portions of the landscape where efforts to limit fire spread would otherwise be successful (Weatherspoon and Skinner, 1996). Regardless, decisions regarding fire hazard in riparian areas will ultimately be made in the face of uncertainty and competing values (Bisson et al., 2003), so some tradeoffs between the needs of human and ecological systems may be inevitable.

Highlights

- Although there are several recent papers reviewing different aspects of wildfire in riparian areas, there is general agreement about a lack of knowledge concerning fire in these environments. There is no published work on wildfires and SEZs in LTB.
- Variation in fuel moisture, vegetation composition, and stream order may result in complex patterns of fire frequency, severity, and behavior within and between SEZs. It is still unclear what constitutes ―uncharacteristically severe” fire in riparian areas.
- Riparian areas are still viewed as sensitive to mechanical fuel reduction techniques, and prescribed fire is generally seen as the most appropriate tool, although in some areas encroaching conifers have become large enough to be very difficult to kill by prescribed fire alone.

Fire and steep slopes

A large portion of LTB is characterized by relatively steep slopes (i.e. >30%). Fire behavior and spread up steeper slopes is analogous to that observed under higher wind speeds, as flames are not perpendicular to the ground surface and more rapidly preheat the fuels ahead of the flaming front. While many of these areas are experiencing similar changes to forests of more moderate slopes (i.e. higher tree densities, fuel loading and continuity), fuel treatment options in these areas are often limited. Erosion potential on steep slopes is much higher, so vegetation modification there can be detrimental to soil stability and water quality. In some cases access can be difficult, and in others many mechanical fuel modifications are simply not feasible (Weatherspoon, 1996). Mechanical treatment equipment is limited to moderate slopes, and other treatment techniques such as hand thinning and helicopter thinning are costly. This creates problems for strategic placement of fuel treatments, despite the fact that these areas might otherwise be good candidates (e.g., downslope of a densely populated location).

Pollet and Omi (2002) and Weatherspoon (1996) suggest that prescribed fire, as well as hand piling followed by jackpot burning, may be effective alternatives on slopes where mechanical treatment is not feasible. Safely using prescribed fire on steep slopes in LTB may therefore be relatively costly, and air quality concerns may severely limit burning, particularly on the west shore of the lake. However, these treatments may be overall less costly than suppression efforts and subsequent post-fire rehabilitation in the same areas if a severe wildfire is to occur.

Highlights

- Mechanical treatment equipment is limited to moderate slopes, and other potential techniques such as hand thinning and helicopter thinning are costly.
- Prescribed fire, as well as hand piling followed by jackpot burning, may be effective alternatives on slopes where mechanical treatment is not feasible

Adequacy of fire effects models

In order to evaluate fuel treatment effectiveness without treatment units being subjected to wildfire, managers need to accurately predict effects (e.g. tree mortality) in residual forest stands under a variety of weather conditions (e.g. 80^{th}, 90^{th}, 95^{th} percentile fire weather). Fuel treatment performance is often based on what proportion of the residual stand will survive a wildfire under certain weather conditions. An example of the modeling process might be as follows. The residual stand is first classified in terms of fuel model and stand characteristics. These data are input into fire behavior models, such as those included in the software package FMAPlus (Carlton, 2004). With proper fuel model classification and weather conditions, FMAPlus can predict crown scorch height which, along with stand tree heights, species, and diameter at breast height (dbh) can be used to predict tree mortality, using models developed by Ryan and Reinhardt (1988). The Ryan and Reinhardt model is the basis for the tree mortality model currently used by the most common fire behavior and effects models used by managers in the USA, namely BehavePlus, First Order Fire Effects Model (FOEFM), and the Fire and Fuels

Extension to the Forest Vegetation Simulator (FFE-FVS) (Hood et al., 2007). The accuracy of these prediction efforts thus depends in large part on both the models themselves (fuel models, fire spread models, mortality models), and the inputs to the models.

Little work has been done specifically testing the adequacy and accuracy of fire effects models in the LTB. However, a recent study by Hood et al. (2007) examined post-fire mortality of the most common conifer species in the Western US after 21 different fires. The species examined included the dominant conifer species in the Lake Tahoe basin, including Jeffrey pine, ponderosa pine (Pinus ponderosa Laws.), red fir, white fir, incense-cedar (Calocedrus decurrens (Torrey) Florin), lodgepole pine and sugar pine (Pinus lambertiana Douglas). Predictions of individual tree and stand level mortality were made based on crown scorch volume and dbh (inputs to the Ryan-Reinhardt model), and were compared with actual mortality 3 years post fire. Results varied by species and fire, but pertinent to the LTB were the findings that model classification of individual red fir trees was among the least accurate by species. At the stand level mortality was generally overpredicted for red fir and incense-cedar. At the fire level, the model tended to overpredict mortality of yellow pines (ponderosa and Jeffrey). Overall, accuracy of individual tree mortality generally increased with increasing probability of mortality. They suggest that model accuracy could be improved by incorporating a variable quantifying stem injury, and by improved bark thickness equations. Accounting for local ground fuel consumption during prescribed fire can also increase model accuracy (Stephens and Finney, 2002). More accurate analysis of fire weather variability and fire behavior prediction inputs, such as more appropriate fuel models for masticated fuel beds, should also improve subsequent effects predictions for mangers designing fuel treatments.

Highlights

- The 1988 Ryan and Reinhardt model is the basis for the tree mortality model currently used by the most common fire effects models used by managers in the USA.
- In a recent study of post-fire mortality of the most common conifer species in the Western United States, the authors suggest that model accuracy could be improved by incorporating a variable quantifying stem injury, and by improved bark thickness equations.
- Additional accuracy may be gained by more accurate analysis of fire weather, more accurate fuel models, or better accounting for local ground fuel consumption in prescribed fire.

Scientific Information on Fire in the LTB

Given that Lake Tahoe is one of the treasures of the Sierra Nevada, there is remarkably little direct scientific information about an ecological process as important as fire. In addition, the challenges that climate change will bring require that we take action now to achieve a more sustainable coexistence with wildfire in the future (Moritz and Stephens, 2008). New fire-related research in the LTB is crucial to answer the questions put forth earlier in this paper.

One key tool in common with all of the questions at hand is the application of models for fire behavior and subsequent fire effects. Though various forms of mastication are becoming popular for biomass treatment in Sierra Nevada forests, relatively little data exists on post-treatment fire behavior and effects. Because we cannot examine these effects in a wildfire or ―worst case scenario" setting, the best option for predicting outcomes would be to have an accurate and well performing model for masticated fuels, including how these fuels decompose. Fire effects models exist for evaluating potential tree mortality after various fuel treatments, but these too require further development and testing for successful application in LTB. In order for any model predictions to be useful, a thorough understanding of local fire weather is also required, since this is what dictates the conditions under which treatments are expected to perform. The importance of fire weather data in LTB is highlighted by the fact that ―high severity" fire weather conditions were estimated to be only 19 km/h (12 mph) based on weather station data near where the Angora Fire burned last year (C.G. Celio et al., 2004). However, gusts of up to 48-64 km/h (30-40 mph) were recorded by weather stations and firefighters during the Angora Fire (Murphy et al., 2007). Improving our understanding of weather related to problem fires in the LTB, having accurate fuel models for new types of fuel beds, and improving fire effects models for species and forest types within the LTB will be vital as we plan to treat more and more of the landscape.

Two of the most difficult environments for fire management decisions – riparian areas and steep slopes – will probably continue to pose challenges in the LTB. Understanding the thresholds at which fire enters or is retarded by SEZs will help us to predict fire behavior and effects in riparian areas. This will also inform management as to whether leaving SEZs untreated is a viable management strategy, although tradeoffs in other important values will still need to be assessed. A similar situation exists concerning fuel treatments on steep slopes, and prescribed fire in these locations should be given greater consideration. In general, more extensive use of prescribed fire in the LTB will require that the benefits of restoring an important natural process and burning in relatively controlled circumstances be factored into a decision-making process that is relatively inflexible (e.g., regarding air quality).

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Soil and Water Quailty Response to Fuels Management in the Lake Tahoe Basin

Paul. S.J. Verburg[1] , Watkins W. Miller[2], Matt D. Busse[3], Erin Rice[4], Mark E. Grismer[4]

1: Division of Earth and Ecosystem Sciences, Desert Research Institute, Reno, NV

2: Department of Natural & Environmental Resource Sciences, University of Nevada, Reno, NV

3: Pacific Southwest Station, United States Forest Service, Redding, CA

4: Department of Biological & Agricultural Engineering, University of California, DAvis, CA

1. Abstract

Fire suppression has caused a large accumulation of biomass in the Lake Tahoe Basin increasing the risk of catastrophic wildfires and dictating the need for a comprehensive fuel management program. However, fuel reduction treatments should be designed to minimize nutrient and sediment releases from soils into streams, groundwater, and ultimately, Lake Tahoe. Current fuel-reduction treatments include hand thinning, mechanical thinning (including cut-to-length, whole-tree harvesting, end lining, over the snow treatment, or mastication) for the initial treatment of standing vegetation. This is typically followed by treatment of residual ground fuels through either pile burning in hand thin units, or mastication within mechanical treatment units. Underburning is utilized as a maintenance treatment once initial fuels have been treated, and occurs approximately 5 to 7 years after the initial fuels treatment. Adequate knowledge of potential risks posed by treatments and Best Management Practices (BMPs) designed to mitigate, or avoid such impacts is essential for managers prior to developing fuel reduction strategies. This paper reviews the potential impacts of prescribed fire and mechanical thinning on soil chemical, physical, and biological properties in semi-arid forest ecosystems.

The main effect of prescribed fire on soil nutrients is a loss of N contained in the forest floor and possibly a transformation of P forms. Soil N and P concentrations may change but these changes are often short-lived and do not always impact stream water chemistry. Prescribed fire can affect soils through the formation of water repellent layers especially when soils are dry and soil litter cover is continuous, thereby decreasing water infiltration and increasing runoff and erosion. Prescribed fire can affect soil biota, especially in wet soils, but it is unclear how these effects impact ecosystem functioning. Burning of slash piles can cause localized, high severity

burn areas that can significantly impact soils but the effects on a watershed scale have not been quantified.

Mechanical thinning can affect soil physical properties such as bulk density and porosity, but these impacts are likely to be small since soils in the Lake Tahoe Basin are typically coarse-textured. The presence of slash on the soil surface can further minimize the impacts of mechanical thinning on soil compaction, but can also increase the intensity of subsequent fires and formation of water repellent layers.

Within the Lake Tahoe Basin, there is considerable concern regarding the management of Stream Environment Zones (SEZs). The wetter soils in SEZs most likely would limit the impacts of prescribed fire on soils but may increase the impacts of mechanical thinning. Pile burning in SEZs in the Tahoe Basin has not been permitted/implemented in the past in the Tahoe Basin, but the first projects to be permitted to include this activity are expected to occur in late 2009.

Although the literature review indicated some general trends, impacts depend on climate conditions, antecedent soil conditions, and soil type. Consequently, management decisions at the site-specific level require further quantitative assessment and follow-up evaluation, preferably using a set of standard measurement techniques and protocols. In addition, many of the studies address small-scale and short-term response to management. It is often unclear if localized impacts can be scaled up to the watershed level. In addition, if studies show adverse management impacts on soil characteristics, the short duration of many studies often limits the possibility to determine if these effects will persist over the long-term.

2. Introduction

Lake Tahoe's fame as one of the world's most spectacular deep mountain lakes is largely due to its exceptional clarity. This clarity was maintained due to low concentrations of nutrients in lake waters resulting in ultra-oligotrophic conditions (Goldman, 1974). Water quality in the lake has been evaluated continuously since the early 1960's. Since that time algal growth has increased by over five percent per year with a corresponding one foot per year decline in water clarity (Reuter and Miller, 2000). This growth was historically co-limited by nitrogen (N) and phosphorus (P), but existing data suggests a long term shift to predominantly P limitation (Goldman et al., 1993). The annual amount of P entering Lake Tahoe was mainly associated with sediment inputs (Hatch, 1997, Logan et al., 1987). In addition to P transport, fine (1-8 μm) sediments play an important role in the decline of water clarity because they scatter light when suspended in water (Swift et al., 2005).

Sediment and nutrients entering the lake are derived from five major sources: atmospheric deposition, stream discharge, overland runoff from intervening areas directly into the lake, groundwater, and shoreline erosion (Reuter, 1998) with surface, shallow subsurface, and groundwater runoff to be responsible for the majority of the sediment/nutrient delivery to Lake Tahoe. Throughout the lake's history, these processes delivered relatively low levels of sediments and nutrients resulting in exceptional water clarity. Over the past century, sedimentation rates have varied (Heyvaert, 1998). Rates increased during the Comstock Mining Era of the late 1800's due to widespread clear-cutting of the basin forests. After a reduction in sedimentation corresponding to a period of lower intensity land use, sedimentation rates again increased beginning in the 1950s to the present. Anthropogenic disturbance has caused the increased nutrient and sediment loading of water in the Tahoe basin by modifying soil chemical and physical properties and corresponding hydrologic responses.

During the past century fire suppression has caused a large accumulation of biomass in the Lake Tahoe Basin increasing the risk of catastrophic wildfires dictating the need for a comprehensive fuel management program. However, fuel reduction treatments should be designed to minimize nutrient and sediment releases from soils into streams, groundwater and, ultimately Lake Tahoe. Forest management may increase pollutant loading by generating smoke and mobilizing nutrients and sediments. In addition, forest management could impact key soil chemical, physical and biological properties that affect the development of native vegetation, and thus long-term ecosystem sustainability.

In this paper we review the literature describing the impacts of forest management on soils and water quality. We focus on chemical, physical and biological process impacts. Current fuel-reduction treatment practices in the Tahoe Basin include hand thinning, mechanical thinning (including cut-to-length, whole-tree harvesting, end lining, over the snow treatment, or mastication) for the initial treatment of standing vegetation. This is typically followed by treatment of residual ground fuels through either pile burning in hand thin units, or mastication within mechanical treatment units. The selection of a particular set of treatments for a given area is primarily based on site resiliency factors such as soil type, slope, proximity to Stream Environment Zones (SEZs), and expected soil moisture conditions. Underburning is utilized once initial fuels have been treated, and is scheduled to occur approximately 5 to 7 years after the initial fuels treatment. Maintenance burns occur after 10 to 20 years. Currently prescribed underburning has occurred on a limited basis in the Tahoe Basin, as the current effort is focused on completing the initial fuels reduction treatments throughout the wildland urban interface.

Our review specifically addresses these management strategies and aims to inform managers to what degree the current research supports the current fuels reduction treatment approach in the

Tahoe Basin, with regard to acceptable levels of management impacts on soil quality. The specific questions we address are:

1) How does forest management in the Tahoe Basin affect the potential build-up, release, and mobility of nutrients, specifically N and P?
2) How does forest management in the Tahoe Basin likely affect soil physical properties such as bulk density, water holding capacity, infiltrability, and other aspects of soil hydrologic function which could impact recharge, runoff, erosion, and nutrient discharge?
3) How does forest management in the Tahoe Basin affect soil biota?

We will attempt to synthesize the literature results and make recommendations regarding the benefits and risks associated with the various management strategies. Finally, we will point out some of the research needs and strategies recommended to advance management.

2.1. Ecological context

2.1.1 Soil nutrients

Nitrogen and P are two of the most critical nutrients necessary for the support of vegetation growth, yet their nutrient cycling and transformation processes differ dramatically. Nitrogen is one of the few nutrients that typically do not occur in parent materials, although some studies have reported the presence of some mineral-related N sources (Holloway et al., 1998). Most N enters terrestrial ecosystems through atmospheric deposition or by biological symbiotic and possibly asymbiotic N fixation. Atmospheric N can enter soils as wet or dry deposition either through direct deposition or as throughfall after canopy interception. Upon entering the soil, N can be taken up by the vegetation and microbial biomass or leached depending on the amount of uptake by biota and the form in which N is present. If N is present as NH_4, it typically adsorbs to the mineral surface and therefore is not prone to leaching. Any NH_4 that is not taken up by the vegetation can be converted to NO_3 via microbial nitrification which can easily leach from the soil profile. Part of the N incorporated in the vegetation can be returned to the soil as above-ground or root litter. This litter will become an energy source for microbial metabolism. If the C/N ratio of the litter is low, typically N will be mineralized; if the C/N ratio is high, it will be immobilized in microbial biomass limiting N availability for the vegetation. Usually, not all litter deposited in a year is decomposed the same year, so organic matter (and associated N) tends to accumulate in the soil either on the forest floor or, after humification, as soil organic matter. The relatively high atmospheric deposition rates estimates of N reported for Lake Tahoe (2 to 6.4 kg N $ha^{-1}yr^{-1}$ wet and dry) indicate that anthropogenic sources are significant (Dolislager et al, 2006). Despite these high levels, plant production in the Lake Tahoe Basin appears to be N limited given low annual N leaching rates form terrestrial ecosystems (e.g. Coats and Goldman, 2001). As a result, any disruptions in soil N availability could affect plant productivity and/or losses of N from soils into aquatic systems.

Phosphorus cycling differs from N cycling in that P has no gaseous form and most of the P enters ecosystems through the weathering of P-containing rocks. Approximately 94-98% of the total P is typically present in the mineral soil rather than the surface litter, although fire suppression in the Lake Tahoe Basin may have caused a significant accumulation of litter and thus organic P (and N) pools. Despite the abundance of total P in many soils, only a small fraction is available for plant uptake or soluble nutrient transport in the most readily available form of ortho-P. Similar to N, any P taken up by plants may enter organic matter through litterfall and can subsequently be mineralized via decomposition of organic matter by soil micro-organisms. Over time, P availability for plants and microbes typically decreases as a result of physical occlusion of P in other minerals, incorporation in resistant organic forms, or precipitation in stable mineral forms.

2.1.2 Soil physical and hydrologic characteristics

Physical properties of soils have a direct impact on hydrologic function, ecosystem productivity, and sustainability (Pickett and White, 1985, Childs et al., 1989). Soil structure, porosity, infiltration, thermal regime, and water storage are all properties that can be affected by management. Soil structure is an important determinant for hydrologic function since structure in combination with texture determines pore size distribution, bulk density and subsequent water infiltration/runoff. These hydrologic properties determine the susceptibility to erosion as well as available water for plant and microbial activity.

Current physical modeling of erosion involves the description of soil aggregate breakdown, subsequent particle detachment, and transport (Nearing and Parker, 1994). Aggregate breakdown rates are a function of aggregate stability, which is determined by several soil properties, including texture (Bradford et al, 1987), percentage Fe and Al (Le Bissonnais and Singer, 1993), exchangeable Ca or sum of exchangeable bases (Meyer and Harmon, 1984), exchangeable Na (Emerson, 1967), and organic matter (Tisdall and Oades, 1982). When soil aggregation is diminished or broken through soil compaction from heavy equipment, skidding or other traffic, soil infiltration rates, water holding capacity and aeration decrease, particularly in finer-textured, wet soils. Often such impacts are temporary and soil re-aggregation occurs in healthy forest soils. The importance and effectiveness of rainfall as an aggregate breakdown mechanism is greatest when soils are wet and aggregates are small (Leguedois and Le Bissonnais, 2004). Breakdown is proportional to rainfall intensity and duration of mechanical energy applied (Le Bissonnais, 1988, as cited by Legout et al., 2005). In the Lake Tahoe Basin, significant erosion events are driven more by occurrence of rain on snow type storms, followed by snowmelt and direct rainfall during summer thunderstorms.

Soils in the Lake Tahoe Basin have formed on granitic and volcanic parent materials, with the former comprising approximately 80% of the basin soils. Soils in the Lake Tahoe Basin typically have low clay contents with 60% of the area covered with soils having 5% or less clay content in the topsoil and 85% of the area covered by soils having less than 10% clay content. Typically, soils derived from volcanic parent materials have a higher clay content than those derived from granitic parent materials (e.g., Grismer and Ellis, 2006). Approximately 50% of the land area is covered by soils having an organic matter content of 5% or less in the topsoil and 80% of the area is covered by soils having less than 10% organic matter content (United States Department of Agriculture Natural Resources Conservation Service, 2007). Munn (1974) conducted one of the earliest rainfall simulation studies in the basin and found that volcanic soils were more erodible than granitic soils, presumably due to textural differences. Indeed, Grismer (2007) reported that granitic soils had larger particle sizes than volcanic soils, resulting in lower runoff rates, sediment concentrations, and sediment yields from bare granitic as compared to bare volcanic soils from similar slopes. Grismer and Hogan (2004, 2005a, 2005b) found that runoff rates, sediment concentrations, and sediment yields for volcanic soils were greater by an order of magnitude than those from granitic soils on slopes ranging from 30-70%. Stabilization of finer textured volcanic soils is of critical importance because these soils produce the greatest yields of particles <8 μm that are especially harmful to water clarity.

Other critical soil physical properties often associated with fire include soil hydrophobicity. Hydrophobic soil conditions develop when soil particles are bound by a substance (usually organic) and soil pores are clogged preventing movement of water. The presence of a water repellent layer can greatly reduce water infiltration, increasing runoff rates and potentially accelerate surface erosion especially in steep terrain. In forest soils such as those in the Tahoe Basin, hydrophobic conditions can result from fire (DeBano 1966), soil fungi (Savage et al., 1969; Debano 2000), or decomposition of pine litter (Meeuwig 1971), and often develop without fire, during late summer and early fall periods. Burcar et al. (1994) observed water repellency in an unburned granitic and volcanic soil in Little Valley adjacent to the Lake Tahoe Basin. Overall, the volcanic soil showed continuous preferential flow with depth that was persistent year around. In contrast, the observed near-surface preferential flow quickly dissipated with depth in the granitic soil. Furthermore, the granitic soil exhibited more typical matrix flow in spring as a result of reduced water repellency and higher soil moisture content despite having coarser texture. During the summer, water repellency was more pronounced, most likely due to the drier soil conditions.

Although this paper mainly focuses on the direct impacts of managements on soils and water quality, management activities can alter hydrologic processes that control water yield, stream flow, and sediment production by changing vegetation (Neary et al., 2005; Robichaud et al., 2006). Trees, understory vegetation, and litter intercept rainfall. Intercepted rainfall is stored and evaporated directly from vegetation, or drips from the vegetation as throughfall. These drops forming on vegetation can be larger than raindrops, and can actually have more kinetic energy than non-intercepted drops (Valentin et al., 2005). Litter layers can also store significant amounts of rain, depending on depth, density, and level of development of the layers (Neary et al., 2005) and litter maintains high infiltration rates as forest soils are quite porous due to accumulations of organic matter, and the activity of earthworms, insects, etc. (Neary et al., 2005). When interception is diminished due to removal of vegetation and/or litter, more rainfall reaches the soil surface, less water evaporates from the surfaces of vegetation, and the erosivity of rainfall is enhanced. Evapotranspiration is decreased by fuel treatments that reduce vegetation cover and may result in increased streamflow and/or groundwater recharge. In combination with decreased interception and infiltration, decreased evapotranspiration can also result in greater overland flow. Additionally, changing these processes may alter streamflow regimes with streamflows following storms being flashier, and having higher peak flows and water yields which may cause increased streambank erosion.

2.1.3 Soil biological properties

Soil organisms are essential for regulating nutrient availability in soils and are instrumental in development of soil structure by transforming organic matter which then cements and stabilizes soil aggregates. In many forest ecosystems, symbiotic relationships are found between plants and microbes where microbes facilitate nutrient supply to plants (symbiotic N fixation, P supply through mycorrhizal fungi), while plants provide C-rich substrates to microbes as an energy-source. Despite the importance of soil organisms, relatively little is known about soil organism diversity and its role in determining soil sustainability. Typically, soil organisms are divided in broad categories such as macro-arthropods, micro-arthropods, bacteria, fungi, protozoa, algae, and viruses. Still, there is a lack of information on the species diversity of soil organisms. For instance, it is estimated that fewer than 1% of all bacteria in soil and water have been identified, compared to 3% of the nematodes and 13% of insects (Edwards and Walton, 1992), although the current advance of new molecular techniques may rapidly increase these numbers. Still, the relationships between these organisms and their role in the soil environments are poorly understood. Furthermore, these communities are often dynamic and may change in size and composition at a variety of time and spatial scales within an ecosystem (Moore and De Ruiter, 1991).

The climate in the Lake Tahoe Basin is characterized by dry summers with occasional summer storms while most precipitation falls as snow. As a result soils are covered by snow during the winter. Most of the moisture enters the soils during the snowmelt period followed by a prolonged period of summer drought. During the summer, precipitation is dominated by infrequent but often high intensity showers/thunderstorms. This distinct seasonality can have an important impact on ecosystem processes as many biological processes in the soil are governed by soil moisture availability and temperature. For instance, decomposition of organic matter is limited under drought conditions. While in mesic systems most decomposition occurs during the summer, in semi-arid systems a significant amount of decomposition actually takes place under snowpack due to moisture availability despite temperatures being lower (Stark, 1973). This is reflected by observed peaks in NO_3 in streamwater during snowmelt (e.g. Coats and Goldman, 2001) since snowmelt may flush out the NO_3 accumulated under the snow during decomposition/nitrification in the absence of nutrient uptake by the vegetation.

3. Sources of literature used

A large amount of information is available regarding the effects of forest management on soils. For this review we focused on literature describing studies that have been conducted within the Lake Tahoe Basin and in areas having a similar climate and/or vegetation. As a result we limited our review to studies conducted in the Southwestern United States. However, studies carried out in other regions were included if the environmental setting and results appeared applicable to the Lake Tahoe Basin. In 2005, the United States Department of Agriculture (USDA) Forest Service published an extensive overview of the effects of wildland fire on soils and water (Neary et al., 2005). In addition, Neary et al. (1999) and Certini (2005) conducted literature reviews on the effects of fire on soils. We used these documents as an initial guide to the available literature on effects of fire on soils but we updated this information with more recent studies. For the effects of mechanical treatments on soils we conducted extensive literature searches focusing on mechanical treatments used for wildfire prevention rather than commercial harvesting. We included reports describing monitoring efforts conducted by the Forest Service in addition to peer-reviewed literature.

4. Management impact on soil nutrients

4.1 Prescribed fire

Numerous studies have been published focusing on the effects of fire (both prescribed and wildfire) on N. One of the most important direct impacts of fire on soils is the loss of soil N through volatilization of N contained in the forest floor containing the most volatile substrates. Nitrogen typically starts to volatilize at 200ºC (392ºF) so even at low fire intensities a significant amount of N can be lost to the atmosphere. This combustion of the forest floor will result in a loss of easily decomposable organic matter that may affect N availability on the short term. In addition, NH_4 can be formed as a direct combustion product of amino acids and proteins which can subsequently be converted to NO_3 through nitrification. Typically, N volatilization and NH_4 availability increases with increasing fire severity (e.g. Blank et al., 1996, Knoepp et al., 2005).

Although there is ample evidence of soil NH_4 and/or NO_3 increasing after wildfires, these increases are not always clear following prescribed fire. For instance, at South Lake Tahoe Johnson et al. (2004), Murphy et al (2006b) and Miller et al (2006) found a clear increase in labile nutrients following the Gondola wildfire but little evidence of increased N availability following prescribed fire. In contrast, Chorover et al. (1994) found an increase in soil solution and streamwater NH_4 and NO_3 concentrations following prescribed fire at a western Sierra Nevada site. Three years following the burn, streamwater NH_4 declined below pre-burn baselines, while NO_3 remained above. In addition, Moghaddas and Stephens (2007) found a large increase in both NH_4 and NO_3 in the mineral soil after prescribed fire on the west side of the Sierra Nevada that persisted up to 8 months after the fire. Increases in nutrients were larger outside of skid trails. Stephens et al. (2004) also found clear increases in soil NH_4, and NO_3 content 3 weeks after a prescribed fire at Sugar Pine Point State Park located on the western side of Lake Tahoe. However, these increases did not result in significant changes in streamwater N. Moghaddas and Stephens (2007) ascribed large increases in soil NH_4 to the accumulation of fuels in the forest floor in response to several decades of fire suppression causing fire severity to be higher than expected. Similarly, large amounts of fuels present in slash piles can result in localized high-severity fires that can significantly impact soil chemical properties (e.g. Korb et al., 2004; Jonsson and Nihlgard, 2004).

Effects of fire on soil P concentrations do not always follow the same patterns as observed for N. Typically P does not volatilize, as the volatilization temperature is 774ºC (1425ºF) (Weast, 1988). Although often more P is present in the mineral soil than in the litter, organic P forms in the litter are more readily available than mineral soil P pools. As a result, complete litter combustion through fire can exhibit larger detrimental effects than expected based on the size of the organic pools alone. Burning can convert organic P to ortho-P (Cade-Menun et al., 2000). In addition, during fire P can combine with available Ca forming non-available Ca-P complexes reducing P availability for vegetation. Murphy et al (2006a) found that prescribed fire caused significantly higher water-extractable ortho-P and bicarbonate-extractable P, but these effects were generally small and, in the case of ortho-P, much less than the temporal variation found in both burned and unburned plots. These authors found no effects of prescribed fire on soil P fluxes as measured by resin and ceramic cup lysimeters. The soils at this site had a volcanic origin with high P adsorption capacity. In addition, this study did not find significant effects of the Gondola wildfire on extractable P concentrations one year after the fire, although data from the first 45 days after burning suggested that there might have been a short-term increase in P mobility. Despite the absence of a significant soil response, this study found increased ortho-P in overland flow runoff that remained apparent in the 2nd year following the wildfire. The soils in this area studied by Murphy et al. (2006b) and Miller et al. (2006) were granitic, which generally have a lower P adsorption capacity than volcanic soils (Susfalk, 2001). Stephens et al. (2004) found an increase in total P in organic and mineral surface soils at Sugar Pine State Park, but did not observe an increase in stream ortho-P concentrations. They speculated that P-rich ash does not increase streamwater concentrations of ortho-P because increased cation concentrations and pH following fire may have caused the precipitation of P into solid PO_4 forms or soil heating may have led to development of Fe oxides and other secondary clay minerals onto which PO_4 can adsorb. Carreira and Niell (1995) found a short-lived (few weeks) increase in labile P fractions following prescribed fire in a semi-arid scrubland in Spain which may have been related to ash deposition. Blank et al. (2007) also found a significant increase in ortho-P in shrublands in the Great Basin subjected to prescribed fire for up to two years after the fire. In addition, Rau et al. (2007) reported significant increases in ortho-P concentrations in near-surface horizons in Great Basin sagebrush ecosystems lasting up to two years following prescribed fire.

Although temperature appears to be the dominant factor in determining soil chemical responses, other factors need to be considered. For instance, Tomkins et al. (1991) observed an increase in soil NH_4 with increasing fuel consumption in Victoria, Australia. Blank et al. (1996) and Gray and Dighton (2006) observed that effects differed by vegetation type indicating that not only temperature but also organic matter composition can affect N release after fires. The effect of vegetation type is also highlighted by Overby and Perry (1996) who found that increases in soil NH_4 and extractable P varied by plant species as a result of differences in quality and quantity of litter accumulated under different chaparral species.

Despite the presence of some general trends on the effects of fire on soil nutrients, the magnitude of responses varies between the different studies. One potential reason for the wide variety in responses found is that temperatures during prescribed fires and even wildfires can be extremely variable and are often not well characterized. As a result, often large spatial variability in soil responses limits detection of statistically significant effects especially since spatial variability in soil properties in unburned areas can be considerable as well. A second factor limiting direct comparison between studies is that the effects of fire are assessed at different timescales. For instance, Stephens et al. (2004) measured effects three weeks after the fire whereas other studies addressed effects of months or even years (e.g. Murphy et al., 2006b; Blank et al., 2007; Rau et al., 2007).

Fire-induced increases in soil N and P concentrations do not always result in increased nutrient concentrations in stream- and/or groundwater. Stephens et al. (2004) and Knoepp and

Swank (1993) did not observe significant effects of prescribed fire on stream concentrations despite measuring significant changes in soil exchangeable NH_4 concentrations. Upon release, NH_4 and especially ortho-P may be directly adsorbed to soil particles (albeit by different mechanisms) especially in volcanic soils having amorphous, highly reactive clay minerals whereas NO_3 can readily leach (e.g. Belillas and Roda, 1993). In addition, persistence of increased nutrient levels may depend on vegetation responses. If vigorous regrowth occurs, it is very likely that any available nutrients will be taken up causing soil nutrient levels to decrease. In many areas of the Sierra Nevada, N fixing species can occupy burned areas, especially after wildfires. As a result, soil N levels may increase following fires due to increased inputs of fixed N (e.g. Johnson, 1995; Johnson et al., 2005).

Highlights

- The largest impact of prescribed fire is the loss of N capital which can impact long-term soil N availability. N losses increase with fire severity.
- Prescribed fire can increase inorganic N and P availability especially when fire severity is high.
- Increases in inorganic soil N and P do not always result in increased nutrient concentrations in streamwater.
- If prescribed fires are managed so that burn severity and intensities are low, adverse impacts are unlikely to occur to soil chemistry and nutrient mobilization into streamwater.

4.2 Mechanical thinning

Fewer studies have been conducted on the effects of mechanical fuel reduction on soil nutrients. Most of the studies related to mechanical harvesting originate from production forests and assess effects of clear-cutting which is more disruptive than selected thinning. In addition, several studies address the effects of mechanical treatments followed by burning of the harvest residues (e.g. Knoepp et al., 2004; Scheuner et al., 2004; Murphy et al., 2006a), limiting the assessment of the direct effects of mechanical treatments on soils. Moghaddas and Stephens

(2007) did not find any effects of mechanical harvest followed by mastication on soil total N, NH_4 and NO_3 concentrations at Blodgett Forest in the western Sierra Nevada. Recent studies specific to the Tahoe Basin, (e.g. Loupe et al., accepted) compared the individual and combined effects of prescribed fire and mechanical harvest (cut-to-length and chipping) on nutrient mobility relative to non-treatment controls. Although Loupe et al. (accepted) did not find significant differences in soil nutrient fluxes, burning in the absence of mechanical harvest or mechanical harvest in the absence of burning resulted in higher N, P and S discharge loads in the surface runoff relative to the non-treatment controls. Mechanical harvest in combination with prescribed fire resulted in runoff discharge loads of N and P that were comparable to the untreated controls.

Mechanical harvesting can impact soil nutrient pools through the removal of organic nutrient sources from a site. Loupe et al. (accepted) hypothesized that, over the long-term, mechanical harvesting would reduce nutrient discharge loading as a result of source depletion. Indeed, studies in production forests show that continuous removal of timber can ultimately result in nutrient deficiencies (e.g. Heilman and Norby, 1998). Effects of mechanical harvesting on soil nutrients are likely to vary by treatment. For instance, Johnson and Curtis (2001) noted that across a wide range of forest ecosystems sawlog harvesting caused increases (18%) in total soil N especially in coniferous forests while whole-tree-harvesting decreased soil N by 6%. However, this study did not address readily available nutrients (i.e. NH_4 and NO_3). Bates et al. (2007) observed a 37% greater litter mass loss in cut juniper treatments in the northern Great Basin after two years. They ascribed these patterns to differences in litter inputs, litter quality and micro-environment. In contrast, Brockway et al. (2002) did not find any effect of mechanical overstory reduction and/or three types of slash treatments (removal, clustering and scattering) on soil chemistry or plant nutrient status. Carter et al. (2002) observed that mechanical whole-tree harvesting and hand-felled bole-only removal did not affect soil total N levels in a loblolly pine stand, but this study did not address plant-available soil nutrients. Thiffault et al. (2007) observed that whole-tree and stem-only harvesting had a smaller impact on soil nutrients than wildfire in boreal coniferous forests near Quebec. However, these authors argued that the nutrient release through wildfire due to deposition of ash and incorporation of recalcitrant organic matter was beneficial for the vegetation as evidenced by foliar nutrient analyses. They suggested that mechanical harvesting techniques may reduce soil fertility in the long term by removing biomass and thus limiting replenishment of soil nutrient pools through litterfall. However, such a reduction in soil nutrients may have an important water quality benefit, according to Miller et al. (2005), who observed high nutrient leaching fluxes from forest floor organic horizons and noted that litter mass had increased due to fire suppression. Therefore, restoring forest floor litter to lower pre-settlement conditions could help to reduce nutrient release to the lake on the longer term.

Whether or not mechanical harvesting affects soil nutrients most likely depends on the amount and type of harvest residues that are left behind and the extent to which they are incorporated into the soil. Carter et al. (2006) showed that bedding (incorporation of residues into the soil using a plow) increased soil N levels up to three years after the treatments. Bedding also increased N mineralization rates the first year after the treatment. Ouro et al. (2001) observed a similar effect of incorporating organic residues in the soil in a radiata pine plantation.

Finally, the activities associated with mechanical harvesting may impact soil properties such as soil structure, influencing water retention and aeration (Ballard, 2000) which can affect (micro)biological activity and thus nutrient availability (see discussion below on effects of mechanical thinning on soil biota).

Highlights

- Mechanical harvesting has potential to decrease long-term site productivity through removal of harvest residues, which could eventually result in decreased soil nutrients.
- A reduction in soil nutrients could be more in-line with pre-settlement conditions and reduce nutrient release to the lake.

5. Soil physical and hydrological properties

5.1 Prescribed fire

Prescribed fire can affect nutrient and sediment runoff through changes in soil physical properties. Fire alters infiltration properties of soils by removing vegetation and litter that shield soil aggregates from rainfall, which enhances aggregate breakdown. Fire also mobilizes and/or volatilizes soil organic matter that maintains soil structure by binding soil particles together (DeBano, 2000). When structure collapses, washing in of particles clogs soil pores reducing infiltration. The effects of fire depend on fire size, severity, location within a watershed, and proportion of watershed burned for a watershed with certain soil, slope, and vegetative characteristics (Neary et al., 2005; Stednick, 2006). The most important factor determining fire effects on runoff and erosion is the level of disturbance to the surface organic material which protects the mineral soil below (Robichaud et al., 2006).

Robichaud (2000) observed variable infiltration rates corresponding to severity following two broadcast burns of debris from timber harvesting in Montana. Results from simulated rain displayed that soils in high severity burn sites temporarily had a 10-40% reduction in hydraulic conductivity compared to unburned soils. High variability meant that, even though most of the burn was low severity, there were local areas of high severity that would be vulnerable to erosion. Martin and Moody (2001) investigated infiltration rates in New Mexico and Colorado following a high severity burn. Differences between steady-state infiltration rates for unburned volcanic and granitic soils under ponderosa pine were statistically insignificant. Changes in infiltration due to burning were expressed as a ratio of burned to unburned infiltration rates. This ratio was 0.15 in (4 mm) volcanic soil with ponderosa pine, 0.38 (10 mm) in volcanic soil with mixed conifer, and 0.38 (10 mm) in granitic soil with ponderosa pine.

One of the most characteristic impacts of prescribed fire is the development and/or enhancement of hydrophobicity (soil water repellency) which can reduce water infiltration and enhance overland flow leading to accelerated sheet and rill erosion (e.g. DeBano, 2000) and the potential for mass loss (Carroll et al, 2007). Water repellency typically occurs at intermediate temperatures where temperatures are high enough to mobilize organic materials and coat soil particles, but low enough that organics do not combust. As a result, most intensive hydrophobicity occurs at burn temperatures between 175ºC (175ºF) and 200ºC (392ºF) (DeBano, 1981). In addition, fungal growth can contribute to the formation of hydrophobic substances in the absence of fire (e.g. Huffman et al., 2001). In a study that included prescribed fire and wildfire, Huffman et al. (2001) found that hydrophobicity increased with increasing burn severity, but statistical differences were difficult to detect due to the large variability within and between sites. The intensity and persistence of water repellency can be severe depending on the fire intensity (e.g. Dryness, 1976; Giovanni et al., 1988), but water repellency may also rapidly dissipate (McNabb et al., 1989). Hubbert et al. (2006) observed that water repellency in a in a chaparral ecosystem had returned to its pre-burn levels 76 days following a prescribed fire. The persistence of water repellency was stronger under ceanothus (*Ceanothus crassifolius*) than under chamise (*Adenostoma fasciculatum*) showing that plant species can impact water repellency characteristics. Huffman et al. (2001) showed that hydrophobicity in a pine forest in the Colorado Front Range following wildfire and prescribed fire decreased with increasing moisture while vegetation type (ponderosa pine vs. lodgepole pine) had no effect. In addition, hydrophobicity appears to be more pronounced in coarse-textured soils (DeBano, 1981; Crockford et al, 1991; Huffman et al., 2001). Despite these general trends, predicting occurrence of water repellency can be challenging. For instance, the Angora wildfire in the Lake Tahoe Basin did not cause as extensive hydrophobicity as was expected based on the fire severity (Tolley and Norman, 2008). In contrast, the high intensity, short duration Gondola wildfire resulted in formation of hydrophobic soils (Carroll et al., 2007). Tolley and Norman (2008) found that hydrophobicity correlated better with aspect than with fire severity, and hypothesized that differences in aspect may have caused differences in moisture content and litter accumulation.

The often large spatial variability in soil and burn conditions can cause water repellency conditions to be extremely variable. Hubbert et al. (2006) observed that variability in water repellency between replicates within a 15 x 15 cm (6 x 6 in) area was as large as the variability seen between sites over a 1.28 ha (3 acre) watershed. They concluded that this mosaic in conditions may cause hydrologic responses to be less severe than when areas are covered with a more continuous water repellent layer. Coelho et al. (2004) noted that spatial variability in water repellency was larger under prescribed fire than under wildfire, causing overland flow and erosion to be less intense under prescribed fire. Although water repellency is often associated with fire, unburned soils can exhibit water repellent conditions (e.g. Burcar et al., 1994) resulting in sometimes limited impacts of prescribed fire relative to unburned controls. Because of occurrence of hydrophobic soils in unburned control sites, Benavides-Solorio and MacDonald

(2001) observed that a high severity burn in the Colorado Front Range caused only a 15-30% increase in runoff/rainfall ratios compared to unburned and low-severity burned sites.

In addition to water repellency, both prescribed fire and wildfire will affect the amount of soil covered either by organic matter and/or vegetation (e.g. Gundale et al 2005) which could impact erosion potential. Vega et al. (2006) showed that annual erosion losses in a scrubland in NW Spain subjected to prescribed fire were significantly correlated with the percentage of bare soil. In addition, they found that litter thickness was inversely correlated with erosion rates. Benavides-Solorio and MacDonald (2001) found that percentage ground cover explained 81% of the variability in sediment yield resulting from simulated rainfall on small plots in the Colorado Front Range. These same authors found that 77% of the sediment production rate was explained by a combination of fire severity, bare soil fraction, rainfall erosivity, soil water repellency and soil texture, with bare soil fraction and rainfall erosivity explaining 62% of the variability (Benavides-Solorio and MacDonald, 2005).

Soil heating can directly impact soil structure. Garcia-Corona et al. (2004) observed that heating of soil above 220ºC (428ºF) increased water aggregate stability and the volume of 0.2-30 µm pores without altering aggregate size distribution or total porosity. At higher temperatures (>380ºC or 716ºF) they observed breakdown of aggregates. The formation of hydrophobic films at low to medium-intensity fires can enhance structure stability (Mataix-Solera and Doerr, 2004) while at high temperatures, organic coatings can be combusted, which decreases structure stability (Badia and Marti, 2003). In this case, the individual surviving aggregates can show greater stability due to formation of cementing oxides (Giovanni and Lucchesi, 1997). Although destruction of soil structure could affect bulk density (e.g. Giovanni et al., 1988), Gundale et al. (2005) did not find any changes in bulk density in prescribed fire treatments with or without prior thinning in ponderosa pine forests in western Montana. In contrast, Boyer and Miller (1994) observed a small but significant increase in bulk density of 7.8% in surface soil following a prescribed fire in a longleaf pine stand. Similarly, O'Dea and Guertin (2003) found an increase in bulk density of 3.3% following a prescribed fire in a southern Arizona grassland. In sandy soils, compaction can increase water holding capacity, which may be beneficial to some plants (Gomez et al., 2002). However, high levels of compaction in most soils limits root penetration (Unger and Kaspar, 1994; Taylor and Brar, 1991) and thus vegetation growth (Carter et al., 2006).

Highlights

- Patchiness in organic matter covering the soil will limit formation of a continuous hydrophobic soil layer, but if too much bare soil is exposed the risk of erosion may increase due to lack of adequate soil cover.
- Because of the presence of natural hydrophobic conditions in unburned soils in the Tahoe Basin during much of the year, the additive potential hydrophobicity from prescribed fire most likely is limited.
- Spatial variability in hydrophobicity due to patchiness in litter cover and burn temperatures may limit the potential for increased surface runoff following prescribed fire as non-hydrophobic patches provide preferential water flow paths.
- Erosion potential decreases with increasing litter cover.
- Effects of prescribed fire on soil structure are likely to be minimal given the relatively low temperatures achieved during prescribed fire compared to wildfire.

5.2 Mechanical thinning

Impacts to soil physical properties resulting from forest management have the potential to cause significant changes in site quality (Grigal, 2000). In managed forest systems, aggregate breakdown and soil compaction can occur from machine traffic, skid trails and landing areas during logging operations particularly when soils are weakest, such as may be the case when soils are wet. Soil structure is destroyed and pore space is lost as bulk density and resistance to soil penetration increase. In addition, pore size distribution may change as macropores are being destroyed which may impact aeration and root growth (Miller et al., 2004). Nolte and Fausey (1986) found that when compaction (as measured by cone penetrometer resistance) doubled, infiltration rates decreased by a factor of 10. Infiltration rates are also reduced when aggregate breakdown causes pores to be sealed. Under these conditions, water is less able to enter the soil and instead forms overland flow, which can detach and transport soil. Infiltration also regulates the depth of water over the soil surface. This water layer protects the soil because it disrupts the process of raindrop detachment. A layer of about three drop diameters deep is sufficient to dissipate most of the drop's kinetic energy (Al-Durrah and Bradford, 1982). While there is an abundance of literature related to disturbance effects in commercial clear-cutting or post-fire logging, these results provide only circumstantial guidance for understanding Lake Tahoe water quality issues associated with forest management, as such logging methods are not employed in the Tahoe Basin.

Moghaddas and Stephens (2007) studied the effects of mechanical treatment on soil compaction in a Sierra Nevada mixed-conifer stand on fine-loamy textured soils formed on granitic parent material. They compared compaction for thin, thin and burn, and control treatments. The mechanical treatments included hand felling and limbing using a chainsaw. Boles were removed using rubber tired or track-lying skidder. Following the harvest, approximately 90% of the understory trees were masticated on site. Soil strength and bulk density were measured as indicators of soil compaction. Soil strength depends in large part on soil moisture content and bulk density, and is considered to be a more sensitive indicator of soil compaction than bulk density (Vazquez et al., 1991; Vaz and Hopmans, 2001). Moghaddas and Stephens (2007) found no significant impact of mechanical treatments on bulk density, but the thin and burn treatment significantly increased soil strength relative to control and thin treatments. They also reported that soil strength in skid trails was consistently greater than non-skid trail areas, but mechanical activity did not significantly increase in bulk density or soil strength in the non-skid trail areas. Similarly, Gundale et al. (2005) found no effects of combined thin and burn treatments on bulk density and concluded that impacts were avoided because harvests were conducted on frozen and snow-covered soil using harvesting techniques designed to minimize soil compaction. In a recent study, Han et al. (2009) studied effects of cut-to-length and whole-tree harvesting on soil compaction in a coniferous forest located on Andosols having a loamy texture. The cut-to-length harvesting system used less area to transport logs to the landings than did the whole-tree harvesting system (19%-20% vs. 24%-25%). At high soil moisture levels (25%-30%), both cut-to-length and whole-tree harvestings caused a significant increase of soil resistance to penetration and bulk density in the track compared with the undisturbed area. In the center of trails, however, only whole-tree harvesting resulted in a significant increase of soil resistance and bulk density compared with the undisturbed area.

Covering soil with harvest residues can have an important impact on soil physical processes. In a laboratory study of an Auburn series soil, Singer et al. (1981) showed that soil movement by splash (excluding interrill transport) was reduced by a factor of 13 when cover was increased from 0 to 96%. Han et al. (2009) observed that presence of slash materials could have a direct impact on soil compaction. In their study slash covered 69% of the forwarding trail area in a cut-to-length harvesting units; 37% was covered by heavy slash (40 kg m^{-2} or 8 lbs ft^{-2}) while 32% was covered by light slash (7.3 kg m^{-2} or 1 lb ft^{-2}). They found that heavy slash was more effective in reducing soil compaction in the cut-to-length units. In another study, Han et al. (2006) showed that presence of slash could prevent compaction at higher soil moisture levels

(>30%) in silt loam soils but had little effect at low moisture levels (<15%). However, in this study, high slash levels (15 kg m^{-2} or 3 lbs ft^{-2}) resulted in increased compaction at high moisture levels while at medium moisture contents high slash levels resulted in decreases in compaction (Han et al., 2006). This study clearly showed that moisture and slash level can interact in ways that are not always predictable. Still, these authors observed that under dry conditions impacts of traffic on soil compaction were smallest (Han et al., 2006). The effects of mastication on soil strength were studied in a stand on the west shore of Lake Tahoe (Hatchett et al., 2006). Soil strength was measured using a cone penetrometer at several distances from tracks at varying depths. Mastication treatments were conducted when gravimetric soil moisture levels were less than 10%. No significant differences in soil compaction were found in 13 of 15 comparisons. Simulated rain on mulched, bare soil, native grass, and undisturbed plots did not indicate any significant impacts of mastication on sediment yields. Impacts by equipment were not localized but instead were distributed over a large area. Although potentially reducing soil compaction and/or erosion, one potential downside of mastication is that deep (>7.5 cm or 3 in) layers of residues can increase subsequent burn severity especially under dry conditions if these residues are ignited (Busse et al., 2005).

Christensen and Norman (2007) evaluated the effects of cut-to-length harvest and forwarding treatments at the Ward (Unit 5) fuels reduction project on the west side of Lake Tahoe. They observed no statistically significant change in percent of ground cover and a marginally significant decrease in saturated hydraulic conductivity. Bulk density significantly increased from 0.83 to 0.88 g cm^{-3} (0.48 to 0.51 oz in^{-3}) (6% change) following treatment, which was below the 10% threshold indicating "detrimental soil compaction" as described by the Regional Soil Quality Standards. Saturated hydraulic conductivity decreased by 20%, but that reduction was not statistically significant at the 90% level. Observations from this study were used as input for the Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989). This model predicted an increase in sediment production from 0.8 tons acre^{-1} yr^{-1} to 0.9 tons acre^{-1} yr^{-1} following the treatment. Increases in erosion were limited because the degree of change measured in bulk density and saturated hydraulic conductivity did not cause much change in predicted runoff.

Slope can affect the amount of soil erosion following mechanical thinning operations. Cram et al. (2007) observed that soils on steep slopes (26% to 43%) in a mixed-conifer forest in central New Mexico were more susceptible to heavy surface disturbance (e.g. deep tire ruts). However, when surface disturbance was only light to moderate, sedimentation and runoff did not exceed undisturbed sites. Edeso et al. (1999) noted that intense site preparation on slopes between 40% and 50% in steep forestlands in northern Spain resulted in considerable decreases in soil organic matter and increases in bulk density, which decreased the hydraulic conductivity and subsequently produced higher runoff. In plowed soils, the higher soil erodibility and the removal of slash and vegetation cover resulted in a four-fold increase of soil losses when compared with no mechanical site preparation. The harvesting and site preparation techniques used in this study (conventional stem-only harvesting, whole-tree harvesting and humus layer removal, and whole-tree harvesting and humus layer removal followed by down-slope deep plowing) were, however, more intense than would be employed for fuel reduction treatments used in the Tahoe Basin. Guerrant et al. (1991) conducted a rainfall simulation experiment on granitic soils (Cagwin series) in the Lake Tahoe Basin. They observed that interrill erosion increased significantly as slope class increased from 15-30% to greater than 30%, but slope had no significant effect on infiltration and runoff. In a follow-up study conducted on three slope classes (<15%, 15-30%,

>30%), Naslas et al. (1994) found that highest erodibility was not always associated with steep slopes. Other factors impacting soil erosion included, soil type, plot condition and duration of a rainfall event. The dependence of erosion on soil type was further confirmed by Grismer and Hogan (2004) who observed a lower water infiltration rate for volcanic than for granitic soils as a result of differences in texture. Consequently, runoff rates will be higher on volcanic soils thereby increasing the erosion risk.

Several studies show that unpaved roads can be an important source of sediments (Grace and Clinton, 2007; Sugden and Woods, 2007). Roads have very low infiltration rates, high rates of surface runoff, and are vulnerable to raindrop splash, resulting in surface erosion rates several orders of magnitude higher than undisturbed forest soil (MacDonald et al., 2004). Luce (1999) demonstrated that forest roads in Oregon often produced small sediment yields but were capable of extremely large yields in certain places. More frequent use by heavier vehicles tends to produce more erosion (Reid and Dunne, 1984), as aggregates are broken down by compaction. MacDonald et al. (2004) also reported that gravelling reduced road sediment production in the El Dorado National forest by approximately an order of magnitude. A report on the upgrading of forest roads in the Lake Tahoe Basin from 2003-2005 (Breibart et al., 2007) evaluated the change in risk of sediment transport as a result of BMP implementation using Water Quality Risk Assessment Protocols (WQRAP), and estimated sediment loads before and after BMP implementation using the WEPP model. The study found that 93% of road surface, drainage, and slope protection upgrades were effective, and that ineffectiveness resulted from plugged cross drains and ditches resulting from the unauthorized disposal of vegetative debris by recreational users in the stream channel. Of the 152 miles (245 km) of roads evaluated, 10.9 miles (17.5 km) (7%) were considered hydrologically connected to surface water bodies, presenting some level of water quality risk. Prior to BMP upgrades, this total was 17.4 miles (28 km). Following the removal of some anomalous results, the WEPP model predicted a decrease in sediment yield from 23.4 to 2.2 tons. The results indicate that overall the road upgrade program was effective in reducing the risk of road-borne sediment migration to water bodies in the Lake Tahoe Basin.

When comparing a variety of mechanical harvesting techniques, Klock (1975) concluded that tractor skidding over bare ground caused the greatest percentage of area with severe soil disturbance (36%), followed by cable skidding (32%), tractor skidding over snow (9.9%), skyline (2.8%), and helicopter removal (0.7%). Erosion and sediment transport generally followed these patterns with the highest percentage of area with erosion with cable skidding (41%), followed by tractor skidding over bare ground (31%), tractor skidding over snow (13%) and helicopter removal (3.4%). Although these numbers may be confounded by differences in slope, road construction, requirements of skid trail designation, operator skill, etc., (e.g. Miller et al., 2004) it is clear that soil disturbance and duff/litter layer removal due to mechanical treatments have a direct impact on erosion potential and are probably the most important factors in management decisions regarding mechanical thinning. However, other factors affected by soil disturbance including microtopography and effective slope length need to be taken into account in addition to amount of disturbed area when assessing erosion potential. Tractor skidding has not been proposed or utilized as a mechanical thinning technique for the large majority of land in the Tahoe Basin in the recent past. In the future this practice will only be considered for use on high capability lands within watersheds well under the threshold of concern for cumulative watershed effects. Handthinning, cut-to-length, end lining, or other low impact techniques will be proposed for more sensitive lands and watersheds. The amount of disturbed area will be managed through skid trail designation and spacing.

Highlights

- Effects of mechanical harvest as currently practiced in the Tahoe Basin on bulk density, compaction and soil strength are likely to be minimal but may occur on skid trails or areas of heavy traffic.
- Presence of harvest residues (chips, slash) can limit the impact of traffic on soil physical characteristics but may increase the risk of subsequent high severity fires.
- Soils on steep slopes are more prone to disturbance and thus risk of erosion.
- Roads may significantly contribute to erosion despite their small surface area, emphasizing the need for application of road BMPs that can be effective in preventing transport of road pollutants to aquatic environments.

6. Soil biological properties

6.1 Prescribed fire

Compared to soil chemical and physical properties much less information is available regarding effects of management and soil biota. Given the uncertainty in quantity of microbes and their functional role in the soil, the effects of management on soil biota are difficult to assess. Prescribed fire can directly affect soil microbes by heating the soil especially close to the soil surface where the majority of the soil biota is present. Depending on the microbial species, soil heating can be lethal (50-210ºC or 122-410 ºF) or can alter their reproductive capabilities (Covington and DeBano, 1990; Klopatek et al., 1988). In the presence of water, direct effects may be more severe as moist heat (pasteurization) is more effective at killing soil micro-organisms than dry heat. Consequently, for a given temperature, moist soils will most likely lead to greater mortality among soil micro-organism than dry soils (Choromanska and DeLuca, 2002). However, moist soils require considerably more energy to reach lethal temperatures compared to dry soils. In general, fungi appear to be more sensitive to temperature than bacteria (e.g. Bååth et al., 1995). Indirectly, microbes can be affected by oxidation of organic matter, thereby limiting C inputs into the soil. Conversely, roots of burned vegetation can suddenly become an easily accessible C source for microbes. In the short term, this increased C availability may stimulate heterotrophic activity. However, over the long term, belowground soil C and heterotrophic activity may decrease especially if aboveground litter inputs decrease as well (Klopatek and Klopatek, 1987).

In contrast to heterotrophic organisms, autotrophic organisms may be stimulated by prescribed fire. Fire can release inorganic N through abiotic and biotic processes. In the absence of competition by plants, nitrifying bacteria can use any NH_4 made available and convert it to NO_3. This NO_3 can either be denitrified or leached. Alternatively, Kaye and Hart (1998) found that the presence of larger NO_3 pools following a low intensity fire was caused by a decrease in microbial NO_3 uptake rather than increased gross nitrification. One particular group of soil-microorganisms that is of special interest is the ectomycorrhizae (EM), often associated with woody plants in western forests. Some studies show that low intensity fires do not affect EM fungal composition, densities or propagules (Jonsson et al., 1999; Korb et al., 2003). In contrast, Smith et al. (2005) showed that prescribed fire resulted in a short-term reduction in EM species richness and live root biomass. Smith et al. (2005) ascribed the contrasting results to the fact that in their study the duff layer was entirely consumed as opposed to the studies of Jonsson et al. (1999) and Korb et al. (2003). Hart et al (2005) suggested that the ability of EM to survive following a fire may depend on their ability to persist in the absence of their host.

Many of the effects of fire on soil biota may be indirect through modification of the soil environment such as soil temperature and moisture regime as well as chemical alteration of the forest floor and mineral soil. However, very few studies have been conducted to address these aspects (Hart et al., 2005) and it is very likely that effects will vary spatially and temporally depending on fire severity, antecedent moisture condition, soil type, etc. In addition, effects of fire on soil biota may be mediated through vegetation responses that include changes in litter quality and quantity. For instance, Brant et al. (2006) observed that root C inputs exerted a large control on microbial community in three forest ecosystems studied.

In general, the effects of fire on soil-dwelling invertebrates are less marked than those on micro-organisms due to their higher mobility that enables them to escape heating. However, reductions in litter mass can greatly reduce mass and number of species of invertebrates (Springett, 1976). In forests, both adverse (Sgardelis et al., 1995) and neutral (Coults, 1945) effects of fires on predominantly litter dwelling macroinvertebrates have been documented. Apigian et al. (2006) found that overall impacts of prescribed fire on leaf litter arthropods in Sierran forest ecosystems were moderate and that changes were taxon-specific and showed no general patterns.

Highlights

- Prescribed fire can affect soil biota but it is not likely that effects are detrimental to ecosystem functioning.
- Impacts of fire on soil biota may be greatest when soils are wet. However, it is not likely that low severity fire causes soil temperatures to reach critical levels detrimental to soil biota because of the high heat capacity of wet soils.

6.2 Mechanical thinning

Effects of mechanical harvesting on soil biota are most likely mediated through changes in soil environmental conditions. The most important effect may be compaction causing a change in porosity, pore size distribution, and soil aeration. Tan et al. (2005) found that management-induced compaction reduced microbial biomass N and net nitrification in a boreal forest in British Columbia 2-3 years following the disturbance. However, Mariani et al. (2006) found an increase in microbial N at the same site in compacted soils 3-7 years following disturbance. In contrast, Busse et al. (2006) found that severe soil compaction did not have any effect on microbial community size or activity at Blodgett experimental forest in the western Sierra Nevada. Yet, removal of overstory biomass resulted in declines in microbial biomass, respiration and fungal phospholipid fatty acids. Hannam et al. (2006) did not find strong effects of various levels of overstory removal on soil microbial biomass in spruce, aspen and mixed stands in northern Alberta, Canada. They ascribed the lack of response to efforts to minimize soil disturbance and natural regeneration of the vegetation. For mechanical treatments common in the Lake Tahoe Basin, such as cut-to-length and mastication treatments, the effects on soil biota may be limited and most likely mediated through the presence of residual slash/chippings. The presence of residue could potentially enhance moisture availability, reduce temperature variation and provide a C source for microbes. Although these changes in environmental conditions are likely to impact soil biota, the extent of these impacts is unclear.

Studies have addressed the effects of mechanical treatments on invertebrates but most studies originate from large-scale and intensive operations such as clear-cutting and subsequent site preparations. These studies show that habitat heterogeneity as a result of these practices can increase arthropod diversity (Haila et al., 1994; Kaila, 1997). However, in other cases, management practices have resulted in negative short- and long-term effects on diversity and abundance of groups (Niemela et al., 1993; Bellocq et al., 2001).

Highlights

- Current mechanical harvesting practices in the basin are likely to have minimal impacts on soil biota because the impact of these practices on soil physical properties is limited.

7. Stream Environment Zones

Within the Lake Tahoe Basin relatively little is known regarding the management of riparian ecosystems contained in the Stream Environment Zones (SEZs; Cobourn, 2006) mainly because little management has been carried out in these areas. Fuels management in these areas has primarily been accomplished through hand thinning. Because hand thinning a costly and inefficient method to achieve desired stand conditions, this has thus far been implemented on a limited basis in the Tahoe Basin.

Downgradient natural wetlands and SEZs have generally been considered to function as nutrient sinks, particularly for N and P. However, wetlands may not always be as effective at removing nutrients from water originating from upland soils as once believed, and in some cases may even function as a nutrient source as water moves through these areas before entering streams (Godfrey et al., 1985; Khalid et al., 1977; Gergans, 2007; Richardson, 1985, 1999). Riparian areas are important because of their ability to reduce flood hazards, act as groundwater recharge and discharge areas, stabilize stream banks and shorelines, and provide critical habitat for a variety of aquatic invertebrates, amphibians, fish, and riparian terrestrial wildlife. Furthermore, riparian areas can act as a buffer against fire, but under dry conditions high fuel loads that tend to accumulate in these more productive areas can act as a corridor or „wick' for fire movement. Effects of prescribed fire on soils in SEZs are likely to be similar as those for uplands and therefore depend on the fire regime (Pettit and Naiman, 2007). In contrast to upland areas, the higher moisture conditions may minimize fire effects on soils with a reduction in C and N losses in areas with high water tables compared to areas with low water table (Blank et al., 2003). Beche et al. (2005) investigated underburning in a riparian zone at Blodgett forest in the Sierra Nevada and detected minimal impacts on adjacent streamwater chemistry suggesting that there were no major effects on soils. The total burned area following this low- to moderately severity fire in this study was relatively small (14%), however, which may have limited the impacts. Still, although more energy is needed to heat wet soils, high intensity fires such as those associated with slash pile burning could potentially increase soil heating, causing detrimental effects on soil organisms (e.g. Choromanska and DeLuca, 2002). Mullen et al. (2006) found that prescribed fire in a high-elevation riparian meadow in Arizona increased soil moisture in the first year following the fire while soil moisture decreased during the second and third year as a result of changes in biomass and associated evapotranspiration. This change in soil moisture status may impact seed germination and vegetation regrowth.

Similar to upland soils, the risks of soil compaction and disturbance during mechanical fuel reduction in SEZs are most likely highest when soils are wet (Mueller et al., 2003). In the fall of 2007, the Heavenly Creek SEZ Demonstration Project was implemented using cut-to-length equipment (Norman et al., 2008). The cut-to-length treatments were associated with a statistically significant decrease in hydraulic conductivity (from 5.5 in/hr to 2.4 in/hr or 14 cm/hr to 6 cm/hr), no statistically significant change in bulk density (suggesting a change in pore size distribution but not total porosity), and a reduction in soil cover by 15%. There were no significant differences between visible equipment tracks, with or without a slash mat, and impacts were similar in untracked areas equipment regardless of presence of slash mats or number of vehicle passes. When these parameters were used as input for the WEPP model it was concluded that, although there were statistically significant changes in hydraulic conductivity, these did not result in an ecologically significant change in erosion and runoff response. The WEPP model predicted that the average annual sediment yield and runoff for all three hillslope profiled in the project to be zero for both pre- and post project conditions. This is primarily because pre-project hydraulic conductivity for the SEZ soil type in this project (and predominant throughout the Basin) was naturally quite high, and therefore can sustain this level of impact without an adverse hydrologic response. This study represents one of the first larger scale studies conducted in SEZs in the Lake Tahoe Basin that assessed impacts of management on soil properties. Very recently, several pilot projects utilizing low impact mechanical harvest techniques within SEZs have been implemented with promising results. It is expected that under dry soil moisture conditions, mechanical treatment methods will be utilized on a more extensive basis where appropriate within these areas.

Highlights

- Effects of prescribed fire (underburning) on soils are likely to be smaller in SEZs compared to upland soils due to higher soil moisture conditions.
- Slash pile burning in SEZs may have larger detrimental effects on soil biota than in upland soils because higher soil moisture may cause increased propagation of heat into the soil.
- Because soils in SEZs are potentially moister for longer periods of time compared to upland soils, the opportunity for utilizing mechanical equipment in these areas will be limited, and highly dependent on soil moisture conditions.

8. Synthesis of existing knowledge

The effects of prescribed fire and mechanical thinning on soils are multi-faceted and complex with effects simultaneously being beneficial for certain soil characteristics while being detrimental for others. Perhaps the biggest immediate impact of prescribed fire in the Lake Tahoe Basin is a loss of N capital contained in the organic surface horizons. These losses may impact long-term site fertility by reducing the amount of potentially mineralizable N. However, decades of fire suppression may have resulted in N stocks that are likely much higher than necessary to maintain pre-fire suppression era forests.

Prescribed fire can increase soil inorganic N and P concentrations with increasing fire severity. The available nutrients may stimulate regrowth of vegetation following fire but if plant NH_4 uptake is low, increased NH_4 availability may stimulate nitrification causing leaching of NO_3 into streams and groundwater. In several studies, increased soil nutrient concentrations following prescribed fire did not result in an increase in streamwater nutrient concentrations. Leaching of P is typically very low since especially ortho-P, the plant available P form, easily adsorbs to the mineral soil. Other pathways through which nutrients can enter aquatic ecosystems include surface runoff through organic surface horizons (e.g. Miller et al., 2005; Loupe et al, 2007). While seasonal variation adds complexity, well-developed organic horizons in fire-suppressed forests can potentially contribute significant amounts of nutrients to Tahoe Basin streams. Mineral soil under the organic layer is hydrophobic until rewetted by significant rainfall or snowmelt (Guerrant, 1991; Naslas, 1994b). Little interaction between runoff and mineral soil means that NH_4 and ortho-PO_4 which normally would adsorb to soil particles remain in solution (Miller et al., 2005). However, the importance of nutrient transport through organic horizons and the management implications have not been assessed. Mechanical thinning does not appear to affect nutrient mobilization, and recent research shows that the combination of prescribed fire in combination with mechanical thinning most likely results in the least impact on short-term nutrient mobilization (Loupe et al., accepted).

Perhaps of greater concern for water quality are releases of nutrients and sediment through erosion. Both prescribed fire and mechanical thinning can increase the risk of erosion. Prescribed fire can cause the formation of water repellent layers which can increase runoff and thus erosion potential. The occurrence of hydrophobicity appears to be most pronounced at intermediate temperatures that can occur during prescribed fire. In addition, occurrence of hydrophobicity is of greater concern when soils are burned under dry compared to moist conditions, suggesting that burning in the spring rather than in the fall might limit formation of hydrophobic soils. Formation of water repellent layers is enhanced by increasing the amount of organic matter covering the mineral soil. As a result, areas having a patchy organic surface horizon are less likely to form a continuous hydrophobic layer. Although bare ground may limit the formation of water repellent layers, presence of bare ground can increase the risk of erosion as a number of studies have observed inverse relationships between soil cover and erosion rates.

In general, prescribed fires are associated with low to moderate fire severity but when fuel loads are high, such as is the case with burning of slash piles, localized effects on soils may be severe. It is, however, unclear if these localized impacts affect erosion and/or nutrient leaching on a watershed scale. In addition, it is unclear how slash pile burning would impact soils in SEZs as these piles may be in closer proximity to water bodies and wetter conditions in SEZs may increase heat propagation in the soil. Pile burning has not been conducted within SEZs in the Tahoe Basin, to date, but it anticipated that pilot projects will be implemented in the near future, with associated research and monitoring to evaluate impacts and efficacy of design features.

Mechanical thinning can cause compaction and loss of soil structure, which may reduce water infiltrability. Since most soils in the Lake Tahoe Basin are relatively coarse-textured and have high infiltration capacities, compaction is not likely to be a major concern. The finer-textured volcanic soils may have a higher risk of detrimental impacts in response to mechanical thinning. Most of the concern regarding soil disturbance is limited to high use areas such as landings and equipment trails, so minimizing traffic within a treated area will reduce the impacts of mechanical thinning on soils. Impacts on soils can be further mitigated by leaving slash materials on the soil surface. However, thick layers of fuel materials left after mastication treatments could increase the risk of high soil temperatures if these residues burn. In addition, incorporation of slash materials into soils could alter nutrient cycling depending on decomposability of the slash materials.

Both prescribed fire and mechanical thinning can directly and indirectly impact soil biota, but it is unclear if these impacts are detrimental. Partial sterilization in response to fire under wet conditions may be undesirable, but the typically moderate severity of prescribed fire is unlikely to eliminate soil biota. Changes in the soil physical properties in response to mechanical thinning can affect soil biota through changes in water holding capacity, aeration and soil temperature regime. Given the limited impacts of mechanical harvesting techniques on bulk density it is unlikely that the soil physical environment and thus soil biota will be dramatically affected.

9. Implications for management in the Lake Tahoe Basin.

- Prescribed fire will have the least impact on soil properties when soils are moist. The lower temperatures achieved compared to dry soils will minimize nutrient release, formation of hydrophobic layers, and impacts on soil biota. High temperatures achieved with slash pile burning carry the highest risk in terms of impacting soils but will likely depend on size of piles and materials contained in these piles. Slash pile burning can locally impact soil chemical, physical, and biological properties but impacts on a watershed scale and/or in SEZs have not been quantified.
- Impacts of mechanical harvesting techniques on soil physical properties are lowest when soils are dry especially in coarse-textured soils. Impacts of mechanical treatments can be further mitigated by selecting the appropriate mechanical harvest technique based on site conditions/resiliency, including consideration of the presence of harvest residues. Mechanical harvesting is not likely to affect soil chemical and biological properties unless severe changes in soil physical properties occur. Presence of harvest residues may limit erosion potential but may increase the risk of high soil temperatures upon ignition.

Discontinuous distribution of harvest residues will limit the formation of continuous hydrophobic layers upon burning but may increase the risk of erosion through the presence of bare soil areas.

10. Research needs and recommendations to advance management strategies

Although current management practices employed in the Lake Tahoe Basin are consistent with the general trends based on literature used in this and previous reviews, these reviews show that effects of management are often site-specific and dependent on the management practice. In addition, few studies have addressed long-term effects (e.g. Hatten et al., 2005), and none of those have been conducted in the Lake Tahoe Basin. As a result, it is critical that current management practices continue to be evaluated in rigorous way to determine (a) if impacts of management on soils exceed background conditions given spatial and temporal variability in soil properties such as nutrient availability and hydrophobicity, (b), if impacts do exceed background condition, whether or not these impacts are detrimental, and (c) if impacts are detrimental, how long do these impacts persist. Less information is available regarding management impacts in SEZs as compared to upland forests because until recently these areas have been primarily treated through hand thinning, and have not been subjected to mechanical or prescribed fire treatments.

A common disposal treatment of harvest residues in the Lake Tahoe Basin is through slash pile burning. This treatment primarily occurs in upland areas that are treated through hand thinning, because they not easily accessible by mechanical treatment techniques (i.e. steep slopes, barriers to access). The effects of these small localized high-intensity events on a watershed scale or effects of pile burning on soils in SEZs have not been quantified. Future research could quantify the effects of pile size and density, slope and distance to water bodies on nutrient and sediment runoff.

In the Lake Tahoe Basin, mastication treatments are commonly used to treat residual ground fuels in areas that are initially treated with mechanical harvest techniques. In less frequent cases where standing fuels are at low densities, whole tree mastication is used to treat standing fuels., Leaving mastication residues on the soil surface or incorporating residues can affect erosion, future fire behavior and nutrient cycling. Management decisions would benefit from research assessing the optimal amount of harvest residues to minimize the risks of erosion, formation of water repellent layers, and occurrence of future high temperature fires. In addition, the long-term impacts of residue incorporation on soil nutrient status are unclear. Research on nutrient cycling impacts should consider not only quantity of residues but also quality as determined by the type of materials incorporated (high vs. low C/N materials, intact vs. chipped, etc.).

Impact assessment of forest fuel reduction management on soils would benefit from having a standard set of evaluation protocols and criteria. Researchers and management agencies should try to establish common sets of defensible measurement techniques and protocols that would facilitate evaluation of fuel reduction management effectiveness across the Lake Tahoe Basin. Affordable and easily applicable techniques should be developed for implementation monitoring conducted before and during the project, to assure site conditions are suitable for the type of treatment activity being conducted. A more intensive set of protocols may be required for pre and post project effects analysis, which should be conducted to assess and compare impacts of different treatment practices across a range of site conditions. Emphasis should be placed on the use of affordable and easily applicable techniques that can be applied by a wide range of users including crews conducting management operations.

In addition to establishing a common set of protocols, it is important to determine the targets of any management practice relative to current and past soil and vegetation conditions. Currently, vegetation structure and organic matter accumulation are a result of decades of fire suppression and therefore may not represent their pre-fire suppression or pre-Comstock state. Hence, it is critical to define the desired management targets relative to existing or pre-existing nutrient pools, transport properties, and potential to degrade water quality.

A potential way to assess the effects of forest management and scale local effects to the watershed level is to use simulation models. Currently, several ongoing studies in the Lake Tahoe Basin are using the process-based WEPP model (Nearing et al., 1989) to simulate soil erosion. The WEPP model allows for assessing single rain events as well as snowmelt, a critical feature for simulating erosion in areas with episodic rain events such as the Lake Tahoe Basin. In addition, the WEPP model can estimate spatial patterns in soil loss and takes into account the variability in hillslope characteristics (Flanagan et al., 1995). The basic structure of WEPP reflects its Universal Soil Loss Equation (USLE) ancestry (Wischmeier and Smith, 1978), with model components for climate, soil, slope and management, and WEPP can be run with a daily time step or in single storm mode. The major determinants of the WEPP erosion processes are soil resistance to detachment, available stream power (transport) and rainfall intensity that, like the USLE, are linked to erosion rates by the soil erodibility (Owoputi and Stolte, 1995).

Assuming dominance of Hortonian and turbulent runoff processes, WEPP models both erosion and deposition on a hillslope, and generates sediment yield mass and particle size distributions. This runoff assumption is more appropriate for highly disturbed areas such as roads than vegetated, less disturbed areas where overland flow is often not observed (Dunne et al., 1991; Croke et al., 1999). Consequently, WEPP does not model saturation excess flow generation thereby limiting its application in shallow slope forested areas of the watershed, though recent improvements better account for the shallow subsurface- or inter-flow processes common in forested watersheds (Wu and Dunn, 2005; Wu et al., 2008). Recent studies have largely focused on expanding capability aspects of WEPP including flow over stony soils (e.g. Li and Abrahams, 1999) and particle sorting (e.g. Flanagan and Nearing, 2000), as well as broadening its application and assessing its performance (e.g. Nearing et al., 1990; Zhang et al., 1996; and Laflen et al., 2004).

It is likely that increasing stream power has a decreasing effect on aggregate disintegration or breakdown as aggregates are reduced to their basic particles; there may be a practical threshold of stream power effects to consider in detachment modeling. As Zhang et al. (2002) comment "a large gap exists between fundamental erosion processes and erosion models … until we are able to fully understand … we are forced to continue using essentially empirical parameters, such as those used by WEPP". Erosion processes are sufficiently complex that questions of laminar versus turbulent flows in the field, the fundamental applicability of the turbulent flow based shear-stress equations at slopes greater than 10%, the discrepancy between measured and modeled soil-shear strength (100's *vs.* 1 Pa, respectively), and raindrop impact (kinetic energy) effects, especially on steeper undisturbed soils remain unresolved, while precise definition of erodibility remains elusive except as defined below in terms of runoff rates.

Based on the rainfall simulation studies Grismer and others (see references) have conducted across the Basin under many different soil conditions, slopes and covers, it is possible to determine the range of infiltration rates (hydraulic conductivities) and interrill erodibilities that apply in the Tahoe Basin and are needed for WEPP modeling efforts. These studies indicate that measured infiltration rates and interrill erodibility are generally much less than the WEPP default values. The data from these studies provide a starting point for parameterization of WEPP modeling efforts in the Basin and have been used in initial TMDL modeling efforts by the Lahontan Regional Water Quality Control Board (Grismer et al., 2007; Lahontan RWQCB, 2008).

The options for simulating impacts of management on soil nutrients are less straightforward. Many biogeochemical simulation models have been developed to simulate ecosystem nutrient cycling processes (e.g., Aber et al., 1978; Kimmins et al., 1984; Pastor and Post, 1985; Parton et al., 1987; Eckersten, 1994; Johnson et al., 2000, Verburg and Johnson, 2001). These models range in their complexity and data requirements. In addition, very few models have equally detailed descriptions of hydrology, geochemistry and forest growth and most models contain detailed descriptions of certain processes while other process are described by simple, empirical relationships (Tiktak and Van Grinsven, 1995). The advantage of the more rudimentary models is the limited data needs compared to the more complex models and the ease of calibration (Verburg and Johnson, 2001). The downside is their limited use to address site-specific issues. Johnson et al. (2000) applied the Nutrient Cycling Model (Liu et al., 1991), a model emphasizing soil chemistry, to simulate biogeochemical processes in Sierra Nevada forest ecosystems but concluded that its application for simulating short-term intra-annual patterns in these processes may not be justified. As a result, managers and scientists would benefit from selecting or developing a model or suite of models that can be used to assess the potential long term impacts of management on soils. One example of such an approach is currently underway by Weisberg et al. (University of Nevada, Reno) who have developed a landscape-level simulation model for analyzing the effects of various fire regimes (historic, current, wildfire) on nutrient cycling in forests throughout the Lake Tahoe Basin. They are combining LANDIS-II, a spatially-explicit and stochastic simulation model of landscape dynamics (Scheller et al. 2007) with the Nutrient Cycling Spreadsheet approach (Verburg and Johnson, 2001) and applies key ecosystem processes, including succession, productivity, fire disturbances, and nutrient cycling, and their effects on biomass, forest floor, and soil mass and nutrient pools. The model adds mass and nutrients to the forest floor through litterfall and mortality, and removes mass through decomposition and fire-induced combustion and mineralization. These types of studies may help to reconstruct Basin-wide fire regimes and their effects on forest ecosystems that can then be used to evaluate impacts of forest management on ecosystem processes.

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12. References

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Effects of Wild and Prescribed Fires on Lake Tahoe Air Quality

Thomas A. Cahill[1]

1: Physics and Atmospheric Sciences and Tahoe Environmental Research Center, University of California, One Shields Ave, Davis CA 95616
(530) 752 4674; (530) 752-1120 Fax (530) 752 9804
tacahill@ucdavis.edu

Abstract

Since fire has always been a component of the Tahoe Basin forests, smoke and its associated degradation of air quality have also been natural components of the basin environment. However, human practices have greatly modified forest conditions, so that expected smoke levels are now very different than natural conditions in location, timing, intensity and impacts on visibility, human health, and lake clarity. In the basin, typical mountain terrain winds trap locally generated smoke near the ground each night and generally release it during subsequent days. Large wildfires have had major impacts on local and regional visibility and on lake clarity. This review focuses on results from the Lake Tahoe Airshed Model (LTAM) developed in the Tahoe Basin Watershed Assessment. The model predicted that pre-European conditions of dry fuel surface based burns at the rate of 30 acres/day (12 ha/day) resulted in a low intensity smoke haze over the lake each morning from roughly May through October that would clear each afternoon, not violate state and federal air quality standards, and have little impact on lake clarity. LTAM analyses of fall burns, including 50 ha (124 acres) and 100 ha (248 acres) prescribed fires, resulted in much higher smoke levels that violated state and federal standards but had only minor impacts on lake clarity. The analyses of various types of prescribed fire indicate that local smoke levels from low intensity (surface) prescribed fires can be much higher than higher intensity (pile) burns, while the latter practice has regional visibility impacts. Modeling results for a hypothetical 1500 ha (3700 acres), 3-day wildfire in the Ward Creek Watershed agreed very well with measured air quality impacts of the 1243 ha (3027 acre) Angora fire in 2007, in terms of the relative location and magnitude of smoke mass within the basin. Options for mitigating smoke impacts include combustion in biomass facilities, burning under dry conditions, burning before rains, and burning under a vegetative canopy or a tarp. Spatially and temporally detailed data are needed to refine air quality models of forest burning, so that managers can improve their use of fire.

Introduction

The choice for people living in the Tahoe Basin is not smoke or no smoke, but the amount, type, and timing of smoke from forest fires. Forest fires have always been a part of the Sierra Nevada and the Lake Tahoe air basin, and always will be. The present problem is a consequence of many factors, including, but not limited to topography and meteorology of the Lake Tahoe basin that makes it especially susceptible to forest-generated and man-made air pollutants, dense regrowth of trees following the 19th century clear-cutting of the basin, the 20th century forest practices that suppressed all fires and allowed the essentially unnatural 19th century re-growth to persist, and the late 20th century impacts of global climate change.

As a result of these factors, forests in the basin are prone to severe wildfire, which can have massive air quality impacts. Land managers must attempt to avoid severe wildfires by bringing forests back to a more fire and drought resistant condition. However, application of one of the primary tools, prescribed fire, is confounded by the sharp increase in basin population, the extension of suburban residences into heavily forested areas, new state and federal air quality regulations, and the inappropriate public expectations for splendid visibility based on the unnaturally good air quality of the late 20th century. Visibility concerns are heightened in scenic areas, where people are used to seeing many miles and visibility reductions are obvious. Smoke plumes from fires tend to be well above the ground, which makes them more visible.

The purpose of this paper is to place into context air quality impacts of alternative options, particularly prescribed burning, to achieve that goal. These options should be considered against the possibility that inaction may increase the likelihood of severe wildfires and massive widespread air quality impacts. Previous air quality monitoring research has been summarized in the Sierra Nevada Ecosystem Project (SNEP) report of 1997 (Cahill et al., 1997) and extended in the USFS Watershed Assessment's Air Quality in the Lake Tahoe Watershed (Cahill and Cliff, 2000), which also included original research on the Captain Pomin prescribed fire of 1999. In addition, between 2002 and the present, there were several major air quality studies within the basin. These studies focused on how air quality was impacting water quality, but many also gave information on smoke in the basin. These included: the TRPA South Lake Tahoe study (Cahill et al., 2002), the Air Resources Board Lake Tahoe Atmospheric Deposition (LTAD) study (Dolislager et al., 2004), the CalTrans Highway 50 sanding and salting study (Cahill et al., 2006), and work by the Desert Research Institute (Gertler et al., 2006). In 2007, the new Tahoe Environmental Research Center (TERC) was formed in a joint DRI/UC Davis collaboration, and a US EPA Region IX grant was awarded to Tom Cahill and Geoff Schladow for particulate measurements and deposition into the lake, with a small component for forest smoke. Through this grant, TERC personnel collected data on the Angora fire.

This paper synthesizes research on how the physical setting influences smoke in the basin, the historical smoke regime, effects of wildfires on air quality, and the effects of prescribed burning on air quality. The analyses are based upon data from wildfires, theoretical predictions of fire behavior, literature analysis of smoke emission, personal observations, one relatively complete prescribed fire test, and modeling to evaluate the likely effects of prescribed fires relative to wildfires. All of these approaches have important limitations (Jenkins et al. 1995, Cahill et al. 1997, Turn et al. 1997). Adequate information is not yet available on the local, regional, and area wide impacts of various prescribed fire regimes.

Physical Setting and Meteorological Regimes

The bowl-shape of the Tahoe Basin defines atmospheric processes almost as much as it defines hydrological processes. The presence of the cold lake at the bottom of this basin maintains an atmospheric regime that, in the absence of strong synoptic weather systems, develops very strong (to 10oC), shallow (30 m or 98 ft) subsidence and radiation inversions at all times throughout the year. In addition, there is often an inversion at roughly 500 m (547 yd) above the lake within the basin. During summers, a regional inversion forms at roughly 1500 m (1640 yd) above the lake, matching the highest mountain tops. In addition, the rapid radiation cooling at night generates gentle (1 m/s or ~3 ft/s) but predictable down slope winds each night, moving from the ridge tops down over the developed areas at the edge of the lake and out over the lake itself. Local pollutant sources within this bowl are trapped by inversions, greatly limiting the volume of air into which they can be mixed, which then allows them to build-up to elevated concentrations. Further, the down slope winds each night move local pollutants from developed areas around the periphery of the lake out over the lake, increasing the opportunity for these pollutants to deposit into the lake itself. This meteorological regime, weak or calm winds and a strong inversion, is the most common pattern at all times of the year (Cahill et al., 1977; Barone et al., 1979, Cahill et al., 1997).

The location of Lake Tahoe directly to the east of the crest of the Sierra Nevada creates the second most common meteorological regime, that of transport from the Sacramento Valley into the Lake Tahoe basin by mountain upslope winds. This patterns develops when the western slopes of the Sierra Nevada are heated, causing the air to rise in a chimney effect and move upslope to the Sierra crest and over into the basin. The strength of this pattern depends on the amount of heating, and thus is strongest in summer, beginning in April and essentially ceasing in late October (Cahill, 1989; Myrup et al., 1989; Ewell 1996, Cahill et al., 1997). This upslope transport pattern is strengthened and even more frequent by the alignment of the Sierra Nevada range across the prevailing westerlies common at this latitude, which combine with the terrain winds to force air up and over the Sierra Nevada from upwind sources in the Sacramento Valley. The other meteorological regimes at Lake Tahoe are defined by strong synoptic patterns that are able to overcome the dominant terrain-defined meteorological regimes of local inversions, nighttime downslope winds, and valley transport. The most important of these patterns is the winter storm regime that brings almost all the precipitation received by the basin, mostly in the form of snow. These winter storms have strong vertical mixing, diluting local and upwind pollutants to low levels while bring in air from the very clean North Pacific sector. This is likely the reason that snowfall within the basin has a relatively low concentration of anthropogenic pollutants such as nitrates and sulfates (Laird et al., 1982; Cahill et al., 1997). The other important pattern is associated with the basin and Range lows that during the summer circulate moisture in from the east, often forming thunderstorms along the Sierra crest. Finally, strong high pressure patterns north and northwest of Lake Tahoe can bring strong, dry winds across the basin at almost any time of the year.

Each of these meteorological regimes has a potential for establishing anthropogenic pollutant concentrations within the basin. The inversion-based basin trapping collects local sources, such as vehicular, urban, and forest burning emissions. Furthermore, these inversions, even if weak, limit the air into which pollutants can be mixed thereby raising them to significant levels. Transport of pollutants from the Sacramento Valley increases the concentrations of both ozone and fine particulates such as sulfates, nitrates, and smoke from industrial, urban, vehicular, agricultural, and forest sources in western slopes of the Sierra Nevada, Sacramento Valley, and the Bay Area. In the winter, the basin is de-coupled from the Sacramento Valley, but participates in the synoptic winter storms, generally from the North Pacific, which bring most of the precipitation into the watershed in the form of snow but along generally clean transport trajectories. The basin and Range lows bring in air from a very clean sector of the arid west (Malm et al., 1994) as do the Northwest highs with their strong dry winds.

In designating Lake Tahoe as an air basin, the California Air Resources Board (ARB) appreciated the fact that terrain plays a major role in air quality at Lake Tahoe. The tall mountains, cold lake, and terrain that forces roads and development close to the lake shore all make spatial gradients very important at Lake Tahoe. A number of important processes dominate the sources and transport of pollutants in the basin. Upwind transport, local sources, tree deposition, lake deposition and transport out of the basin are all major dynamical factors at Lake Tahoe. An overview of the important atmospheric processes is shown in Figure 1.

Highlights:

- The most common weather pattern in the basin is weak winds and strong inversions that trap local pollutant sources within the bowl-shaped basin.
- Mountain upslope winds transport air from the Sacramento Valley into the Lake Tahoe basin, often bringing in smoke from wildfires.
- Winter storms tend to dilute air pollutants.

Historical Air Quality

Information on the air quality at Lake Tahoe is qualitatively available since the mid 19th century, from comments by early visitors such as Mark Twain and pictures from the 19th and early 20th centuries (Thompson 1972), but detailed information only dates from the mid-1970s. Even now, quantitative long term data are available at only limited sites and times. The availability of air quality data since the 1970s is available from a variety of sources, but no continuous record exists for all air pollutant data. Studies of fire scars on tree rings indicate that wildfires and fires set by Native Americans were common in the basin and throughout low and mid-elevations of the Sierra Nevada, and that these fires generally burned at low severity (SNEP 1997).

During the widespread clearcutting of the Comstock era, historical photographs show considerable smoke from slash burning. Few data are available on air quality once the logging ceased. Beginning in the early 20th century, effective fire suppression was initiated, allowing the second growth forest to become denser and more fire prone. However, because of the almost total suppression of forest fires, air quality was excellent except in the immediate vicinity of the small and scattered towns, where burning of wood was a major source of heat. During the 1950s, tourism development accelerated with the construction of the Interstate 80 freeway for the Squaw Valley Winter Olympics in 1960. Rapid growth in tourism and second home development led to a number of air quality concerns, including wood smoke from residences, carbon monoxide, and lead from cars.

In response to growing concerns over air pollution, the California Air Resources Board in 1973 performed a summer study at about a dozen sites around Lake Tahoe (CARB, 1974), confirming the high lead and carbon monoxide levels. About ½ of all parameters measured were higher at impacted sites than in downtown Los Angeles (Goldman and Cahill 1975). In 1977, CARB identified the Lake Tahoe Air basin as a separate entity, started making routine measurements of air quality, and imposed a visibility requirement of 30 miles (48 km), 3 times the state standard of 10 miles (16 km). The newly re-constituted Tahoe Regional Planning Agency (TRPA) developed basin "carrying capacity" standards. These included both sub-regional (urban) and regional (basin-wide) standards for visibility. Monitoring was started in

1988, documenting an excellent record of visibility that persisted until 2004 (Molenar, 2000). In 2004, both TRPA and the CARB essentially terminated routine measurements within the basin. However, the Bliss site was retained by IMPROVE (Malm et al. 1994) as a baseline site for the Desolation wilderness area, and continues to collect data every third day for PM_{10} mass, $PM_{2.5}$ mass and chemical species.

Current Air Quality and Pollutant Sources

The TRPA visibility and aerosol monitoring program from 1988 to 2003 was able to resolve several key questions current conditions at Lake Tahoe. Paired sites were maintained at Bliss State park (BLIS), 200 m (656 ft) above the lake just north of Emerald Bay, and South Lake Tahoe (SOLA), near Highway 50 at the lake. Note that SOLA lies under the 30 m (98 ft) surface based winter inversion, trapping ground-based pollution sources, while BLIS lies above it. Organic matter in the atmosphere over Lake Tahoe is overwhelmingly derived from wood smoke, from upwind, urban or forest sources. Early research established that BLIS only responded to materials being transported into the basin from upwind, while SOLA responded both to upwind and local influences.

The SOLA data reflect urban conditions including vehicles and smoke, both of which become particularly important during winter. Visibly smoking vehicles, including older cars, diesel cars, trucks and buses dominate the vehicular sources. Following spring thaw, road aerosol emissions are also significant. Figure 2 presents values for $PM_{2.5}$ and PM_{10} mass, and Figure 3 presents fine $PM_{2.5}$ soil and organic matter. The soil data shows an anomalous peak each spring, which comes from Asia (VanCuren and Cahill 2004). The organic matter is mostly wood smoke, with some automotive component. Urban smoke levels measured at South Lake Tahoe have been dropping steadily since the mid-1990s as natural gas started replacing wood burning fire places, especially in new construction. In spring and summer, half is from upwind sources, but in fall and especially winter, the sources are overwhelmingly local. Note that all upwind prescribed fire in the fall shoulder season on the western Sierra slopes would appear in the BLIS record, but little is seen. These observations indicate that smoke from prescribed fires on the western slopes of the Sierra Nevada in fall does not readily transport into the basin, for the same reason that smoke generated within the basin in these seasons tend to remain.

Relationship of Smoke to Visibility

Mass loadings can be modest even in visibly dense smoke. We measured a relationship using results of studies of Oregon and Washington fires (Radke et al., 1990). Results (Table 1) indicated that visibility due to smoke must be reduced to 9.0 km (5.6 miles) before one reaches the California standard for PM_{10} of 50 $\mu g/m^3$ and to 3.0±1.8 km (1.9±1.1 mi) before one reaches the federal particulate air quality standard for PM_{10} of 150 $\mu g/m^3$. The same relationship is found for IMPROVE's fine (D_p< 2.5 µm) particulate mass. A "best fit" between visibility and mean annual mass at forty-four sites gave 3.0 kilometers (1.9 miles) for the federal standard of 150 $\mu g/m^3$, assuming no contribution from particles greater 2.5µm diameter (S. Copeland, USFS, Personal Communciation, 1995). The corresponding visibility at the 50$\mu g/m^3$ California standard is 9.1 km (5.7 miles). Note that the uncertainty on all these estimates is at least ± 50%.

Highlights:

- Health-related impacts are usually addressed by the 24 hr $PM_{2.5}$ mass standard.
- Visibility is governed by a 30-mile California State standard, which translates to a relatively low particulate matter concentration.
- Sources of particular matter during the fall and winter are overwhelmingly local.
- Smoke from prescribed fires outside of the basin during the fall does not readily come into the basin.

Measured Air Quality Effects of Wildfires

Large crown fires almost certainly occurred in pre-historic times but were much less common than in the present era (SNEP, 1997). Crown fires are facilitated by the presence of ladder fuels; dense, closed canopies; and synoptic or terrain winds. The strong daily terrain winds along the western face of the Sierra Nevada provide strong winds every afternoon and evening from late spring to fall (Myrup et al., 1994; Cahill et al., 1997). Crown fires result in lofting and dispersion of minerals such as phosphorus that normally are not seen in airborne smoke from low temperature fires, such as prescribed fires or home woodburning. Nutrient deposition is dominated by coarser particles, generally above and occasionally much above 1.0 µm, which settle readily to local surfaces. Severe fires have resulted in algal blooms in Lake Tahoe, unlike less severe ground or prescribed fires. The smoke plumes from severe crown fires also impact protected Class I areas of the United States where visibility must be protected (USEPA, 1999).

Oregon Biscuit Complex (2002, out of basin)

The Biscuit Complex fire burned almost 4,000 ha (9,884 acres) per day from July 13 though September 5, 2002, covering over 200,000 ha (494,209 acres) in the Kalmiopsis wilderness area and Siskiyou National Forest of Oregon (The Wilderness Society, 2008). Only an estimated 16% of the burn was crowning, and there were areas with only modest or no damage within the perimeter. During much of the fire period, smoke was blown predominantly in an easterly direction on the typical prevailing summer winds. On occasion, however, the synoptic winds changed direction, dramatically raising air pollution levels in areas far to the South across California, including Lake Tahoe. $PM_{2.5}$ measurements were made at South Lake Tahoe, regretfully only one day in six, and missing the largest impact period August 14 through 16 (Figure 4).

At the same time, a study was in progress at South Lake Tahoe for TRPA (Cahill et al., 2003) and caught the impact of the Oregon fires with the unambiguous fine potassium tracer derived from volatilization of tree sap (Figure 5). Visibility was sharply degraded for days, with the far end of the lake invisible from South Lake Tahoe. The mass excesses around August 30 were not due to wood smoke. Using the trajectory program HYSPLIT 4 (Draxler and Rolph, 2003; Rolph, 2003), we were able to trace the smoke down into the upper Sacramento Valley, at which point it was pulled up into the Tahoe basin by terrain winds after 4 days of travel from its source in Oregon. While the peak days of the smoke impact were not seen in the ARB one-day-in-six mass measurements, the estimated $PM_{2.5}$ was roughly 20 to 25 $\mu g/m^3$, very close to the 25 to 30 $\mu g/m^3$ seen in Sacramento on the same days. Thus, little attenuation occurred during the transport up the slope and into the Lake Tahoe basin.

Cleveland fire (1992, out of basin)

The Cleveland forest fire of September 1992 burned up the western slope of the Sierra Nevada almost directly west of the Tahoe basin. It burned roughly 10,000 ha (24,710 acres) in 4 days, with the smoke plume trending generally north east in the terrain winds. Thus, the fire had limited impact on the Tahoe basin, but even so sharply restricted visibility. Truckee was directly in the path of the smoke plume during daylight hours, experiencing $PM_{2.5}$ levels that were similar to typical winter days (Cahill et al., 1997). The maximum smoke from the Cleveland fire, about 150 $\mu g/m^3$ over 24 hours, was six times higher than the smoke generated from the much larger but more distant Biscuit fire. Because the Cleveland fire was so well documented, it was the source of some of the emission factors used in the LTAM model.

Highlights:
Wildfire-generated smoke emissions are likely to exceed all state and federal air quality standards and are clearly capable of causing serious health problems.

Angora fire (2007, in basin)

The Angora fire started in the afternoon of June 24 in the southwest corner of the Tahoe basin south of Fallen Leaf Lake. Strong terrain winds blew the fire in the northeast direction along a heavily forested and densely populated ridge. The meteorology of the situation was favorable in that the smoke was blown onto the lake and then was constrained to a narrow plume in the middle of the lake as it went due north. The net result was to limit personal exposure to the heaviest smoke except for those directly in the path of the plume. The Tahoe Environmental Research Center deployed air samplers on June 25-26 and June 27–28 at several sites around the lake. The highest readings in the smoke plumes are extreme, well beyond all state and federal air quality standards, and clearly capable of serious health impacts (Table 2). Smoke levels exceeded that from the fall, out-of-basin Cleveland fire. The smoke clearly lingered, with high levels even as the fire was being brought under control. These sustained levels were partially caused by smoke trapping within the basin inversions.

Modeling Comparisons of Fire Regimes

Concentrations of particulate matter in the atmosphere are expressed in mass per unit volume. The mass responds to the emission rate, the volume to dispersion of the pollutant. From the point of view of air quality, several parameters are vital in understanding smoke impacts of fires:

1. The amount of energy released per unit area, which results in the lofting of the smoke,
2. The emission rate of the fire.
3. The volume of air into which the smoke is mixed
4. The extent to which vegetation captures particles before they have a chance to become part of the regional atmosphere.

For severe wildfires, the energy released per unit is enormous, pushing smoke clouds high in the atmosphere where they can linger and transport for thousands of kilometers. The same fires generate strong vertical winds that sweep up debris and ash. The emission rates are enormous, for a large fraction of the total forest biomass, including soil litter, is incinerated, Trees lose their stored nitrogen reserves, largely in green needles, which become part of the smoke plume and eventually helps fuel downwind ozone production. Crown fires often consume the canopy vegetation that can remove particles from the atmosphere.

Understory burns typically minimize emission rates by burning during the driest conditions that safety considerations will permit. Present efforts to burn in the shoulder seasons lose the advantages of historical burning practices that focused on the summer period. Consequently, low energy prescribed burning generates high, localized particulates at the ground-level, which often persist for weeks. However, particle deposition and removal rates can be enhanced as smoke lingers in the tree canopy, especially at night.

Pile burns contain more fuel, and are generally covered to keep the fuel dry to minimize emission rates. However, energy release is high, and the smoke is lofted quickly through the forest canopy and generally rises until it meets an inversion or is swept out of the area on synoptic winds. Pile burning generates less pollution locally since the fire generated lofting pulls in clean air and the burn durations are generally short. However, the smoke does generate air pollution at the regional scale. Rain can effectively remove wood smoke, and pile burns are often timed to maximize this effect.

Modeling Prescribed Fires Using the Lake Tahoe Airshed Model (LTAM)

The Lake Tahoe Airshed Model (LTAM) was designed to identify the relative fraction of in-basin and out-of-basin, natural and anthropogenic components of the atmosphere of the Lake Tahoe basin, and to evaluate the effects of atmospheric pollutants in the Lake Tahoe air basin on lake clarity, visibility, human health, and forest health. The LTAM is capable, however, of making credible predictions only when the source data are included. In the case of several types of prescribed fires, these data are not yet available. Further study of the impact of fire on the Lake Tahoe ecosystem, especially the impact of smoke on lake clarity, visibility, and human health, is necessary to better define parameters for integrated management models in general, and the LTAM in particular.

Meteorological conditions in the model are divided into summer day, summer night, and winter (non-storm) conditions. Late spring, May and early June, is considered comparable to the summer-time regime. Fall (late September through late October) is modeled as a combination of summer day and night and winter meteorological regimes. Meteorological conditions are general LTAM meteorology for summer and winter. The LTAM modeling output is often restricted to $PM_{2.5}$, because it represents the most significant component of particular matter and the most significant threat to human health. However, the LTAM can be used to predict the concentration of a variety of pollutants across the basin, including total suspended particulates (TSP), NO_x, hydrocarbons, or any other known products from combustion.

Pre-settlement fire regime

The LTAM was used to analyze the pre-settlement fire regime. The modeled scenario assumed a 40-year return interval divided across the total burn season (May through October), equaling 12 ha (30 acres) burned per day. The scenario divided this acreage equally into three 4 ha (10 acre) fires spread across the basin, one in the Ward Creek watershed, one in the forested area near Meeks Bay, and one near Sand Harbor on the east shore. The peak PM 2.5 impact of 29 $\mu g/m^3$ would have been below the EPA 24-hour standard of 35 $\mu g/m^3$ (Figure 6a). The corresponding visibility range would have been roughly 19 miles (31 km) at lake level, which would have blocked vision of the far shore on a north-south transect, and more than 50 miles (80 km) at ridge tops. By mid-morning, westerly winds would have blown the smoke out of the basin and visibility would be excellent except in the immediate vicinity to the fires. The relatively low smoke mass in the LTAM model run was due to the limited number of acres burned each day, good ventilation in summer, and dry fuel.

For the pre-European estimates generated by LTAM, the modeled smoke levels were low because of several assumptions:

1. The area burned/day was low.
2. These fires were presumed to be burning at three well-separated sites in the basin, thus using most of the air volume in the basin for dilution

3. The fires were presumed to burn over 6 months, May though October, during which strong westerly winds occurred each day. This resulted in good ventilation for about 12 hours each day, and no holdover smoke from the prior day's burns.

In addition, the fuel would have been dry. These fires were also possible because there was a mature forest that had been repeatedly burned, and thus lacked the high tree density and ladder fuels that have made the current fire regime so hazardous. The result was a maximum smoke mass of about 29 $\mu g/m^3$ in mid-lake, meeting current US EPA and CARB standards for protection of human health.

Fall prescribed burn ("shoulder season")

Another modeled scenario involved prescribed burning within the Ward Creek watershed occurring in October, when ventilation is poorer. For the model based on a 40-year burn cycle, 50 ha (124 acres) of forest within the watershed was estimated to burn. The model based on a 20-year cycle assumed that twice as many acres would be burned annually. LTAM predicts that violations would occur close to the fire source for the 50 ha (124 acre) scenario (Figure 6b); however the model predicts that violations of the new federal standard of 35 $\mu g/m^3$ would occur over essentially the entire basin for the more aggressive 100 ha (247 acre) scenario (Figure 6c); A model run for the same scenario for a typical summer period (not shown) predicts less violations, mostly due to the increased ventilation of the basin during that time.

August wildfire

The LTAM was also used to model an August wildfire burning approximately 75% of the forested part of the Ward Creek watershed, representing 1500 ha (3700 acres). The output is broken up into three days of burning, with day 1 consuming about 60% of the area, day 2 at 25%

and day 3 at 15%. Some smoke carryover from the previous day was included in days 2 and 3 in the LTAM predictions. The model predicted that smoke from such a fire would completely fill the basin with smoke (Figure 7).

Although the wildfire burns an order of magnitude more land than the prescribed fires, the number of resulting violation days is predicted by the LTAM to be roughly equivalent: 2 to 3 violation days for the 40-year fire, 3 days for the 20-year fire, and 4 to 5 days for the wildfire. The apparent discrepancy is due mostly to the increased ventilation of the basin during the late spring and summer months. Furthermore, a wildfire lofts smoke higher than in a prescribed fire, causing impacts farther downwind.

Validation of LTAM Results

Summer prescribed burn

Simple field experiments help to validate the predictions derived from the LTAM. We performed a limited experiment for prescribed fire modeling during the preparation of the Watershed Assessment. On June 9, 1999, the Captain Pomin prescribed burn commenced near Spooner Summit, consuming approximately 18 ha (45 acres). The LTAM predicted a significant visibility reduction over Lake Tahoe for the inversion period, from sunrise until about 11 a.m. A west to southwest wind is typically present during the daytime, so the majority of smoke should not directly impact the basin. However, in the late evening and early morning hours, an inversion in the basin, as modeled by the “summer night” meteorological conditions in the LTAM, forces smoke to settle near the lake surface until the winds pick up again the following day. The LTAM predicted that an 18 ha (44 acre) fire on the east side of the basin would obscure the west shore and mountains above during this inversion period. Photographs taken on the morning of June 10, 1999 from the lake shore in Glenbrook, Nevada qualitatively confirm this LTAM prediction (Figures 8 and 9). Furthermore, photographs taken from the Lake Tahoe overlook at Echo Summit on Highway 50 (Figure 10) indicate a rather uniform distribution of smoke over the lake with a slightly greater density near the center. LTAM predicts similar features for the natural condition. It should be noted that most of the visible smoke from combustion is $PM_{2.5}$ due to the high efficiency for scattering light. Therefore visible smoke is a good qualitative indicator of $PM_{2.5}$ concentration which is what is modeled by the LTAM. Quantitative mass measurements have only recently become available for prescribed burns in the Tahoe basin, as have data on concentration and chemical composition of the smoke from fires that may have an impact on lake clarity and the ecosystem as a whole. Further research of this sort is needed to evaluate the validity of the LTAM model.

Winter prescribed burn

A small prescribed burn during March 24, 2008 provided a recent test of the LTAM model during winter conditions. Weaker downslope winds during this season disperse smoke less than in the summer, resulting in typically high local smoke concentrations (Figure 11). From the visibility estimates (below), the smoke mass was roughly 50 $\mu g/m^3$.

Angora wildfire

The results measured during the 1243 ha (3072 acres) Angora wildfire near South Lake Tahoe can be compared to the LTAM results for a modeled 1500 ha (3707 acre) wildfire in the Ward Creek Watershed. The modeled wildfire was assumed to burn for 3 days in August, while the Angora fire burned mostly in three days from June 25-28. The LTAM predicted mid-lake values for Day 1 (200 $\mu g/m^3$) and Day 2 (85 $\mu g/m^3$) of the hypothetical Ward Creek wildfire.

The modeled two-day average (137.5 $\mu g/m^3$) is very close to the average value (152.5 $\mu g/m^3$) of two days of sampling at mid-lake during the Angora wildfire (Table 2). Therefore, the modeled wildfire gave smoke mass results that were similar to that measured from Angora, despite differences in the month and location of the wildfire.

Highlights:

- Understory burns typically generate high ground level particulates that persist locally for long periods, particularly during the fall.
- Pile burns tend to generate less local smoke but loft particulates higher, creating regional impacts.
- Wildfire generates extremely high particular levels that pose threats to human health.
- The LTAM results for a small wildfire in the Ward Creek Watershed corresponded well to actual results measured during the Angora wildfire.

Mitigation of smoke impacts

Combusting wood with a perfect fuel-air mixture results in only gasses, notably H_2O and CO_2 with minor amounts of NO_2 and SO_2, and incombustible mineral fractions in the ash. Off-site biomass burning permits much greater control of the combustion process, allowing smoke impacts to be greatly reduced. However, such ideal conditions are extremely difficult to achieve in the fuel-rich forests, resulting in high production of smoke.

Mitigation of smoke impacts will depend on what types of impact one wishes to mitigate. Much forest fire smoke consists of white, condensed water vapor, which affects visibility but not particulate matter. Both health and visibility impacts relate to smoke particles in the range from roughly 0.2 μm to 1 μm, well within the 2.5 μm standard. Note that these particles are so fine that they essentially never settle, and removal has to proceed by other methods such as diffusion to surfaces or incorporation into clouds.

Basic strategies for mitigating smoke impacts are to minimize the mass at the source or during transport, to minimize water content of fuels, and to reduce the amount of fuel burned per unit time. Covering burn piles with a tarp can keep fuels dry with adequate oxygen (Turn et al., 1997). Surface or area burns, on the other hand, have to contend with poorer fuel-air mixtures and often wetter fuel. For this reason, these are best conducted in dry conditions. Note that in the LTAM model, the water content of the fuel was not included since it was assumed that the prescribed fire in the Ward Creek watershed was started before significant rains had fallen.

Another strategy for mitigating smoke is to remove particles from the air once they are emitted. Because the typical settling rate of smoke particles is extremely low, about 0.01 cm/sec (0.004 in/s) (Seinfeld and Pandis 1997), removal rates from smoke in the free atmosphere in dry conditions can usually be neglected. However, both rainfall and vegetation can help to remove smoke particles from the area. Because these data have only recently been generated, these mitigations are not a part of LTAM.

The chemical properties of wood smoke allow it to readily absorb water and grow into larger particles, which can then settle at high velocities. This effect can often be seen when a column of smoke from a forest fire reaches the dew point, at which time some particles absorb water and form a cloud. Similar effects have been reported in the San Joaquin Valley in winter, showing that wood smoke is efficiently scavenged in fogs droplets. Thus, burning in wet conditions will enhance the removal of smoke particles from the air by a factor of 100 or more.

The smoke particles are small enough to adhere to vegetation until they are washed off in rain. In a study to test the effectiveness of particle removal by trees near roadways, measurements were made of the scavenging in wood smoke onto vegetation in a 2 m (7 ft) wind tunnel (Fujii et al., 2007). The results (Figure 12) show efficient removal of particles by vegetation at low wind velocities, which would be typical, for example, of a surface burn at night under a forest canopy. Thus, the very conditions that give high local surface-based $PM_{2.5}$ readings also result in efficient removal of the smoke from the air before it becomes part of the regional air mass. However, people breathe air at ground level, so such conditions in inhabited areas can cause health problems. On the other hand, such conditions result in less long scale transport to Class I areas where visibility is protected.

Burning under windy conditions can help to dilute and disperse smoke. For example, the Angora fire of 2007, driven by strong winds, burned about 400 ha/day (988 acres/day), Despite a much greater rate of consumption than under the modeled pre-European fire regime, the mid-lake smoke mass was only a factor of 7 times higher in the Angora fire due to the dilution effect. However, increasing wind velocities can increase the mass of emitted smoke per unit time, and thus cancel part of the expected reduction.

Nevertheless, it is current practice to initiate pile burns and other prescribed fires into increasing wind velocities associated with frontal storms, aiding in suppression of any subsequent fires and scavenging some of the smoke by wet deposition. However, if anticipated rain storms do not materialize, then fires can burn for a month or more.

Highlights:
Several options are available to mitigate smoke emissions, including:

- Removing fuels from the forest and burning them as biomass under tightly controlled conditions
- Burning during dry conditions
- Covering piles with a tarp
- Timing burns to occur before anticipated rains
- Burning under a vegetated canopy

Conclusions and Future Research Needs

The Tahoe Basin's current vulnerability to severe wildfires poses great threats to air quality, and it is against this hazard that smoke from prescribed fires must be evaluated. Nevertheless, increased use of prescribed fire in the Tahoe basin has potential to violate federal, state and regional air quality standards for human health and visibility. Information available to fire managers is usually inadequate to predict and mitigate these impacts, partially because of the variations in fuel and local meteorological conditions, and partially because adequate air quality analyses, especially for lofted and transported smoke, are extremely limited. To evaluate the impact of fuel management practices at Lake Tahoe will require further study, since the limited data (one day in three 24 hr filters at only the Bliss SP IMPROVE site) presently collected by state and federal air quality agencies do not adequately address the needs of the Tahoe basin. The key information needs include:

1. continuous, temporally detailed monitoring data at more sites throughout the basin,
2. vertical data to resolve smoke lofting and transport,
3. local evaluations of impacts from prescribed fires, and
4. data on smoke particle size and chemical composition to evaluate impacts on visibility and lake clarity.

Current research at the Tahoe Environmental Research Center (TERC) is addressing many of these issues, including a year of mid-lake continuous aerosol sampling by size, time, and composition, but this program will end in September, 2008. While TERC is committed to continuing parts of the program, much more can and should be done now that the technology has been developed. In addition, the degree of vertical lofting of smoke and removal by vegetation requires information that could be gained by something as simple as a set of 4 digital cameras taking images 3 times per day. It is imperative to understand the linkages among emission, transport and deposition of smoke constituents throughout the basin to better constrain integrated modeling tools for management use. Prescribed fire will remain a critical tool for resolving the excessive fuel build-up within the Tahoe basin.

Acknowledgments

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Table 1—Approximate relationship between forest smoke mass and visibility.

Visibility (km)	Visibility (miles)	Forest smoke mass ($\mu g/m^3$)
25.3	15.8	2.5
21.6	13.5	5.0
15.6	9.0	15
10.9	6.8	35
9.0	**5.6**	**50**
7.6	4.6	65
5.2	3.3	100
3.0	**1.9**	**150**

Bold values represent calibration points from the literature.

Table 2—24-hour average fine particulate matter (PM_{10}) readings during the Angora Fire (Reuter et al., 2008)

Location	June 25-26	June 27-28
South Lake Tahoe High School (2 hr)	8,551$\mu g/m^3$	292 $\mu g/m^3$
South Lake Tahoe house	264 $\mu g/m^3$	56 $\mu g/m^3$
Sunnyside	28 $\mu g/m^3$	14 $\mu g/m^3$
Tahoe City	56 $\mu g/m^3$	42 $\mu g/m^3$
Mid-lake buoy #1 (north)	69 $\mu g/m^3$	56 $\mu g/m^3$
Mid-lake buoy #4 (central)	111 $\mu g/m^3$	194 $\mu g/m^3$

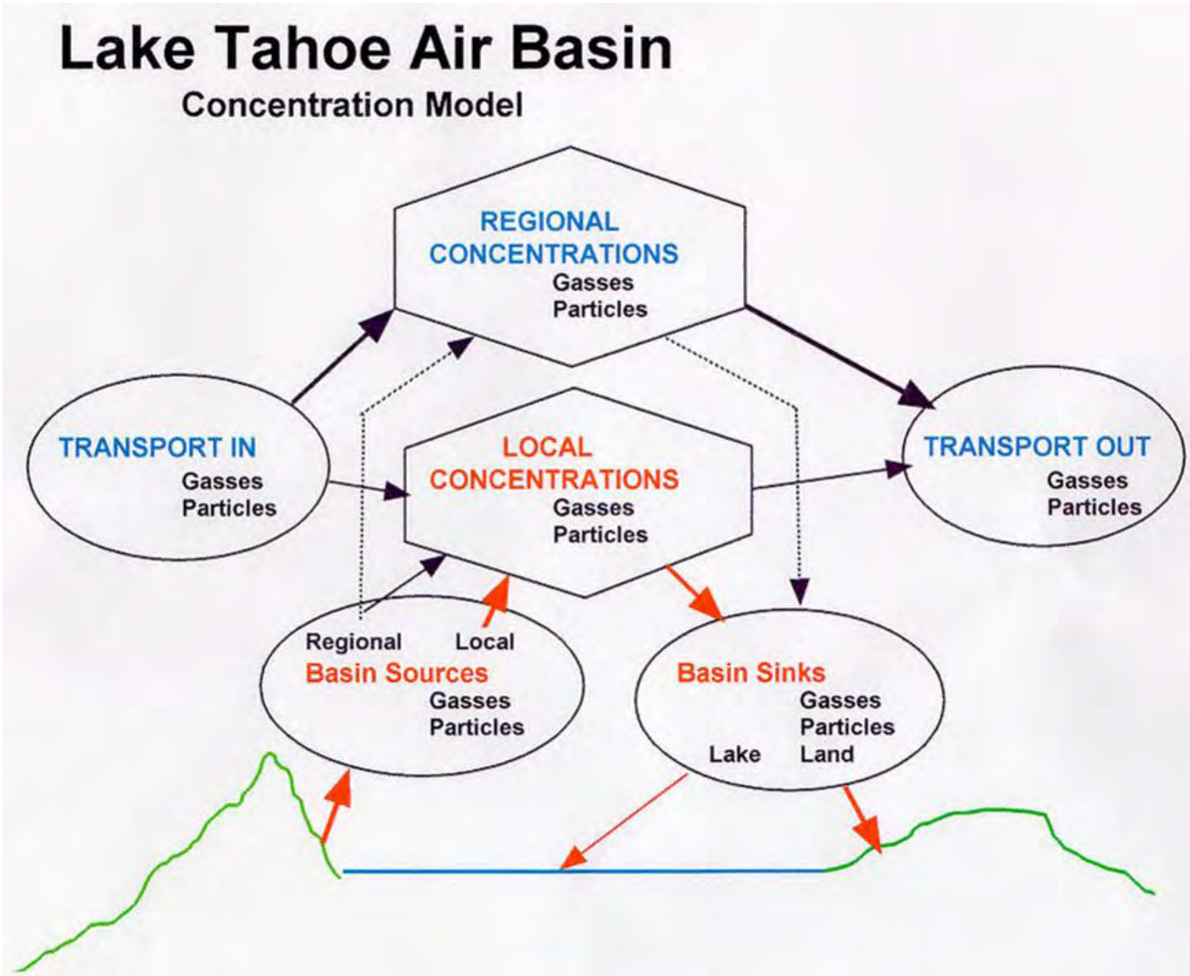


Figure 1—Schematic air model for the Lake Tahoe basin based on concentration of pollutants.

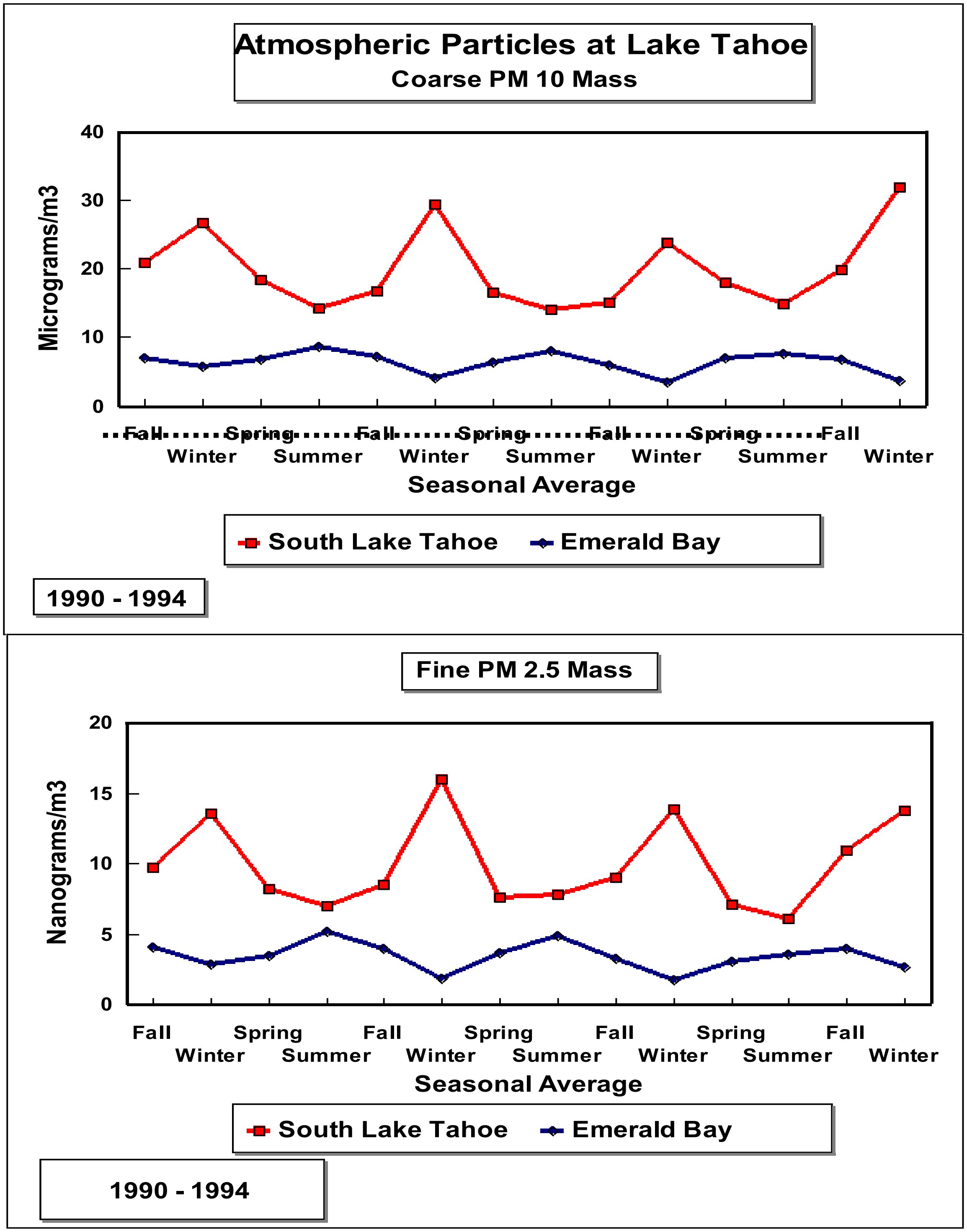
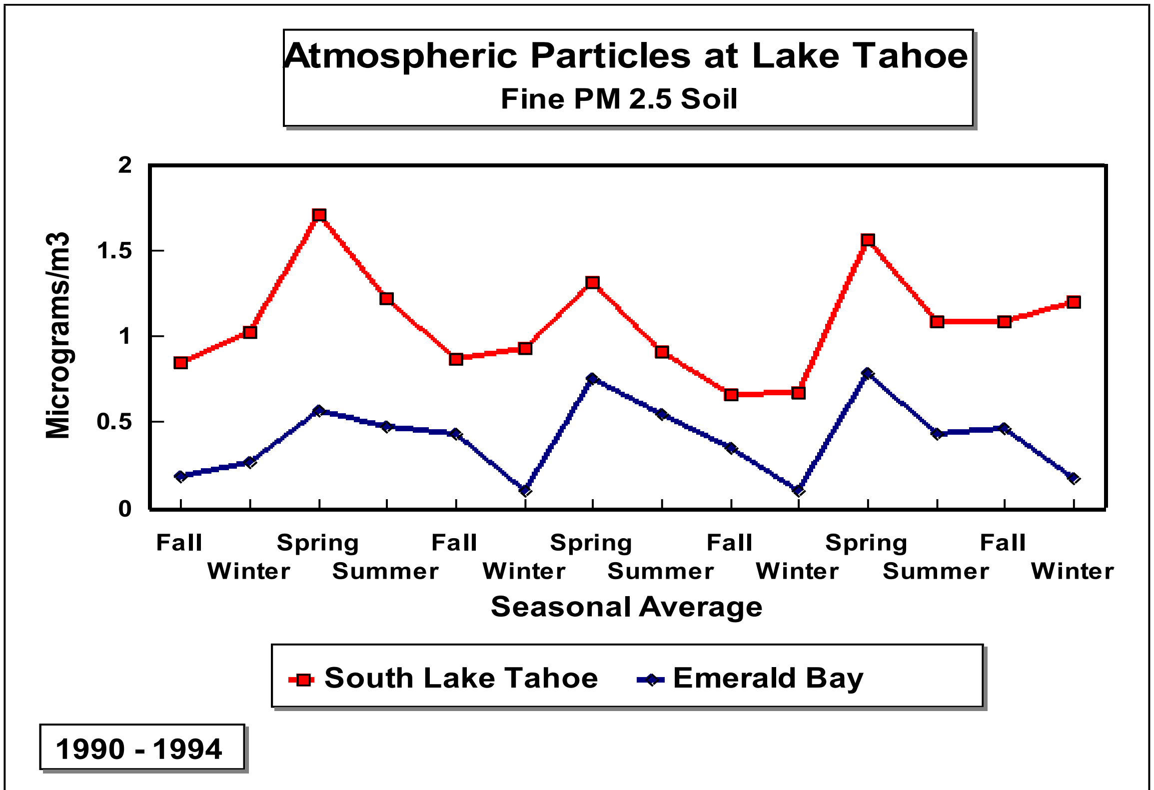


Figure 2—Seasonal concentration of $PM_{2.5}$ and PM_{10} mass South Lake Tahoe and D.L. Bliss State Park, all seasons, for the period 1990 through 1994.



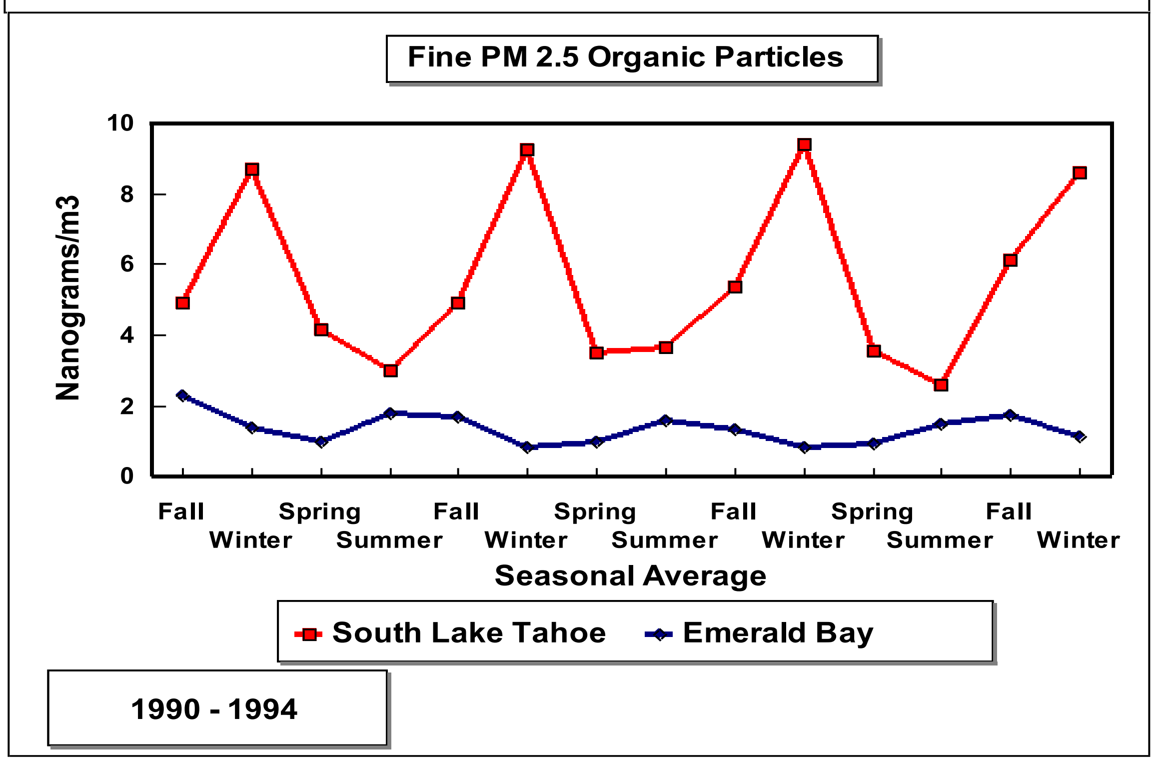


Figure 3—Seasonal concentration of $PM_{2.5}$ soil and organic matter (mostly wood smoke) South Lake Tahoe and D.L. Bliss State Park, all seasons, for the period 1990 through 1994.

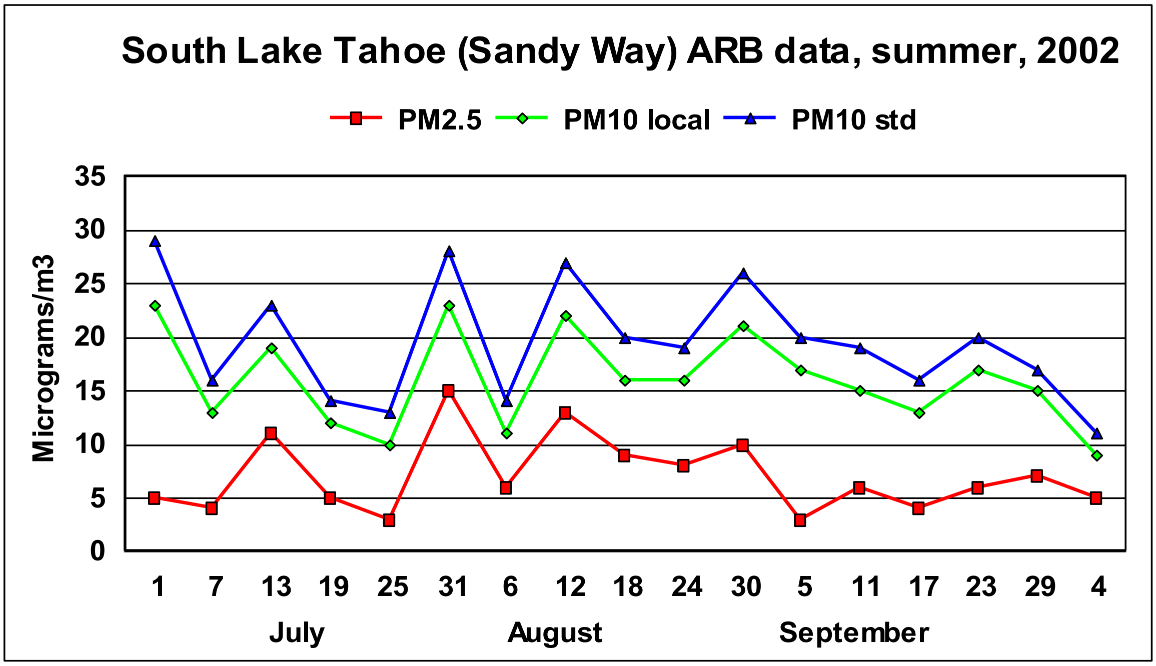


Figure 4—$PM_{2.5}$ mass at South Lake Tahoe during the Biscuit fire.

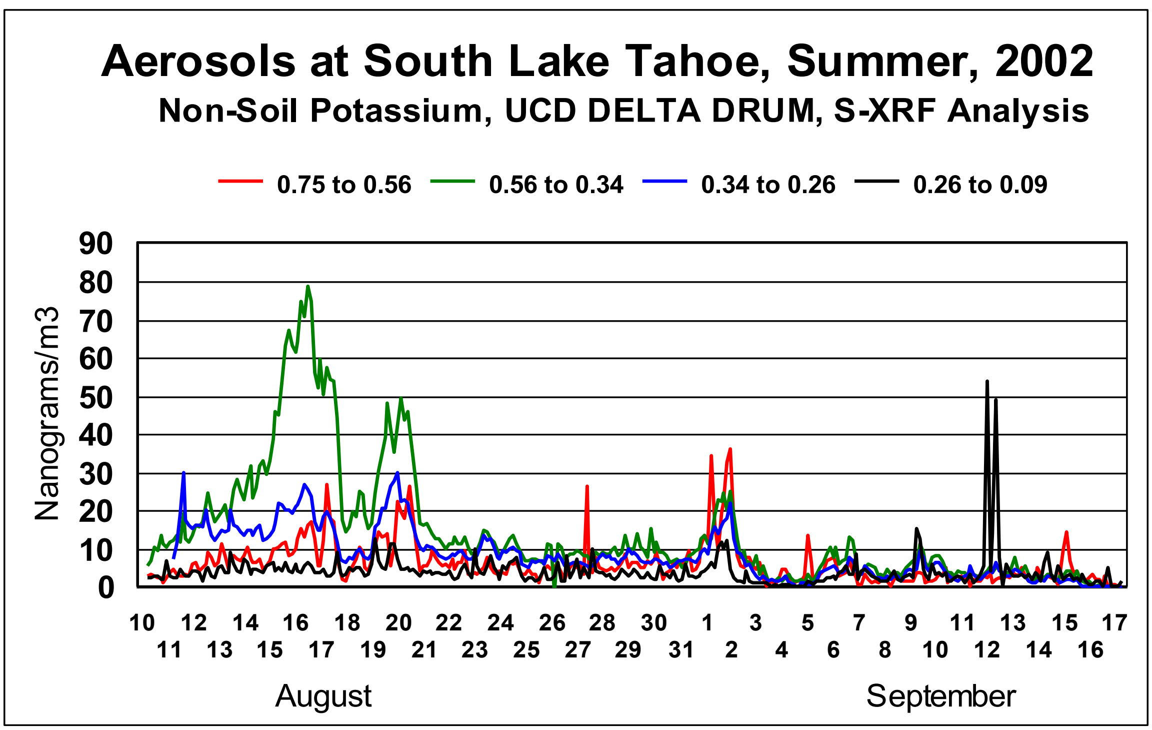


Figure 5—Size-resolved smoke tracers at South Lake Tahoe during the Biscuit fire.

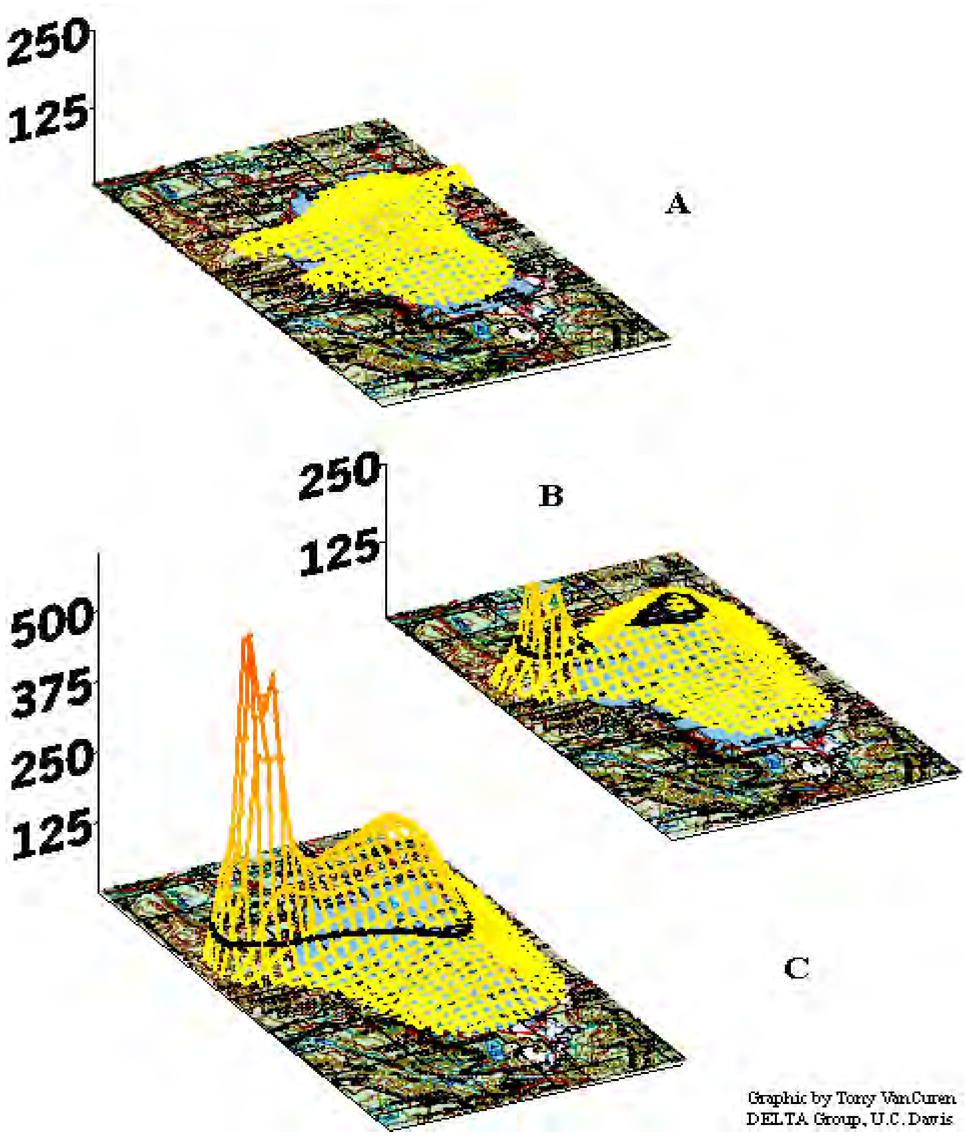


Figure 6—$PM_{2.5}$ concentration predictions from the Lake Tahoe Airshed Model (LTAM) outputs based on a 24-hour average superimposed on the basin map. (A) shows results from the pre-settlement fire scenario. (B) and (C) show results for two differents amounts (50 ha and 100 ha, respectively) of prescribed burning per year in the Ward Creek Watershed. The black isoplith indicates the former federal 24 hour standard of 65 g/m^3. The peak concentrations for A, B, and C are 29, 165, and 500 g/m^3, respectively.

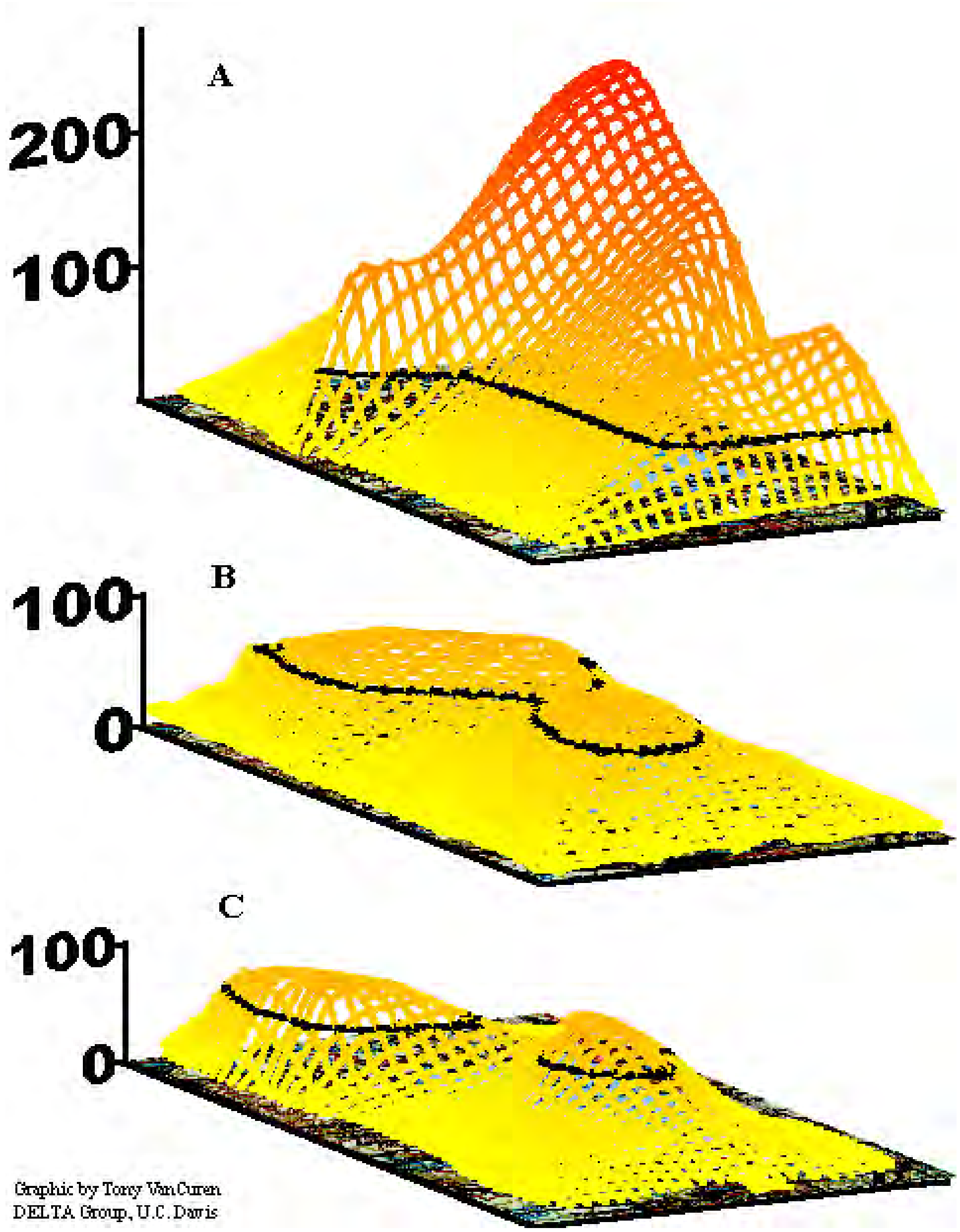


Figure 7—24-hour average $PM_{2.5}$ concentration LTAM output superimposed on the basin map for hypothetical wildfire in the Ward Creek watershed. The wildfire is broken up into three days of burning. Day 1 is 60% of the total acreage, day 2 is 25%, and day 3 is 15%. The black isoplith indicates the former federal standard of 65 $\mu g/m^3$ $PM_{2.5}$ 24-hour average. Day 1 indicates a maximum $PM_{2.5}$ 24-hour average of 200 $\mu g/m^3$. By day 3, the plume is breaking up as fire is theoretically suppressed.

Figure 8—Photograph of smoke from Captain Pomin prescribed fire looking southwest from Glenbrook NV. The mountain range above the southwest shore is barely visible.

Figure 9—Photograph of west shore of Lake Tahoe showing complete loss of visibility of the shoreline to the north and partial loss to the south. Taken from Glenbrook, NV on June 10, 1999 following the Captain Pomin prescribed fire.

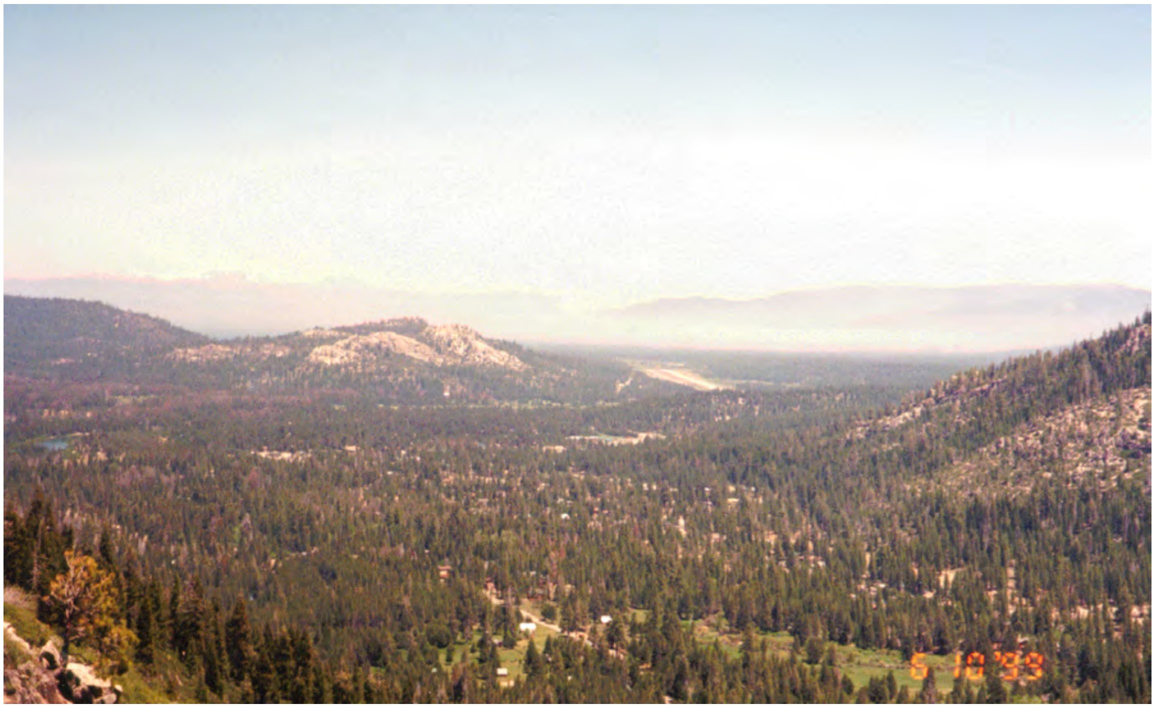


Figure 10—Photograph taken June 10, 1999, the day following the Captain Pomin prescribed fire, from Echo Summit, showing that visibility over the lake was reduced to less than 15 miles.

Figures 11a and 11b—Smoke from a small prescribed fire near the Kingsbury Grade being dispersed at 9:30 AM (a) and 2:30 PM (b), March 24, 2008. Westerly flows blow the smoke to the southeast and out of the basin.

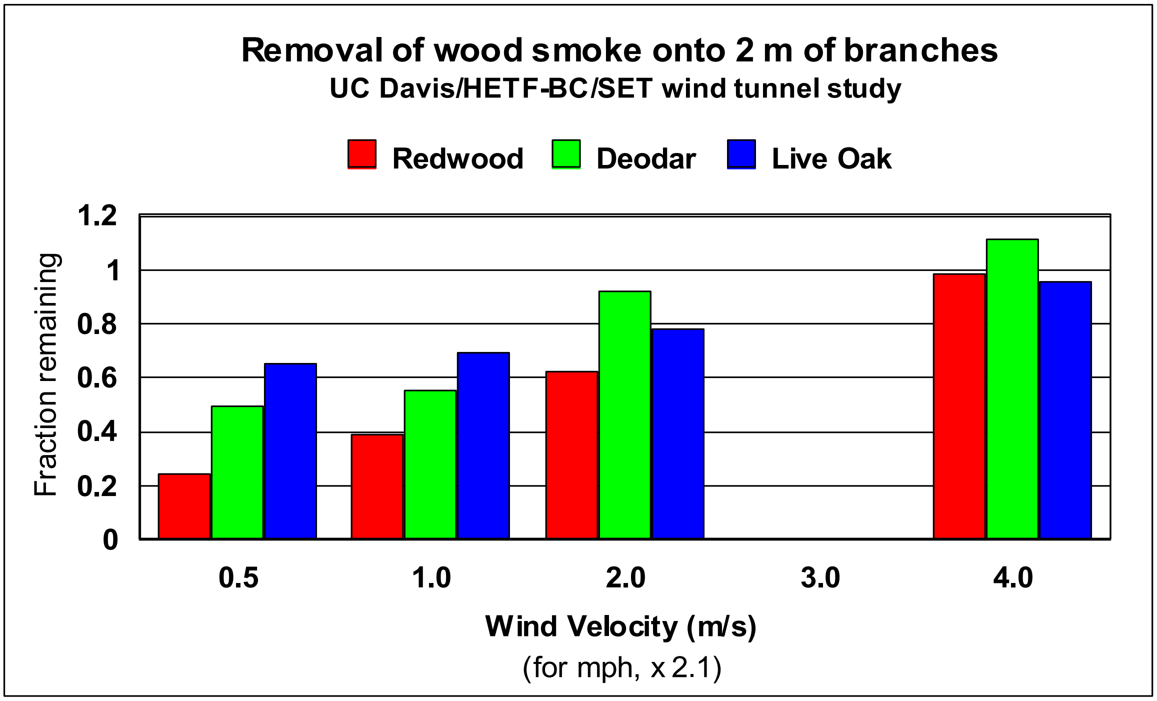


Figure 12—Fraction of particles remaining after passing through 2 m of lightly packed vegetation.

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Wildlife Habitat and Community Responses to Fuels Management in the Lake Tahoe Basin

Patricia N. Manley, Ph.D.[1]

1:Sierra Nevada Research Center, Pacific Southwest Research Station, U.S. Forest Service, 1731 Research Park Dr, Davis, CA 95618, email: pmanley@fs.fed.us, 530-759-1719 (ph), 530-747-0241 (fx)

Abstract

Reduction of the threat of fire in forested ecosystems has the potential to be in direct conflict with the conservation and restoration of biological diversity and ecosystem sustainability. This conflict is particularly acute in the Lake Tahoe basin (Sierra Nevada), given its unique combination of high threat of fire, high economic values, vulnerable biological diversity, and substantial motivation to rapidly treat large portions of the landscape This paper explores the status of knowledge about the potential effects of fuels reduction treatments on wildlife habitats, populations, and communities in the Lake Tahoe basin, with applicability throughout the Sierra Nevada, based on studies conducted in the ecologically similar ecosystems in California and the west. The majority of research conducted on wildlife habitat relationships in the west has been in unmanaged and even-aged managed forests. The few experimental studies of the effects of thinning and prescribed fire for fuels reduction have been limited to the use of mechanical equipment and on-site disposal of non-merchantable material. Wildlife research is inherently both labor intensive and time consuming, thus particularly expensive and difficult to execute. In general, wildlife responses to fuels treatments have been highly variable among studies as a function of the area's management history, the pre-treatment condition of the sites and surrounding landscape, and the nature of the treatment. Fuels treatments can have substantial effects on forest structural characteristics that are important to many species of wildlife. By design, they reduce tree density, basal area, and canopy closure, and increase average tree diameter, in increasing order of magnitude of change: fire alone, thinning alone, thinning plus fire. Mature forest associated species are most likely to be negatively impacted by thinning, prescribed fire, or their combination. In contrast, prescribed fire appears to have the greatest positive benefit to early seral and ground-associated species. Fuels treatments can also greatly affect ground cover and ground-based food resources for many wildlife species, with the greatest negative impact associated with chipping and mastication. The greatest strides toward turning risks to rewards in terms of fuels management interactions with wildlife habitats, populations, and communities will come from collaboration between research and management. Three primary areas of fruitful research-management interface are identified: 1) use existing information to develop desired forest and wildlife conditions at stand and landscape scales, 2) use existing information to develop operational guidelines, indicators of desired conditions, and predictive tools, 3) identify and pursue opportunities for monitoring and research to fill high priority information gaps and reduce uncertainties through prospective and retrospective data collection efforts.

Key words: Wildlife; Habitat; Forest fuels; Thinning; Prescribed fire; Lake Tahoe, Sierra Nevada

Introduction

Forest managers in the west face multiple challenges in navigating the potential perils that intensive and extensive fuels treatments pose to maintaining and restoring wildlife communities (Tiedemann et al. 2000). In fact, one of the biggest challenges may lie in clearly understanding the difference between maintaining and restoring wildlife communities. On one hand, land management agencies are mandated to maintain native species, and reductions in the distribution and abundance of species, particularly more rare species, resulting from management are cause for concern. On the other hand, there is consensus about the need to manage forests differently in an attempt to reduce the risk of high severity wildfire and improve forest health and resilience. These challenges are particularly acute in the Lake Tahoe basin, given its unique combination of high threat of fire, high economic values at risk, substantial financial capacity, and motivation to treat large portions of the landscape over a relatively short period of time. Determining the potential effects of extensive fuels treatments in Lake Tahoe basin requires inquiry into the intersection of past and present conditions and dynamics of disturbances, habitats, and populations.

Forest management can alter habitat conditions for many animal species and change community composition and structure. Habitat requirements are environmental features that are essential for a species to maintain a breeding population in a particular stand or landscape, thereby contributing to the maintenance of native biodiversity of forested ecosystems (Morrison et al. 2006). Measures of habitat that are most often available to wildlife biologists are often limited to tree characteristics (composition, size, density, canopy closure). The factors that determine the occurrence and persistence of species and communities, however, include a broad set of conditions encompassing vegetation, special habitat elements, co-occurring species, disturbance, and disease at site and landscape scales. For example, special elements such as broken topped trees, large uprooted trees, large logs, or rock grottos are often required to meet den or nest site needs of avian and mammalian predators. Coarse woody debris also provides cover and food sources for many species in conifer forests (Verner and Boss 1980, Bull et al. 1997, Bull 2002, Maser et al. 1984). Predators and prey can affect each others presence, abundance, and persistence. Plant productivity can affect food and cover resource availability, particularly for lower trophic level species, namely small mammals, songbirds, amphibians and reptiles (Kyle and Block 2000, Kotliar et al. 2002, Wilson and Puettmann 2007). Invertebrate populations play a variety of roles in the forest, including as food resources for many wildlife species.

The frequency and intensity of site disturbance itself can shape wildlife community composition and structure. Within a species' geographic range, the status of these conditions at the site scale and in the surrounding landscape will affect their potential occurrence and abundance. Larger-scale phenomena, such as disease, climate change, and the spread of exotic species also can greatly affect the distribution and abundance of species, such as the chytrid fungus currently affecting many amphibian populations (Halliday 1998). Responses of animal populations and communities to any large-scale manipulation of forest conditions, including projected fuels treatments, need to consider the current status of populations and communities and the changes that fuels treatments may invoke in stand and landscape conditions. Natural disturbances affect several spatial scales, invoking high within-stand and within-landscape heterogeneity (see Wilson and Puettmann 2007). If the maintenance of existing plant and animal species (i.e., biological diversity) is an objective, management's effect on the amount, distribution, and heterogeneity of habitat conditions at stand and landscape scales is a key consideration.

The influence of habitat conditions at multiple scales on populations and communities is well established (Johnson 1980, Wiens et al. 1987, Hunter 1990). Stand density management can elicit strong wildlife responses, but the responses of individual species or populations are variable among studies, potentially reflecting a disjunction between the scale of the treatment (stand) and multiple scales of response (stand and landscape; Wilson and Puettmann 2007). Habitat selection can be characterized as hierarchical, with the largest scales determining the geographic range of a species, and successively smaller scales determining habitat selection for location of territories, foraging, and nesting (Orians and Wittenberger 1991).

It should be noted that wildlife research is inherently both labor intensive and time consuming thus generally expensive to execute. In order to obtain the kinds and volume of data needed to shed scientifically defensible light on a cause-and-effect question, a significant dedication of resources and time is required, ideally three or more years of pre and post treatment data with sufficient replications to account for the inherent variability in ecosystems. These factors largely are responsible the relative paucity of wildlife research available for the Lake Tahoe Basin and elsewhere. The studies that do exist either are limited to the initial few years following treatment, or they attempt to capture longer-term responses by sampling sites a varying numbers of years since treatment but lack pre-treatment data.

Lake Tahoe Basin

The Lake Tahoe basin has a unique set of environmental features relative to other locations in the Sierra Nevada and throughout the west (Manley et al. 2000). Besides Lake Tahoe itself, the basin is unique in its steep elevational cline from montane ecosystems at lake level to alpine ecosystems on the surrounding peaks, and its location of the basin along the transition between the Sierra Nevada and Great Basin ecoregions. The combination of these two features alone result in high diversity per unit area of small populations of plant communities and animal species relative to other higher elevation locations. The unique history of the basin – large areas of the basin clear cut within a short period (~ 50 years) of time – further contributes to the distinctive environmental conditions that exist in the basin today.

Public lands dominate the Lake Tahoe basin, where National Forest System (NFS) lands occupy nearly 80% of the land area, and state lands (California and Nevada) are the next largest land holding around the lake. Sustaining species and ecosystem diversity is a primary management objective on these public lands, made particularly challenging by the diversity and relatively small population sizes of many species in the basin (Schlesinger and Romsos 2000). Vertebrates are commonly the focus of diversity conservation and restoration, although they represent a small proportion of all species in forested ecosystems. In the basin, birds and mammals constitute the majority of vertebrate species in forested ecosystems. Reptile and amphibian species are few in number, and no terrestrial salamander species occur in the basin. Invertebrates constitute a significant portion of biological diversity and are essential to maintaining many ecosystem processes and services. Management measures rarely include terrestrial invertebrates even though management responses have been documented for a number of taxonomic groups and species (e.g., Niwa and Peck 2002, Sort and Negron 2003, Sanford et al. 2008) mainly because they lack legislative protection and their high diversity can make them difficult to measure and assess in a manner that informs management.

Urban development is also changing the landscape of the basin. Urban development has reduced and fragmented forests at lower elevations in proximity to Lake Tahoe, and human disturbance is an increasingly prevalent stressor operating within forest stands. The amount of urban development and human use can both affect species composition, diversity, abundance, and in some cases the behavior of plant, vertebrate and invertebrate forest associates (Beckmann and Berger 2003a, Manley et al. 2006, Heckmann et al. 2008, Schlesinger et al. 2008). These studies demonstrate that habitat loss, fragmentation and human disturbance can affect the composition and abundance of species and the character of animal communities, regardless of the quality of habitat conditions. Although the effects of urbanization are not addressed here, it is important to consider the cumulative and interactive effects of forest management and urbanization in basin, where fuels management is likely to be most intensive in more urbanized areas.

The native species composition of the basin is a function of centuries of evolution and competition in response to climate, vegetation, and human predation. The composition and abundance of animal species shift in response to changing environmental conditions over decades and centuries. The Lake Tahoe Watershed Assessment identified species that appear to have declined over the past century based on historical data compared to more recent surveys (Romsos et al. 2000); however, historical data on wildlife species are primarily from the early 1900s, after the extensive clearcutting occurred in the mid 1800s. Major shifts in community composition do not appear to have occurred, whereas changes in abundance, although less well documented, have been documented for some species. Species that have increased in abundance, such as coyote, black bear, Steller's jay, and California ground squirrel, find current climates, urban development, vegetation conditions, and/or co-occurring species more favorable (Beckmann and Berger 2003a, Schlesinger et al. 2008). Species documented as occurring in the basin only within the last century consist of generalist species or species associated with drier environments or lower elevations.

Predictions about conditions that would exist today if certain alterations had not occurred are commonly informed by historical data and existing conditions that are relatively unaltered. In the Lake Tahoe basin, both information sources are scant, which make it difficult to develop reference conditions for animal populations and communities in the Lake Tahoe basin. It follows that restoration objectives are similarly unclear, other than maintaining existing species composition and potentially restoring populations of species that have been greatly reduced or extirpated. The formulation of a more comprehensive understanding of what constitutes ecological integrity - the condition that will support and sustain the complete complement of native species - is needed to fully evaluate the effect of fuels treatments on plants and animals. Data that do exist (namely past and present species occurrence, habitat associations, and ecological characteristics) that could be used to predict species distributions and community characteristics associated with the reference landscape configuration. This contextual foundation, combined with the knowledge of management effects on vegetation, habitat, and species, would make it possible to conduct a comprehensive evaluation of the effects of various fuels treatment options on ecological integrity and biological diversity. Without this foundation, evaluations are limited to estimated responses to stand treatments, which are likely to underestimate the effects.

Potential benefits and risks of fuels treatments

A compelling potential benefit of fuels reduction treatments is a reduction in the riskof high-severity wildfire. There is mounting evidence that current forest conditions in the basin, as well as throughout the western United States, that were created by past forest management, fire suppression, and changing climates have resulted in unhealthy and unstable circumstances in many forest stands. Management intervention of some kind is needed for many areas to reorient the trajectory of forest development toward more fire resilient conditions. It is clear that reducing the prevalence of high severity large fires will benefit wildlife populations by reducing losses in habitat. The imminent question is how to address these long-term management objectives while minimizing negative short-term effects on wildlife populations and habitat.

In a landscape as complex as the basin, spatial connectivity is likely to be an important feature in maintaining and restoring biological diversity. Although some basin-wide modeling of forest conditions and fire risks (Manley et al. 2000) and biodiversity (Manley et al. 2000, Manley et al. 2007) has been conducted, a comprehensive evaluation of the ability of various landscape configurations to maintain and restore desired forested conditions and biological diversity remains to be conducted. With such an evaluation in hand, fuels treatments could be designed and implemented to protect and enhance key sites, landscape connectivity, and overall forest health and resilience. Treatments could also contribute to forest restoration objectives for biological diversity; however, to realize this benefit requires an understanding of how current conditions differ from historical, if habitat conditions and species interdependencies have been compromised over time, and what are the ecological objectives for forest and biodiversity restoration.

The potential benefits of fuels treatments are countered by the potential for near-term degradation in habitat suitability and occupancy by species dependent on forests with high vegetation density and complexity. The magnitude of fuels reduction treatments planned in the basin – nearly 75% of the lower montane zone (Long et al. *this volume*) – will surely affect animal populations and communities. At the stand scale, species most at risk are those associated with understory vegetation, high canopy complexity, high canopy cover, and late seral conditions. In addition, changes in habitat and community characteristics not typically identified as treatment targets, but which are altered by treatments – lichen, moisture, fungi, litter, invertebrates, understory plant composition and vigor, interspecific competition – can and will substantially affect wildlife populations and communities. At the landscape scale, the challenge is to ensure that sufficient amount and distribution of suitable habitat is provided to maintain populations that are dependent upon conditions that may be reduced in the short-term as fuels reduction treatments are implemented across the landscape. Landscapes in transition run the risk of temporarily creating conditions that are not able to sustain one or more native species, essentially losing an ecological bridge from past to future.

Key questions

The key questions addressed in this paper reflect management uncertainties pertaining to both habitat and populations at multiple scales.

1. How do different silvicultural and prescribed fire treatments targeting fuels reduction affect wildlife habitat at stand and landscape scales?
2. How do animal populations and communities respond to changes in habitat and disturbance associated with different silvicultural and prescribed fire treatments targeting fuels reduction?

Primary Information Sources

Given the singular character of the Lake Tahoe basin, research and monitoring conducted in the basin provides the most reliable source of information for determining the potential effects of fuels reduction treatments. Limited research and monitoring of fuels reduction treatments have been conducted in the Lake Tahoe basin, which creates uncertainty in the outcome of wide-spread fuels treatments on wildlife population distribution and abundance and resulting changes in community dynamics. Certainly, ecological correlates exist elsewhere in the Sierra Nevada and the west for certain elements of ecosystems in the basin, and many species have large geographic ranges that encompass other similar conifer forest types in the Sierra and elsewhere. Overall, research on the effects of fuels reduction treatments on wildlife species and communities is limited to a small subset of the studies of fuels treatments in the west. Research results from outside the basin can provide insights into the potential response of certain species and communities to various treatments where research has been conducted in close ecological correlates. Where specific information is lacking, the consistencies in observed responses across different conifer-dominated ecosystems can provide indications of which types of responses are most probable, and the likely magnitude and direction of those responses. This level of specificity, however, is only useful in providing general guidance for initial treatment design. It generally is inadequate to substantially reduce uncertainties where they exist in treatment implementation.

The Upland Fuels Treatment project (Manley 2007, Stanton and Daley 2007) is the only research conducted to date in the basin on the effects of fuels reduction treatments on wildlife, invertebrates, or understory plants, and one of only a few to evaluate the effects of treatments on vegetation structure and fuels. This project recently began in 2006 and currently consists of eight paired treatments sites with varied fuels treatment prescriptions (four mechanically treated, four hand treated). It is one the most taxonomically comprehensive research efforts on the effects of fuel treatments on wildlife and biodiversity conducted in the Sierra Nevada, akin to the

Fire and Fire Surrogates study conducted close to Lake Tahoe on the west slope of the Sierra Nevada at he University of California Blodgett Experimental Forest in Eldorado County (Apigian et al. 2006, Amacher 2007).

The Fire and Fire Surrogate (FFS) project (Weatherspoon and McIver 2000) is the primary source of published information on the effects of fuels reduction treatments on habitat and animal populations and communities (Bigelow and Manley *this issue*). The FFS Blodgett study included investigations on the effects of thinning and/or burning treatments on birds, small mammals, carnivore habitat suitability, and invertebrates. The FFS Sequoia and Arizona studies included investigations into small mammal responses to burning and/or thinning.

Few additional studies addressing animal responses to fuels treatments have been conducted elsewhere in the west over the past 10 years (see Bigelow and Manley *this issue*), most of which were funded by the Joint Fire Science program (a list of funded projects is available on the web, www.firescience.gov). The Teakettle study included investigations of the effects of thinning and fire on chipmunks and squirrels (Sciuridae; Meyer et al. 2007). The Goosenest and Blacks Mountain studies (Oliver 2000, Ritchie 2005) located in northern California investigated the effects of thinning and fire on birds and small mammals, as well as vegetation, but published results on animal responses are limited (Oliver 2000, Ritchie 2005, Sperry et al. 2008). Studies in the Rocky Mountains and Pacific Northwest have been conducted on the effects of even-aged management and prescribed fire on a wildlife (Pilliod et al. 2003, Bury 2004, Pilliod et al. 2006, Saab et al. 2006, Saab et al. 2007), and offer insights into the potential effects of fuels treatments

The Birds and Burns Network project (Saab et al. 2007) is an effort to promote and coordinate research on the effects of wildfire and prescribed fire on birds. Study areas are located throughout the northwest and southwest portions of the U.S., and studies on the effects of prescribed fire are still in progress. Information on the project and a list of associated publications are available on the web (www.rmrs.nau.edu/wildlife/birdsnburns).

One additional research program is underway on the Plumas National Forest through the Pacific Southwest Research Station, the University of California at Davis, and PRBO Conservation Science. This program includes small mammal and terrestrial bird components that examine existing conditions and responses to the implementation of fuel breaks (thinning from below). Results are still in development but large areas have been surveyed and large data sets on habitat relationships of both small mammals and birds are being accumulated (see www.psw.fs.fed.us/snrc/plas).

Highlights

- Limited research and monitoring have been conducted in the Lake Tahoe basin of the effects of fuels reduction treatments on vegetation or wildlife.
- All experimental studies of thinning effects used mechanical equipment and disposed of non-merchantable material on site.
- The few studies conducted in different ecosystems and with different treatment characteristics provide a limited source of inference about the expected effects of fuels treatments on wildlife in the basin.

Existing Scientific Findings - Habitat

Forest Structure

Changes in forest structure associated with fuels treatments are directly a function of the specifications of the treatment itself. Fuels reduction prescriptions typically target reductions in tree density, basal area, and canopy closure (Table 1; also see Bigelow and Manley *this issue*), but other important aspects of forest structure affected include average tree diameter and densities of snags and logs (Table 1). The effect of fuels treatments on habitat suitability depends to a large degree on the vegetation type and the quality of habitat prior to treatment. Mature forests on high productivity sites are likely to provide suitable habitat to a diverse complement of old forest associated species, and would have reduced suitability for these species after treatment at least in the first years after treatment. Conversely, mature forests on low productivity sites or sites impacted by other factors (e.g., high human use, isolated by urban development) may have lower initial suitability for old forest associates, and although treatments would alter suitability for many species, they may not reduce its suitability for these specialists.

Thinning

Mechanical harvest followed by chipping, mastication, and/or prescribed fire is the most common method used to reduce fuels. Mechanical treatments typically substantially alter forest structure because mechanical harvesters require a minimum space to operate between trees and they can safely remove large diameter trees. Thinnings conducted by hand using chainsaws are conducted on slopes too great to allow for a mechanical operation. Hand thinning tends to be lower intensity than mechanical thinning because only small diameter trees (e.g., <35 cm or 14 in dbh) can be removed, resulting in higher remaining tree density and canopy complexity. No studies have been reported on the magnitude of effects of hand treatments, however, so only mechanical treatments are discussed here.

Mechanical treatments in the FFS Blodgett study resulted in reductions in average tree density by 56 to 71%, in average canopy closure by 12 to 19%, and increases in average diameter by 38 to 52% (Stephens and Moghaddas 2005a). Based on habitat types as defined in the California Wildlife Habitat Relationships database (Mayer and Laudenslayer 1988), these changes in forest structure would not result in a change in size class (i.e., size class 4 [30 to 60 cm or 12 in to 24 in dbh] before and after), but would result in a change in canopy cover class from >60% (canopy cover D) to 50 to 60% (canopy cover M). Truex and Zielinski (unpublished report, 2005) interpreted changes in forest structure in the FFS Blodgett study on resting and foraging habitat suitability for the Pacific fisher. They found that resting habitat for fisher was significantly reduced as a result of reductions in canopy closure from mechanical treatments. In the Teakettle study, North et al. (2007) and Innes et al. (2006) reported that, as expected, mechanical thinning treatments affected canopy closure in proportion to thinning intensity (greater reduction in overstory compared to understory thin; Table 1). Canopy closure was high prior to treatment (approximately 80%), and although canopy closure was reduced by up to 20%, it did not represent a change CWHR class (i.e., declined to as low as 60% but remained in canopy cover class D). Similarly, North et al. (2007) reported that quadratic mean diameter (QMD) was not significantly different among treatments. Prior to treatment, QMD was small (20 cm or 8 in; CWHR size class 3) compared to lower montane forests in Lake Tahoe (47 to 49 cm or 19 in dbh, CWHR size class 4; Table 1), and then increased with all treatments by 10-20%. Even treatments with the greatest increase in QMD (understory thin with burn; 29 cm or 11 in QMD) did not change its CWHR size class designation. Obviously these reported changes (or lack thereof) in CWHR classes are an artifact of broad class categories and QMD rather than real changes in habitat. Agency professionals using such data should be aware of these nuances when interpreting results.

Prescribed fire

Prescribed fire has a more limited effect on forest structure than thinning. Tree density and canopy closure was significantly reduced by prescribed fire alone, but to a lesser degree than mechanical treatments in the FFS Blodgett study (Stephens and Moghaddas 2005b). Truex and Zielinski (unpublished report 2005) found that the additional reductions in canopy closure resulting from prescribed fire following mechanical treatments in the FFS Blodgett study further reduced the suitability of resting habitat. For sites with prescribed fire only, fall burns had significant negative effects on canopy closure and resting habitat suitability, whereas spring burns had little effect. In contrast, the Teakettle study reported no change in canopy cover with prescribed fire, but they did observe a 10-20% increase in QMD, regardless of whether or not it was preceded by mechanical treatment (North et al. 2007).

Highlights

- Fuels treatments reduced tree density, basal area, and canopy closure, and increased average diameter, in increasing order of magnitude of change: fire alone, thinning alone, thinning plus fire.
- More often than not, treatments did not result in a change in CWHR habitat classification, making CWHR a fairly insensitive tool for evaluating the effects of understory thinning on wildlife habitat.

Snags and Coarse Woody Debris

Dead wood serves many important functions in supporting wildlife species. Large snags and logs (coarse woody debris; CWD) provide a source of cover, food, and nest sites for dozens of species of wildlife, many of which require dead wood for one or more essential life history functions (Bolen and Robinson 1995, Hunter 2000, Laudenslayer et al. 2002). Fuels treatments tend to reduce snag and log densities, but to different degrees and through different mechanisms. Ecologically appropriate post-treatment densities of dead wood can be difficult to determine, give high levels of dead wood in fire-suppressed forests. Stephens (2004) found high variability in dead wood densities in the conifer forests of northern Mexico, ecological correlates to conifer forests in the Sierra Nevada. Minimum retention standards for dead wood are usually specified to benefit wildlife, commonly ranging from 1 to 3 snags and logs per ha (0.4 to 1.3 snags and logs per ac). Thinning typically results in a reduction of snags, but largely as a result of logistics and safety – they are not a target for removal during thinning. Similarly, log densities can be increased or reduced as a result of thinning, depending on whether or not small diameter material is being left on the site or removed (biomass generation). Prescribed fires are designed to burn at low intensities on the ground such that larger diameter trees and snags would not catch on fire. As expected, logs are burned or consumed in the process. Changes in snag and log densities observed across the fuels treatments studies confirm these general tenets, but provide some greater specificity as to the magnitude of changes that can be expected under various conditions. In the Lake Tahoe basin, snag densities in the lower montane zone range from 13 to 44 snags > 13 cm or 5 in dbh per ha, a similar density as forests in the FFS Blodgett study and the Teakettle study (Table). Coarse woody debris (CWD), however, appears to be much higher in the Lake Tahoe basin compared to these other study areas, with the basin averaging 98 m^3/ha in mixed conifer and the FFS Blodgett and Teakettle studies ranging from 31 to 52 m^3/ha (Table 1). The FFS Sequoia study had more comparable CWD densities, ranging from 71 to 96 m^3/ha. Reductions in snag and log densities do not necessarily represent a decline in habitat suitability for dependent species, given the high densities on some sites.

Thinning

In the FFS Blodgett study, Stephens and Moghoddas (2005b) reported that treatments resulted in 30 to 60% declines in the density of snags >15 cm (6 in) dbh, with mechanical treatments showing the greatest (60%) decline (47.0 to 17.6 stems/ha; Table 1). Small snag (<15 cm or 6 in dbh) density was significantly lower only in mechanically treated sites compared to controls. They also found that mechanical treatments showed no change in CWD (>15 cm or 6 in diameter at the large end) volume, despite the use of mastication to dispose of small diameter woody material. These results reflect in part the study objective of maintaining CWD for forest function, an attribute not commonly identified in standard fuels treatment prescriptions.

The Teakettle study also tracked changes in CWD resulting from thinning and burning, and found that CWD volume and cover increased and CWD biomass declined slightly with thinning alone (Table 1). Remnant harvested material increased volume and cover, whereas losses in biomass were primarily a function of declines in large diameter material. Unlike the Lake Tahoe basin, cover values on control sites (representing starting conditions) were low (<10% cover, <65 Mg/ha), so the magnitude of change is limited relative to conditions in the Lake Tahoe basin.

Prescribed fire

As expected, fire reduces snags and logs regardless of the combination of treatments or season of burn, but the magnitude of reduction is greatly influenced by the timing treatment. In the Sierra Nevada, Stephens and Moghoddas (2005b) reported that prescribed fire killed trees, with the majority of being smaller diameter (<30 cm or 12 in dbh), thus the recruitment of new snags from fire-induced mortality partially offset the loss of smaller snags from mechanical harvest (approximately 10% replacement). In ponderosa pine forests in the northwestern and southwestern U.S., Saab et al. (2006) found that snag densities increased with prescribed fire from 28 to 73%, respectively, but increases were not statistically significant. Snag densities in these study areas, however, appeared to be low prior to burning, averaging 6 to 7 snags per ha >22 cm (9 in) dbh, whereas Blodgett and Teakettle study sites in the Sierra Nevada ranged from an average of 21 to 48 snags per ha >15 cm (6 in) dbh.

Smaller snags generally provide only a subset functions for snag dependent species, thus the functions provided by larger diameter snags are not likely to be mitigated by prescribed fire.

For example, the average diameter of snags with excavated cavities ranged from 32 to 57 cm (13 to 22 in), whereas snags without cavities averaged 10 to 25 cm (4 to 10 in) in a study in eastside pine in Washington (Bevis and Martin 2002). They found similar patterns in foraging, with snag diameters used for feeding averaging 29 cm (11 in) dbh compared to the overall average of 17 cm (7 in) dbh.

In contrast to thinning alone, treatments including prescribed fire consistently result in substantial reductions CWD. Reductions in volume vary from 45 to 80% across studies in the Sierra Nevada (Stephens and Moghaddas 2005b, Converse et al. 2006b, Innes et al. 2006, Wayman and North 2007) with the amount of reduction being a function of timing of burns (fall burns are hotter than spring burns) and the amount of CWD prior to burning. In the FFS Blodgett study, average CWD volume was reduced 46 to 81%, with the fire only treatments showing nearly twice the reduction compared to mechanically treated sites that were subsequently burned (Stephens and Moghoddas 2005b). The Teakettle study also found that CWD volume decreased with burning in all treatments except when paired with overstory thin, whereas CWD cover showed little change as a result of burning (Innes et al. 2006, Wayman and North 2007). In the FFS Sequoia study, Knapp et al. (2005) found that CWD was significantly reduced in terms of volume and mass, cover, and length, with late season (fall) burns resulting in greater declines (86%) compared to early season (spring) burns (59% decline). Patchiness of burns also differed between seasons, which can affect within-stand habitat heterogeneity, an important element in habitat suitability. Specifically, early season burns left approximately five times more litter and duff unconsumed in areas where fire passed over the forest floor than late season burns. Early season burns were also significantly patchier and the size of unburned patches tended to be smaller. Thus, early season burns had many ecological benefits. Early season burns pose other risks to wildlife (e.g., nesting birds) that should be taken into consideration when contemplating wide-spread use of early season burning. Understanding target snag and log values would greatly help interpretations of ecological significance of expected reductions in snags and logs resulting from treatments, and would help set goals for their retention or restoration post-treatment. The relationship between snag and log densities and wildlife species occurrence and abundance are scarce.

Highlights

- Thinning and prescribed fire alone or in combination result in reduced density of larger diameter snags.
- Fire alone or following thinning tends to have a neutral to positive effect on small snags by consuming some while creating others.
- Thinning and prescribed fire have opposite effects on coarse woody debris: thinning alone tends to have a neutral or positive effect on coarse woody debris volume and cover, whereas fire (with or without thinning) results in a substantial reductions (45 to 80%) in log volume.

Understory Vegetation and Litter

Vegetative ground cover plays numerous roles in providing for the needs of wildlife species. Shrubs and herbs offer food and cover for numerous species of songbirds and small mammals. (Taylor and Barmore 1980, Carey and Johnson 1995, Wilson and Carey 2000, Saab and Powell 2005). Herbaceous cover is generally higher on sites with lower tree densities and lower canopy cover as a function of increased light and nutrients. Thus, reductions in tree density and canopy cover resulting from treatments would be expected to have a positive effect on vegetative ground cover. In the lower montane zone in the Lake Tahoe basin, litter is the predominant ground cover (approximately 50%) followed by shrubs (9 to 18%) and bare ground (5 to 13%; Roth et al. 2008).

Thinning

The treatment of remaining woody material can substantially change herbaceous plant species responses (Bigelow and Manley *this issue*). In general, the act of mechanical thinning will reduce (at least temporarily) vegetative ground cover through collision and trampling. Further, the extent and depth of small woody material following thinning as a result of chipping, mastication, or high log and branch volumes will likely inhibit the ability of shrubs and herbs to recover. The FFS Blodgett study observed similar responses, where herb and shrub cover declined from 5 to 8 percentage points within 1 to 2 years of mechanical treatments with and without fire, but none were statistically significant (Amacher et al. 2008). These changes represented 26 to 29% reductions in herb and shrub cover, with the greatest reductions associated with mechanical only treatments. Similarly, the Teakettle study found that shrub cover (15 to nearly 30% pre-treatment) declined with thinning, but not significantly. The FFS Arizona study observed similar declines (30 to 90%) in shrub cover with thinning (Converse et al. 2006a). Most of the shrubs were ponderosa pine seedlings, however, so shrub responses may not be representative of true shrub dominated understories that exist in many locations in the Lake Tahoe basin. Alternatively, Converse et al. (2006b) uniquely reported immediate increases in herb cover (60 to 200%) following thinning, with herb cover being was positively associated with thinning intensity.

Prescribed fire

Prescribed fire or pile and burn also are likely to initially reduce plant cover (e.g., (Agee 1993, Collins et al. 2007). Burning appears to enhance the recovery and expansion of herbaceous plant cover relative to pre-treatment conditions and create high heterogeneity in ground cover, a potential benefit to many ground foraging and dwelling species. In contrast, shrubs recover slowly after fires and may not meet or exceed pre-treatment conditions for an extended period of time. Short-term responses observed in the recent fuel treatment studies conducted in the west are consistent with these general tenets.

The primary thinning studies consulted reported consistent and expected results regarding the effects of fire on herbs and shrubs. The FFS Blodgett study found that fire stimulated understory growth, which resulted in increased plant cover in fire only treatments and mitigated some of the losses resulting from mechanical treatments. Similarly, the Teakettle study found that burning appeared to stimulate herb cover and richness, particularly when preceded by thinning (Wayman and North 2007). As with thinning, shrub cover declined with prescribed fire only treatments, but not significantly.

Highlights

- Thinning has variable effects on understory herb and shrub richness and cover, depending on community composition and starting conditions of cover by substrate type.
- Herb cover response is most likely to be neutral or positive when fire is used alone or in conjunction with thinning.
- Shrub cover is most often reduced with fuels treatments, with fire resulting in a more substantial reduction in shrub cover compared to thinning alone.

Truffles

Ectomycorrhizal fungi serve valuable ecosystem functions in forested ecosystems by enhancing water and nutrient uptake by conifer trees (Molina et al. 1992). Below-ground truffles are a common type of ectomycorrhizal fungi fruiting body, and they, in turn, serve as a valuable food source for many small mammal species (Fogel and Trappe 1978, Maser et al. 1978). Hypogeous fungi are of moderate nutritional value compared to seeds, but they are available throughout the snow-free seasons. Small mammals contribute to the benefits provided by truffles by dispersing their spores as they pass through their digestive system, thus distributing the fungi throughout the forest (Maser et al. 1978, Kotter and Farentinos 1984, Maser and Maser 1988, Colgan and Claridge 2002).

Fuel treatments, as do other silvicultural treatments, have the potential to greatly affect the occurrence and abundance of truffles by changing CWD, litter, canopy closure, and microclimatic conditions, and soil conditions. No studies of the effects of fuels reduction treatments on truffles have been conducted in the Lake Tahoe basin or elsewhere; however studies of truffles in the basin and studies of the effects of similar stand treatments conducted in the Sierra Nevada and the Pacific Northwest offer insights as to the potential magnitude of effects fuels treatments in the basin may have on truffles and their consumers.

Pyare and Longland (2001) studied truffle consumption by small mammals in red fir forests on the west shore of Lake Tahoe in the Ward Creek and Blackwood Creek watersheds. They found hypogeous fungi in 100% of fecal samples from northern flying squirrel (*Glaucomys sabrinus*) and Douglas squirrel (*Tamiasciurus douglassii*), and over 60% of the golden-mantled ground squirrel and around 40% for the two species of chipmunks combined (*Neotamias speciosus* and *N. quadrimaculatus*). Flying squirrel consumed over twice as many different genera of fungi ($n = 16$) compared to any other species ($n \leq 7$), with two fungal genera (*Gauthieria* and *Martellia*) being the dominant genera consumed. Mushrooms were also an important dietary item, occurring in 60 to 100% of samples of all species except northern flying squirrels. Alternatively, deer mouse (*Peromyscus maniculatus*) and golden-mantled ground squirrel (*Spermophilus lateralis*) were the primary consumers of vegetation, occurring in nearly 100% of their samples and <40% of any other species, suggesting that these two species, along with voles (*Microtus sp.*), may be affected the most by changes in herbaceous plant cover in forest understories.

Two additional studies of truffles and small mammals conducted outside the basin but in the Sierra Nevada observed similar associations as observed by Pyare and Longland (2002): the Teakettle study to the south (Meyer and North 2005, Meyer et al. 2005) and a study on the Lassen National Forest to the north (Waters and Zabel 1995, Zabel and Waters 1997). In the Teakettle Experimental Forest, Meyer et al. (2005) found fungal spores in nearly every (99%) flying squirrel diet sample, but also observed a similarly high frequency of occurrence (95%) in the diet of *T. speciosus* (lodgepole chipmunk). As reported by Pyre and Longland (2001), flying squirrels were observed to be more dependent and selective in terms of the fungi species consumed. In the Lassen area, Waters and Zabel (1995) found truffle frequency to be the strongest habitat correlate with northern flying squirrel abundance. *Gauthieria* was identified as an important food item and dominant truffle consumed in all three study areas (Zabel and Waters 1997, Pyare and Longland 2001, Meyer et al. 2005), as well as in the Pacific Northwest (Carey et al. 2002). Additional fungi species of dietary importance to squirrels and chipmunks included *Rhizopogon* and *Gastroboletus* (Meyer et al. 2005). A substantial breadth and depth of research on truffles and forest associated small mammals has been conducted in the Pacific Northwest by Carey and colleagues (Carey and Johnson 1995, Carey et al. 1999, Carey 2000b, 2000a, Carey et al. 2002), with complementary findings to those in the Sierra Nevada.

Meyer et al. (2005) found in the Teakettle study that the two primary fungi (*Gauthieria* and *Rhizopogon*) consumed by small mammals in their study area were negatively affected within the first two years following burning and thinning (more intensive thin resulted in a greater effect), with no treatment interaction. Truffle frequency and richness were >2 times greater in unburned than burned, and truffle biomass was 12 times greater in unburned than burned. Similarly, truffle frequency and richness were 2 to 5 times greater in unthinned sites compared to understory and overstory thinnings. Truffle biomass uniquely showed a positive response to understory thinning.

Three additional studies provide insights into longer-term responses of truffles to forest thinning based on retrospective surveys. The limitation of most retrospective studies is they do not have pre-treatment data, and therefore they must rely on ecologically similar control sites to represent untreated conditions. No two sites have the same ecological conditions or disturbance history, so such retrospective studies have an element of unquantifiable error. The benefit, however, is that they provide insights into longer-term responses, which, if substantial, can offer a high level of confidence despite the error associated with ecological variation among sites and years since treatment. Waters and Zabel (1995) compared truffle frequency and abundance in unmanaged >200 yrs old forest to those in two treatments: 10-year old shelterwood cuts (39 to 60 trees/ha remaining) conducted in old growth white fir and red fir stands; and 75 to 95 year old second-growth stands created by clearcutting. Although flying squirrel abundance did vary with truffle abundance, they found truffle frequency to be the strongest habitat correlate with flying squirrel abundance. Truffle frequencies in the second growth stands were 37% lower and those in the shelterwood were 85% lower than in old growth stands.

Waters et al. (1994) reported on another retrospective analysis from a different set of sites on the Lassen National Forest. Single-aged forest sites ($n = 21$) resulting from a stand-replacing fire were logged 10 years previously in small blocks of 0.4 ha (~1 acre) with two thinning intensities: moderate (remove 35% of basal area) and heavy (remove 70% of basal area). Half of each site was subsequently to prescribed fire. Another set of similarly size sites ($n = 12$) were also thinned by similar intensities (moderate and heavy). They found no difference in truffle frequency or abundance among the thin and burn treatments. One of the important genera, *Gautieria*, was found more frequently in unthinned units.

In the conifer forests of the Pacific Northwest, Carey et al. (2002) sampled second growth Douglas fir and hemlock forest. One treatment consisted of a 70-year old second-growth stand that had been thinned roughly 30 and 10 years prior to sampling, resulting a moderately dense stand (200 trees/ha). The other treatment was a 60 year-old shelterwood (6 trees/ha) that had received no subsequent thinning ("unthinned"). They did not have an old forest control site, but simply compared the condition of these two harvest treatments. They found no significant difference between the two treatments on truffle frequency, which was low in both treatments (0-9%); however frequencies were generally higher for every species in the unthinned sites, resulting in slightly higher fungi diversity in unthinned forests. Chipmunks (*Neotamias* sp.) consumed vascular plants in both treatment types in relative proportion to their occurrence; however, flying squirrels uncharacteristically consumed vascular plants but only in thinned forests only, suggesting that more preferable food resources were limited.

Pyare and Longland (2001) conducted their research in one of the few old growth stands remaining in the basin (Barbour et al. 2002), with the majority of forested stands in the lower montane zone being around 100 years old, similar to the second growth stands sampled by Waters and Zabel (1995) and Carey (2000b). Based on the reduced richness and frequency observed in these second growth stands, most forests in the basin may already support a reduced population of truffles compared to pristine forest conditions, and thinning is likely to reduce them further.

Highlights

- Truffles serve important ecosystem functions, including providing a critical food resource to many squirrel and chipmunk species, particularly the northern flying squirrel.
- Some genera of truffles appear to be particularly prevalent in squirrel and chipmunk diets across studies in the Sierra Nevada, namely *Gauthieria* and *Rhizopogon*.
- Truffle frequency and diversity are reduced in areas that have been subject to timber harvest (including thinning) or prescribed fire, even decades after treatment; however, abundance is not similarly affected.
- Truffle frequency and diversity are likely to have the greatest influence on northern flying squirrel occurrence.

Existing Research Findings—Animal Populations and Communities

Limited attention has been directed toward understanding the effects of fuels treatments in the basin on wildlife habitat and populations. Only one field study of wildlife responses to fuels treatments has been conducted, and it is in progress. Some studies on the effects of fuels treatments and other similar silvicultural treatments conducted elsewhere in the Sierra Nevada and the west have evaluated effects on wildlife populations and/or habitat. These studies provide some direct evidence of potential effects on a limited suite of species. In this section, I report on the composite of evidence provided by a composite of experimental and retrospective studies of thinning and prescribed fire treatments, as well as general information on expected responses of wildlife taxa based on their life history and responses to other progenitors of habitat change. The suite of taxa discussed is limited to those for which research or syntheses on responses to fuels treatments have been conducted in the west: songbirds and woodpeckers, small mammals, mammalian carnivores, and amphibians and reptiles.

No research has been completed in the Lake Tahoe basin on the effects of fuels treatments on wildlife species or communities; however an assessment of potential effects was conducted by Holl (2007). His assessment was based on agency plans to treat 35,000 ac (14, 164 ha) of forest in the lower montane zone (~40%) over the next 10-15 years. Using the California Wildlife Habitat Relationships (CWHR) database (California Department of Fish and Game 2006) and existing vegetation maps, he reported that 155 vertebrate species were associated with the Sierran mixed conifer and Jeffrey pine forests of the lower montane zone in the Lake Tahoe basin. Based on species associations with open vs. dense canopy conditions and their food resource associations, Holl (2007) estimated that a greater number of species were associated with the more open canopy conditions likely to be created by fuels treatments. The majority of species, however, were associated with ground-based food resources, which were also likely to be negatively impacted by fuels treatments, with the net effect being a potential decline in species richness. He predicted that species closely associated with shrub understories and snags and logs were likely to be negatively affected and may be at risk as a result of treatments, including 49 focal species as identified in the Lake Tahoe Watershed Assessment (Manley and Schlesinger 2000). He also suggested that all but one of the primary prey species (Douglas squirrel [*Tamiasciurus douglasii*]) for most of the top carnivores in the basin (Northern goshawk [*Accipiter gentilis*], California spotted owl [*Strix occidentalis*], and American marten [*Martes americana*]) would decline as a result of treatments because of the assumed reduction in understory resources (i.e., food and cover). He noted that reductions in species richness may occur, but that they were likely to be more consistent with historical richness levels associated with more open stands and more frequent disturbance from wildfire. The assessment is limited in its ability to make inferences about actual effects given its qualitative nature; however, it does identify some important potential effects on wildlife of extensive fuel treatments in the Lake Tahoe basin.

Highlights

- One field study of wildlife responses to fuels treatments has been initiated in the Lake Tahoe basin, and it is in progress.
- Studies are largely limited to a few years before and after treatment or retrospective studies without pre-treatment data. They also mostly target stand-scale responses, thus longer-term responses and cumulative effects of treatments across landscapes over time are lacking.
- An analysis of potential effects of wide-spread fuel reduction treatments indicated potential declines in many forest-associated species, including species of special interest.

Songbirds and Woodpeckers

Bird communities perform many essential ecosystem services, and they are affected by many factors, including disturbance history and vegetation structure and composition (e.g., Cody 1987, Wiens 1992a, 1992b). Fuels reduction treatments affect many aspects of vegetation structure and composition in both the overstory and understory, with the greatest changes occurring in the understory. The recent North American summary on bird responses to prescribed fire (Saab and Powell 2005) and North American meta-analysis of partial harvest effects on birds (Vanderwel et al. 2007), provide valuable new insights on bird species sensitivities and community thresholds that are consistent within and among ecoregions that can be used to gauge responses to prescribed fire and forest thinning.

Vanderwal et al.'s (2007) analysis of 34 species responses to partial harvesting (thinning) identified 14 species with consistently negative responses and species with consistently positive responses. They found that bird species most affected by partial harvests were those associated with mature forest conditions, but a concomitant positive response in early seral associates was not observed. Although their work included only one study from California (Siegel and DeSante 2003), the 18 studies from the western United States included a number of species present in the Lake Tahoe basin. Based on 50% retention thresholds (fuels reduction thinning in Lake Tahoe commonly removes 40-50% of the basal area or stem density; Stanton and Dailey 2007), seven species were identified as expected to decline by at least 50%, three of which occur in the basin: Brown Creeper (*Certhia americana*), Hermit Thrush (*Catharus guttatus*), and Golden-crowned Kinglet (*Regulus satrapa*). The Red-breasted Nuthatch (*Sitta Canadensis*) declined by at least 25% under the same 50% retention criteria. Conversely, five species were expected to increase by at least 50% with 50% tree retention, including two ground nesters (Chipping Sparrow [*Spizella passerine*] and Dark-eyed Junco [*Junco hyemalis*]) and a nest parasite (Brown-headed Cowbird [*Molothrus ater*]).

The majority of studies suggest that thinning or the combination of thinning and burning result in declines in snags and logs, which in turn negatively affect cavity excavators and nesters, particularly the larger-bodied primary cavity nesters (Finch et al. 1997, Machmer 2002, Pilliod et al. 2006). The importance of maintaining legacy elements, such as large trees, snags, and logs, decadent trees, and decayed dead wood, is well established (Franklin et al. 2002). Although fire and deliberate snag creation (e.g., girdling trees) can help replenish snags lost during harvest operations, it takes a number of years before decay is sufficient for them to meet the needs of most snag obligates. The retention and restoration of legacy elements in forests may be even more critical in fuels treatments than even-age management scenarios, particularly in the Lake Tahoe basin, because such a large proportion of the lower montane landscape is scheduled for treatment (Long et al. *this volume*).

In the Sierra Nevada, Amacher (2007) reported on changes in bird abundance associated with treatments on the FFS Blodgett study. He observed increases in American Robin (*Turdus migratorius*) abundance in mechanical thinnings followed by prescribed fire, an increase in Hammond's Flycatcher (*Empidonax hammondii*) abundance and a decrease in Golden-crowned Kinglet abundance with any type of treatment compared to controls. This study also indicated that Western Wood-peewee (*Contopus sordidulus*) may nest more frequently in treated stands, particularly stands subject to thinning. Amacher (2007) saw no substantial change in foraging substrate use by nine bird species representing a variety of ecological strategies. This is one of few studies to examine foraging behavior in association with fuels treatments. In different study, Siegel and DeSante (2003) detected a greater abundance of canopy-, cavity-, and shrub-nesting species on recently thinned plots compared to plots that had not been thinned for 30 years in Sierran mixed conifer forests in the northern Sierra Nevada. Thinned stands were characterized by lower canopy cover, lower density of small and medium conifers, and greater understory cover. No differences in productivity were detected in the 37 bird species they monitored.

Responses to fire with or without thinning appear to be greater than those associated with thinning alone. Consistent patterns in short-term responses reported by Saab and Powell (2005) included the positive response of aerial, ground, and bark insectivores, as well as cavity nesters, ground nesters, and canopy nesters. Negative responses were observed for foliage gleaners, open-cup nesters, and shrub nesters. Prescribed fire has many risks to wildlife, regardless of resulting changes in habitat conditions (Smith 2000). Prescribed burns conducted in the spring are likely to impact reproductive success of adults by killing eggs or nestlings, particularly species that nest near the ground, or by invoking nest abandonment. Although prescribed fires are intended to be low intensity, they can vary in their intensity throughout the burned area, and forest legacy elements (large trees, snags, and logs) that are destroyed by fire will take decades to be replenished.

As with most other species groups, longer-term response data for sites with pre-treatment data are largely lacking, as are studies of winter use and analysis of cumulative effects of treatments at the landscape scale. Short-term responses may not be representative of longer-term trends (Hannon and Drapeau 2005), and landscape conditions have significant ecological influence on species composition and even abundance.

Highlights

- Mature forest associated bird species are most likely to be negatively impacted by thinning, and fire (with or without thinning) appears to benefit early seral and ground-associated bird species.
- The retention of legacy forest elements, such as large snags and logs, is an important to maintaining native species over time in areas where much of the landscape will be treated.
- Woodpeckers as primary cavity nesters play an important ecological role in forests, and they require snags with some level of decay.

Small Mammals

Small mammals constitute an ecologically significant component of the vertebrate community in forested ecosystems through their participation in the consumption and dispersal of seeds and spores, their function as soil aerators and tunnelers, and their contribution to the prey base for the majority of upper-tropic level avian and mammalian carnivores (e.g., Tevis 1956, Maser et al. 1978, Price and Jenkins 1986, Willson 1992, Jones and Lawton 1994, Long and Smith 2000). A large number of studies have been conducted on the effects of timber harvest on small mammals, but relatively few on the effects of fuels reduction treatments. Most timber harvest studies are either retrospective and lack pre-treatment data (sampling a set of sites representing a range of years since treatment; e.g., Duguay et al. 1999) or they have pre-treatment data with controls, but only sample 1 to 3 years post treatment. Results from the few studies that have been conducted are limited to making inferences about a handful of species, namely northern flying squirrel, deer mouse, and few chipmunk species. Most likely capture rates and/or trap effort are too low to obtain sufficient sample sizes to address changes in small mammal community composition and structure. Nonetheless, existing studies provide valuable insights into the effects of fuels reduction treatments on the most common species, which constitute the primary contributors to ecosystem services and prey availability.

Amacher et al. (2008) report on the results of small mammal sampling on the FFS Blodgett study. They sampled using 36 Sherman traps per site open for nine nights once during the summer months. They observed a positive response of California ground squirrel (*Spermophilus beechyii*) abundance over the four sample years, regardless of the treatment. Greater increases were observed in thinned and/or burned sites compared to controls, but they were not statistically significant. Long-eared chipmunk (*Neotamias quadrimaculatus*) and brush mouse (*Peromyscus boylii*) abundance also tended to be higher on treated sites, but not significantly. Deer mouse showed a treatment by year effect, with decreases observed in association with thinning, and increases observed in association with fire alone or following thinning. These results suggest that high levels of downed woody material (i.e., fine fuels, masticated material) may depress small mammal populations, particularly mice, which in turn may be reversed to some degree by prescribed fire. No habitat variables were identified as important determinants of the abundance of any of the four species analyzed.

Monroe and Converse (2006) looked at the effects of prescribed fire on small mammals in the FFS Sequoia study in the southern Sierra. They sampled using 44 Sherman traps per site open for 4-5 nights three times during the summer months. They found limited differences among the treatments for the four parameters analyzed: deer mouse density and age ratio, lodgepole chipmunk density, and small mammal biomass. Deer mouse density greater on burned (spring or fall) sites, and small mammal biomass decreased slightly on burned (spring or fall) sites. As with Amacher et al. (2008), annual variation was high, potentially swamping treatment effects.

Converse et al. (2006b) sampled small mammals in the Arizona FFS study. They used the same sampling methods as Monroe and Converse (2006), and they found different habitat elements associated with the abundance each of the four species analyzed. Deer mouse abundance most closely responded tree density, as did gray-collared chipmunk (*Tamias cinereicollis*), and both responded positively to reductions in tree density with thinning and/or fire. Golden-mantled ground squirrel and Mexican woodrat (*Neotoma mexicana*) both responded closely and positively to shrub density (primarily ponderosa pine seedlings), which declined with treatment. Mexican woodrat and gray-collared chipmunk were positively associated with coarse woody debris, which declined on burned sites.

Converse et al. (2006c) summarized finding on small mammal responses across eight of the 13 FFS study areas. The purpose of the analysis was to determine what responses were consistent across study areas and therefore were predictable regardless of the geographic location of treatments, and those responses that varied among study areas and therefore would require site-specific monitoring or study to accurately determine responses. They were able to summarize data for three individual species (deer mouse, yellow-pine chipmunk [*Neotamias amoenus*], and golden-mantled ground squirrel) and two genera (*Neotamias* and *Peromyscus*), as well as total biomass. Total biomass was the only response variable that responded consistently across all study areas and treatments (thin, fire, thin and fire), showing a positive association with treatment, presumably in response to assumed increases in habitat complexity (Goodwin and Hungerford 1979, Carey and Johnson 1995, Wilson and Carey 2000, Carey and Harrington 2001).

Individual species responses were variable among treatments and study sites. Converse et al. (2006c) discusses of evidence from a broad array of studies, which demonstrate some general trends in responses of deer mice and chipmunks: positive short-term responses of deer mouse to thinning and prescribed fire, positive short-term responses of chipmunks to thinning, and negative short-term responses to prescribed fire. As Converse et al. (2006c) highlight, variations in responses are a function of many factors, but an important one being the starting condition of sites. If initial conditions of sites are generally poor for small mammals (e.g., high density of small diameter trees), fuels treatments are likely to improve habitat conditions for most species, whereas if initial conditions are highly favorable to small mammals (e.g., mosaic of stand structure characteristics), fuels treatments are likely to degrade habitat conditions for most species. Clearly, longer-term responses are not well known. These findings indicate that site-specific research or monitoring are needed to determine how to maintain or enhance small mammal populations in relation to fuels treatments in a given area such as the Lake Tahoe basin.

The large body of literature exists regarding the habitat requirements and management effects on northern flying squirrel, but only a few related to thinning treatments akin to fuels reduction treatments. Meyer et al. (2007) sampled small mammals in the Teakettle study area. They used nine Tomahawk traps per treatment site attached to tree boles to target northern flying squirrels. Traps were left them open for three nights twice during the summer months. They found that probability of occurrence of flying squirrels increased with increased canopy cover in thinned stands and increased litter depth in burned stands. Waters and Zabel (1995) working in the Lassen area found that flying squirrel densities were consistently greater in old forests compared to young (70 yrs old) forests, and were significantly higher compared to shelterwood stands. No differences in body mass, sex ratio, or age distributions were observed among timber harvest prescriptions.

Carey et al. (1999) found in Douglas-fir forests of the Pacific Northwest that northern flying squirrel abundance positively correlated with CWD, which in turn was positively correlated with truffle abundance. In the Olympic peninsula, Carey (1995) found that northern flying squirrel abundance was primary correlated with understory vegetation and the abundance of mast-bearing trees rather than coarse woody debris. Carey (2000b) found that northern flying squirrels were less abundant in thinned forests compared to legacy (old growth) forests, whereas chipmunks were more abundant in thinned forests. Carey et al. (2002) concluded that flying squirrel abundance may be determined by a variety of factors, including availability of dens (Carey et al. 1997, Carey 2001), predation (Carey et al. 1992, Wilson and Carey 1996, Wilson and Carey 2000), competition with chipmunks and Douglas squirrels (which can maintain or increase in abundance in thinned forests; Carey and Harrington 2001), and ancillary food sources (Ransome and Sullivan 1997, Thysell et al. 1997, Carey and Harrington 2001).

Highlights

- Total small mammal biomass is likely to remain neutral or increase in the first few years following treatments, particularly if sites are burned. Responses to fuels treatments, however, vary widely among species and locations, and they are, in large part, a function of habitat quality prior to treatment.
- Northern flying squirrels are particularly vulnerable to habitat changes occurring as a result of thinning and prescribed fire, given their dependence on old forest conditions and high canopy closure, including their dependence on truffles as a food source.

Mammalian Carnivores

The Lake Tahoe basin has a diverse mammalian carnivore community for a landscape of its size owing to the diversity of ecosystems and confluence of zoogeographic regions. Based on survey work conducted in the basin over the past 10 years (Roth et al. 2007, Manley et al. 2008), 10 species of mammalian carnivores and omnivores have been detected in the basin. The most prevalent mammalian carnivores in the basin are black bear (*Ursus americanus*), coyote (*Canis latrans*), and American marten. The more rarely but regularly detected species include bobcat (*Lynx rufus*), spotted skunk (*Spilogale putoris*), long-tailed weasel (*Mustela frenata*), ermine (*Mustela erminea*), and raccoon (*Procyon lotor*).

Many of the mammalian carnivores in the basin may be sensitive to habitat modification. As a group, carnivores exhibit characteristics that may sensitize them to alteration of habitat. These characteristics include large home range requirements, low fecundity, and territorial behavior, all of which can lead to low population densities (Peterson 1988). Because of their high vagility, carnivores are likely to respond to habitat changes at mutiple spatial scales (stand, watershed, landscape). Upper trophic level species are known to serve important regulatory functions in ecosystems, contributing to a balance between primary producers (plants) and primary consumers (herbivores). Carnivores are important ecologically as they: 1) affect the abundance and distribution of prey species (Crooks and Soule 1999, Henke and Bryant 1999); 2) affect plant fitness through seed dispersal and predation (Willson 1992); and 3) influence distributions of other carnivore species, especially each other (Harrison et al. 1989, Litvaitis and Harrison 1989). Alteration in the composition of native carnivore communities can have cascading effects through ecosystems leading to changes in the composition and abundance of small mammals and birds, as well as likely alterations in plant communities (Willson 1992, Crooks and Soule 1999, Henke and Bryant 1999).

Research and monitoring data on the response of mammalian carnivores to fuels reduction treatments are lacking in the Lake Tahoe and are scant in general (Fisher and Wilkinson 2005, Pilliod et al. 2006). Fuels treatments have the potential to greatly affect habitat conditions for mammalian carnivores immediately and for many decades after treatment (e.g., Passovoy and Fule 2006). The species most vulnerable to fuels treatments are those with special habitat needs associated with old forests (e.g., large logs or snags), those whose populations exist primarily at lower elevations where treatments are expected to be most intensive and extensive, species that are sensitive to disturbance, and species whose populations are already of concern. American marten, black bear, coyote are among the top predators in the Lake Tahoe basin, they are the most frequently encountered mammalian carnivores, and they are of particular public and/or management significance. Other native mammalian carnivores that may be sensitive to habitat modifications include bobcat, spotted skunk, striped skunk (*Mephitis mephitis*), ermine, and long-tailed weasel. Given the dearth of information on the status of the more rare mammalian carnivores in the basin, I focused on the three most commonly occurring species - black bear, coyote, and American marten – which represent a range of considerations in terms of population status and vulnerability to fuels reduction treatments, and for which sufficient information exists to make reasoned inferences about the potential effects of fuels treatments.

Black bears in the Lake Tahoe basin are an increasing presence in urbanizing areas as they leave wildland habitats for resource-rich urban environments (Beckmann and Berger 2003a, 2003b). The close proximity of most planned fuels treatments to human development demands attention to the composite effects of forest management, human development, and human disturbance. Indeed, increased exploitation of urban zones has lead to shifts in all aspects of black bear ecology (e.g., foraging patterns, denning behavior, and space use), and a dramatic rise in reports of human/bear conflicts. Black bears typically use areas with abundant downed wood and high shrub cover in mature forests, with higher canopy closure selected for traveling and resting (Bull et al. 1997, Bull et al. 2000). In undeveloped landscapes, thinning and prescribed fire may have positive or negative effects on habitat quality, depending on the starting conditions of stands and changes in plant and woody debris invoked by treatments (e.g., Hamilton 1981). Fuels reduction treatments commonly reduce all of these habitat elements, and therefore are likely to reduce habitat quality for bears. Habitat quality may recover to some degree with increases in shrub and herb cover that can follow fuels treatments where pile and burning or prescribed fire are employed. Reductions in habitat quality in urbanized areas may result in increasing use and reliance on human sources of cover and food, and in turn affect many aspects of the black bear population and human interactions. For example, a study in the ponderosa pine forests of Arizona found that only 12% of bedding sites were in thinned forests due to insufficient horizontal cover. Black bears in the Lake Tahoe basin commonly use human structures for cover, such as decks of cabins and seldom used vacation homes.

Losses of cover and den sites in forests adjacent to human development may create increased utilization of and dependence on human structures, and consequently increase human-bear conflicts. Increased interactions between humans and bears have multiple consequences – few of which are positive. Wildlife management agencies must respond to calls concerning nuisance bears, and in many cases the bears must be killed. Research by Beckmann and Berger (2003a, 2003b) showed that urban bears in the Lake Tahoe basin forage less and yet are 30% heavier than their wildland counterparts. Males appear to spend the majority of their time in urban areas and may exclude females from access to human food resources resulting in spatial segregation of male and female bears which could have important implications for bear populations (Lackey 2004). Additional modification of urban interface areas could have unanticipated consequences for bear populations by increasing the separation between urban and wildland populations and habitats.

Coyotes, like black bears, are an increasingly common sight in the Lake Tahoe basin and appear to be able to take advantage of areas with and without anthropogenic development (Manley et al. 2006). The potential for coyote interactions and conflict with humans and domestic animals is a source of concern in many communities (Gompper 2002). Coyote behavior is may be altered in urban environments, though the shifts may not be as dramatic as those of black bears. In urbanizing areas, coyotes become primarily nocturnal whereas their wildland counterparts may be active at any time of day (Riley et al. 2003, Way et al. 2004, Manley et al. 2007). Though less information exists regarding coyote ecology in the Lake Tahoe basin, coyotes appear to be associated with more open habitats and may be better able to exploit urban environments when they are in proximity to remnant native habitats (Manley et al. 2007), potentially leading to increased coyote-human conflicts. It is plausible, if not likely, that fuels treatments throughout much of the lower montane zone could further increase coyote populations through improved habitat conditions and reduced competition. This sets the stage for increased pressure on already stressed small mammal communities and cascading effects on ground dwelling invertebrates and plants.

Recent research has identified shifts in distribution and activity patterns of carnivores associated with urbanization and human use (Beckmann and Berger 2003a, 2003b, Manley et al. 2007, Beckmann and Lackey 2008). Two of these species, bear and coyote, may be attracted to certain attributes in the surrounding urban matrix and, as a result, may come into conflict with humans. Both species have exhibited an increase in occurrence within and adjacent to urban areas (Beckmann and Berger 2003 a, 2003b, Manley et al. 2007). Black bears and coyotes show altered periods of activity in developed areas relative to wildland areas, perhaps in avoidance of peak periods of human activity (Beckmann and Berger 2003a, 2003b, Manley et al. 2007). Such shifts in occupancy and behavior may be magnified or otherwise altered by further habitat modification within the urban interface. Given the potential for human-wildlife conflict involving black bears and coyotes, there is an urgent need for further information on the status, distribution and abundance of these species in urban and wildland zones in the basin, and their responses to habitat modification in proximity to urban areas.

The American marten occupies high-elevation late-seral conifer forests in the Sierra Nevada (Spencer et al. 1983, Zielinski et al. 2005). Marten populations are of conservation concern in the Lake Tahoe basin, although they appear to be reasonably well distributed in the west and south portions of the basin (Slauson and Zielinski 2008). Slauson and Zielsinski (2008) suggest that the west side of the basin serves as an important north-south connector for marten populations in the Sierra Nevada. Plans for fuels reduction treatments are most extensive on the west side of the basin, with some extending to the upper portions of watersheds. American marten is known to be sensitive to habitat fragmentation and loss, and multiple studies have found that habitat losses exceeding 30% are unlikely to be frequented by marten. Bull and Blumton (1999) found that martens avoided forests thinned for fuels reduction. Therefore, the potential exists for stand, landscape, and range-wide effects from fuels treatments implemented in the basin. High canopy cover and large logs and snags are critical habitat elements for the marten. For example, Manley et al. (2007) found that marten was absent from forested sites with greater than 30% human development in the surrounding landscape. A species-specific analysis of the potential impacts of fuels treatments on the marten appears warranted and important.

Highlights

- Mammalian carnivores are sensitive to habitat changes resulting from fuels reduction treatment; however, research on specific responses is scant.
- Wildlife communities, including mammalian carnivores, are altered by human use and development. The proximity of fuels treatments to human development requires consideration of the fact that existing wildlife communities may already be compromised or more sensitive to habitat alteration than wildland areas.
- Black bear populations could be significantly affected, but in a complex manner. Their responses are likely to be a combination of a decreased carrying capacity of forests and increased use of human resources, resulting in changes in behavior and population demographics.
- Black bear responses to standard fuels treatments are likely to be a combination of decreased carrying capacity of forests, increased use of human resources, changes in behavior, resulting in potentially significant changes in black bear population dynamics and increased human-bear interactions.
- Coyotes may benefit from increased disturbance and habitat alterations resulting from standard fuels treatments in forests proximal to urban areas, resulting in unknown ecological and social impacts.
- American marten is likely to be negatively impacted by standard fuels treatments, and treatments on the west side of the basin could impact larger-scale population connectivity in the Sierra Nevada.

Amphibians and Reptiles

Information on the effects of fire and fuels management practices in the Sierra or the west is very limited. No specific studies have been conducted looking at the effects of fuels reduction thinnings on reptiles (Pilliod et al. 2006). A few studies have garnered information on the effects of fire on amphibians, but fuels reduction treatment effects were not the objective (Ruggerio et al. 1991, Cole et al. 1997). Studies and reviews of the effects of fire (Russell et al. 1999, Bury et al. 2002, Ford et al. 2002, Pilliod et al. 2003) and forestry practices in general (Bury 2004) make inferences to the extent possible about the effects of fuels treatments based on similar management activities. Terrestrial reptiles are generally adapted more xeric environments and are likely to benefit from reductions of dense understory or overstory conditions resulting from fuels treatments (Bury and Pearl 1999, Altman et al. 2001, Ford et al. 2002). Some species, particularly lizards, may prefer post-fire environments (Russell et al. 1999, Litt et al. 2001, Moseley et al. 2003). One local study in a California oak woodland showed no negative effect of fire on reptiles (Vreeland and Tietje 2002). Information is too limited, however, to assume reptiles are not affected, and some studies suggest that prescribed fire can be followed by short-term population declines in reptiles (Singh et al. 2002, Setser and Cavitt 2003). For example, many species, such as the rubber boa (*Charina bottae*), are dependent upon large coarse woody debris for cover and nesting, which is reduced by fire and, to a lesser degree, thinning.

Although terrestrial salamanders may be the amphibians most at-risk from fire and thinning, the basin only has one species of salamander, long-toed salamander (*Ambystoma macrodactylum*), and it is aquatic. Almost no information is available on the effects of thinning or fire on aquatic amphibians during the times they use terrestrial environments (Bury 2004). One study was conducted in a lodgepole pine forest in Montana, and found that selectively harvested stands supported 70% fewer long-toed salamanders (Naughton et al. 2000). Aquatic amphibians are particularly vulnerable to fire and more xeric stand conditions that may result from thinning. The mortality of juveniles and adults have been shown to have a strong influence on population dynamics of some species of frogs and toads (Biek et al. 2002). The season of a fire can greatly affect the potential impact on reptiles and amphibians (Pilliod et al. 2003, Bury 2004). During spring, aquatic breeding amphibians are commonly migrating to water to breed. Mortality of amphibians during prescribed and wildland fires are thought to occur rarely (Lyon et al. 1978, Russell et al. 1999, Smith 2000); however, some evidence suggests that amphibians may not be able to protect themselves from fires under some circumstances (Grafe et al. 2002). Decreases in canopy closure resulting from thinning are likely to increase air temperatures, decreased soil moisture, and lower habitat complexity, negatively affecting habitat for dispersing and hibernating amphibian species (Dupuis and Steventon 1999).

Highlights

- Virtually no information is available about the effects of fuels treatments on amphibians and reptiles, although surveys in the northwest suggest that amphibians benefit from high canopy cover and densities of large downed logs, which are reduced with thinning. Further, fire effects research elsewhere indicates that fire can harm or kill reptiles and amphibians depending on the timing of the fire.
- Maintaining unburned areas near burned areas or creating a burn mosaic is likely to help maintain amphibian and reptile populations where prescribed fire is being applied.

Conclusions

Synthesis of Existing Knowledge

The majority of research conducted in the west on wildlife habitat relationships has been in unmanaged and even-aged management treatments, and most studies have investigated stand-scale responses. Further, the few experimental studies of the effects of thinning for fuels treatment have been limited to the use of mechanical equipment and disposal of non-merchantable material on the site. Finally, wildlife responses to fuels treatments in these studies have been highly variable as a function of management history, starting condition of sites and the surrounding landscape, and nature of the treatment. Despite these limitations, research conducted to-date has furthered our understanding of the potential effects of fuels reduction treatments on wildlife habitat, populations, and communities.

Fuels reduction treatments can have substantial effects on forest structural characteristics that are important to many species of wildlife. By design, treatments reduce tree density, basal area, and canopy closure, and increase average tree diameter, in increasing order of magnitude of change: fire alone, thinning alone, thinning plus fire. More often than not, however, treatments do not result in a change in CWHR habitat classification, making CWHR an insensitive tool for determining the effects of forest structure on wildlife habitat. Thinning and prescribed fire both reduce snag densities, particularly large snags, whereas only fire substantially reduces log densities. There are potential longer term benefits to wildlife populations that balance these short-term impacts, namely a reduction in the likelihood of extensive high severity wildfire and through restoration of a more resilient forest dominated by fewer but larger trees.

Fuels reduction treatments can also greatly affect ground cover and ground-based food resources for many wildlife species. The greatest potential short-term negative impact on ground-based resources for wildlife appears to be chipping and mastication. Both of these practices, if they result in a thick layer of cellulose material blanketing the forest floor, will inhibit herbaceous plant and shrub growth and cover. The effect of chipping or mastication on truffles has not been studied, but their frequency and abundance are also likely to be diminished. Shrubs and truffles are both vulnerable to reductions from thinning practices, and can require many years or decades to recover, if then. Alternatively, herb and grass cover are not likely to be negatively affected by thinning, and more often than not respond positively to prescribed fire. Mature forest associated species are most likely to be negatively impacted by thinning, prescribed fire, or their combination, at least in the short term. In contrast, prescribed fire appears to have the greatest positive initial benefit to early seral and ground-associated species. Responses to fuels treatments, however, vary widely among species and locations, and they are, in large part, a function of habitat quality prior to treatment. For a few species, it is clear that fuels treatments pose a potential threat to their occupancy of stands or extensively treated landscapes. Northern flying squirrels are particularly vulnerable to habitat changes occurring as a result of thinning and prescribed fire, given their dependence on old forest conditions and high canopy closure, including their dependence on truffles as a food source. Likewise, American marten is likely to be negatively impacted by standard fuels treatments through loss of canopy coarse woody debris, and treatments on the west side of the basin have the potential to impact larger-scale population connectivity in the Sierra Nevada. Black bear populations could be significantly affected, but in a complex manner involving interactions with humans. Their responses are likely to be a combination of a decreased carrying capacity of forests and increased use of human resources, resulting in changes in behavior and population demographics. Coyotes may benefit from increased disturbance and habitat alterations in forests near neighborhoods, resulting in unknown ecological and social impacts. Wildlife communities are already altered by human use and development in forests near urban development. Evaluating and planning for the effects of fuels treatments on wildlife merits consideration of the potentially greater sensitivity to habitat alteration than expected in wildland areas.

The Lake Tahoe Basin Challenge

Retention of existing native species is not only required on public lands, but it is wise in light of overarching management objectives to sustain ecosystems. The latitude of management to alter ecosystems in the Lake Tahoe basin lies in the ability to affect the distribution and abundance of individual species and the ability of ecological zones (e.g., life zones, watersheds) to support their full complement of native species. Certainly, forest management is substantially more difficult given the added objective of maintaining diverse wildlife populations and communities throughout a landscape. While most forest and fire management may be met by focusing on conditions at the stand scale, wildlife species are one type of connective tissue spanning landscapes and ecologically linking stands. Thus, habitat management compels one to consider ecological conditions simultaneously at multiple spatial scales and understand how we expect conditions to change over time.

The renovation of a house is a fruitful analogy for exploring the challenges of forest ecosystem restoration. First, one needs a floor plan to help us understand what conditions need to be maintained where they currently exist, what conditions need to be reduced or increased and where those changes need to occur. One needs to balance multiple objectives in designing the new floor plan, including cost, efficiency, regulatory requirements, and needs of the residents and neighbors. The floor plan translates to a scientifically founded set of spatially explicit desired conditions that describe what stand-scale conditions (e.g. old-growth emphasis vs. fire-safe emphasis) are to be created or maintained, where they will exist on the landscape, and what emergent landscape-scale heterogeneity will result. Next, one needs a set of tools to accomplish each transition and an implementation plan that helps one determine the most effective sequence and timing of steps (e.g., don't refinish the floors before hanging the drywall). In the context of forest management, the tools include various silvicultural prescriptions, biomass treatments, prescribed fire techniques, and habitat protection measures. Understanding the effectiveness of these tools and how to use them in concert to achieve desired conditions is essential, including the ability to predict with adequate accuracy the effect of stand-scale treatments on stand and landscape conditions. Finally, one needs to pay attention to the valuable intrinsic elements of the property, and retaining or restoring historical remnants (e.g., old-growth tongue-and-groove wainscoting) that define a property and give it its unique character. In forested landscapes, this means the retention and restoration of legacy forest elements, such as large snags, large logs, and decadent trees, and careful treatment of rare and/or ecologically significant elements, such as rare plant populations, long-standing nest or roost sites, and special management of hardwood inclusions and riparian ecosystems.

The substantial momentum to reduce the threat of fire in the Lake Tahoe basin as quickly as possible, combined with the potential for significant ecological effects and a dearth of sufficient knowledge to accurately predict and avoid undesirable effects, calls for an adaptive management approach to fuels treatments. Basin-specific evaluations and predictions would greatly contribute to understanding basin-specific responses in sufficient detail to simultaneously achieve the multiple land management objectives of reduced threat of fire, improved forest health, conservation of biological diversity, and long-term sustainability of forested ecosystems. In instances where information is limited to generalizations, research and monitoring in the basin will be particularly important allies of management as treatments are implemented.

Further, the close proximity of most planned fuels treatments to human development necessitates that attention be paid to the composite effects of forest management, human development, and human disturbance. The composition and behavior of wildlife in developed environments may differ from that of their counterparts in less developed areas due to adaptations to human-induced stressors (Ditchkoff et al. 2006, George and Crooks 2006, Manley et al. 2006). As the research conducted by Manley et al. (2006) has demonstrated, wildlife communities in forested ecosystems in the Lake Tahoe basin change in response to higher levels of human development and use. Thus, wildlife responses observed outside the basin in undeveloped areas may not be indicative of responses that will occur in the basin. This interaction complicates the task of planning and evaluation of fuels treatments and developing target conditions for forest restoration.

Recommendations to Advance Wildlife Management Successes

Adaptive management

- Research and management could work together to identify opportunities and mechanisms by which the greatest risks and uncertainties pertaining to fuels treatments effects on the conservation and restoration of wildlife can be reduced in an expedient and effective manner.

- Research and management could jointly design and fund research and monitoring to address information needs and capitalize on opportunities created in the course of treatment implementation.
- A wealth of retrospective research opportunities exist in the basin where pre-treatment data exist for vegetation (e.g., forest inventory plots), and, in many cases wildlife species composition and abundance (e.g., Multi-species Inventory and Monitoring sites). Within a few years, the basin could have a much greater understanding of potential stand (and even landscape) scale responses.

Forest condition objectives

- Spatial heterogeneity is important to sustain diverse native wildlife communities; desired conditions for stands and landscapes could specify the amount and location of various vegetative and habitat conditions that would support diverse wildlife communities.
- The retention of legacy elements (large logs, large snags, decadent trees, special use sites) is key; the desired or required density, character (decay, scorching), and distribution (clumped, scattered). A range of species and taxonomic-specific snag, and log retention guidelines could be developed that are expected to accomplish various objectives, such as various levels of support for snag and log dependent species, for soil retention and productivity, etc. In many cases, guidelines already exist for special use sites, but a review and evaluation of their adequacy would help strengthen and maintain their integrity.
- Cumulative effects of treatments across the landscape will greatly affect the persistence of species with large home ranges and/or limited distributions in the basin. Landscape-scale predictive models of historical habitat distributions, combined with existing

biodiversity hotspots and areas of high priority fire risk and threat reduction, can provide guidance as to appropriate balance of priorities for various locations on the landscape. Subsequent monitoring will be vital to determining the accuracy of predictions such that management can be adjusted as needed.

- The effects of fuels treatments on wildlife species and communities are not independent of the concomitant effects of human development and use in and around forest stands. Determining and managing for desired conditions for wildlife communities in urbanized environments would benefit from consideration of the interface of the effects of forest management and urban development and disturbance.

Forest management techniques

- A suite of forest treatment prescriptions could be developed that represents effective techniques for achieving various desired outcomes (short- and long-term) based on a combination of existing conditions and priority management objectives for an area.
- Techniques for reducing losses of decadent trees, large snags, and large logs during mechanical treatments could be compiled into a guidebook for managers.
- Prescribed fire has many benefits, but it also has some negative effects on wildlife and habitat. Spring burns may hold the greatest promise for minimizing many of the negative effects of prescribed burning. Guidelines could be developed to help reduce or avoid negative impacts on amphibians, reptiles, and breeding birds.
- Variable density thinnings, group-selection techniques, and combinations of different harvest and post-harvest treatment techniques could be implemented and studied to determine those that best meet different desired short-term and estimated long-term responses.

- Maintaining unburned areas near burned areas or creating a burn mosaic is likely to help maintain forest legacy elements and reduce impacts to amphibian and reptile populations where prescribed fire is being applied.

Implementation tools

- A manual of silvicultural techniques (including timing, stand-, and landscape-scale features) could be developed for that basin that describes under what conditions various outcomes can be achieved with the combinations of techniques, including changes in fuels, fire behavior, habitat features, sensitive species, exotic plants, biodiversity, forest growth, soil conditions, air quality, and any other key environmental objectives.
- Measures of desired conditions (i.e., indicators) are needed; measures that that are readily obtained through monitoring and validated with research. Some indicators have been identified by different agencies over time for various purposes, but no set of measures currently exists for determining that status of forest conditions relative to desired.
- A predictive tool could be developed for the basin that can portray changes in habitat, populations, and communities precipitated by fuels management activities. Ideally, the tool would interpret changes in terms of measures of desired conditions, which could include individual species and multiple-species metrics. The tool would be based on empirical data from sites in the basin and ecologically similar forest types outside the basin.
- The predictive tool would be most effective if it projected changes in forest conditions over time (which would require a forest growth model) such that longer-term outcomes could be estimated, including changes in habitat conditions, biodiversity, forest health, and fire danger and risk.

Table 1—Forest structure characteristics in Lake Tahoe and four forest management experiments recently conducted in California

		Canopy closure (%)		QMD (cm)		Stem density (stems/ha)		Snags (stems/ha)		CWD (m^3/ha)	
Study	Treatment	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Lake Tahoe[1]	Jeffrey pine	56		47		248		13		*6.2*	
	Mixed conifer	61		49		263		44		*18.4*	
	Lodgepole	47		18		246		31		*19.6*	
	Subalpine conifer	42		48		253		18		*16.1*	
Teakettle[2]	Control										
	US thin	81	73	20	23	469	240	36	37	46	61
	OS thin	81	63	20	22	469	150	31	32	31	29
	burn	81	80	20	22	469	354	23	91	41	33
	USthin+burn	81	71	20	29	469	143	45	120	37	28
	OSthin+burn	81	60	20	24	469	94	58	123	32	25
Blodgett[3]	Control	69	75	55	56	1101	1110	28	30	52	97
	Thin	66	58	52	50	972	429	47	18	52	55
	Burn	68	65	50	48	850	452	21	29	53	10
	Thin+burn	63	51	55	39	823	239	48	28	52	29
Knapp[4]	Control									*96*	*86*
	Early burn									*71*	*31*
	Late burn									*66*	*15*

Goosenest[5]	Control		28	28	623	823	
	Large tree		33	43	535	168	
	Pine		30	43	623	193	
	Pine + fire		30	43	530	175	

[1] Roth et al. (2008): trees and snags > 13 cm diameter at breast height (dbh), logs > 7.6 cm diameter, logs in tons/ac

[2] North et al. (2007) was source of tree density and quadratic mean diameter (QMD), only one pre-treatment value given for all sites, trees > 5 cm dbh; Innes et al. (2006) was source for snags and coarse woody debris (CWD): snags > 5 cm dbh, CWD > 30 cm minimum diameter.

[3] Stephens and Moghaddas (2005): trees > 10 cm dbh; snags > 15 cm dbh; logs >15 cm minimum diameter

[4] Knapp et al. (2005): logs in Mg/ha

[5] Ritchie (2005): trees > 10 cm dbh

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Appendix A: Current Tahoe Basin Experimental and Modeling Studies of Fuel Treatment Effects

The following list includes current SNPLMA-funded research projects that are evaluating effects of fuel reduction treatments. In addition to these projects, various management entities, are conducting monitoring and pilot projects to evaluate effects. For example, the Lake Tahoe Basin Management Unit is planning to monitor effects of pile burning. In addition, some research projects are being funded from other sources, including the Tahoe Nevada License Plate program and the Lahontan Regional Water Quality Control Board.

Project Name	Lead Investigator(s)	Design Considerations	Treatments Evaluated	Responses Evaluated
Silvicultural prescriptions to restore forest health	Patricia N. Manley and Malcolm North, US Forest Service, Pacific Southwest Research Station; Dennis D. Murphy and T. Will Richardson, University of Nevada	Before-After-Control-Impact (BACI) design, with clusters of 4 treatment + 1 control sites. Each cluster will be replicated in at least 4 different locations.	Regular canopy tree spacing (fire emphasis) and clustered tree retention (restoration emphasis), with mastication or pile burning	Vegetation, soil properties, truffles, diversity of birds, small mammals, ants, invertebrates, and habitat and prey for key wildlife species of special concern (Northern Goshawk, California Spotted Owl, and American marten)
Biodiversity response to burn intensity and post-fire restoration	Patricia N. Manley, US Forest Service, Pacific Southwest Research Station; Dennis D. Murphy and T. Will Richardson, University of Nevada	Angora fire area, monitoring pre-fire to three years post-fire	Wildfire (areas of different fire severity) and post-fire treatments (tree removal)	Invertebrates, birds, small mammals
Effectiveness of upland fuel reduction treatments	Pat Manley, USFS Pacific Southwest Research Station; Bruce M. Pavlik, Mills College; Dennis Murphy, University of Nevada Reno	Seven pairs of treatment/control sites located in typical mixed-conifer forest conditions; pre- and post-treatment monitoring	Mechanical thinning and chipping	Basal area, tree density and spacing, canopy base height, canopy closure, number of canopy layers, snags, vegetation cover & frequency, fuel loads, songbirds, woodpeckers, small mammals, butterflies and ants
Balancing fuel reduction, soil exposure, and erosion potential	Andrew P. Stubblefield and J. Morgan Varner, Humboldt State University; Eric Knapp, USFS Pacific Southwest	8 sites across fir-dominated and pine-dominated stands on volcanic and granitic soils, rainfall simulation of runoff/erosion,	Mastication, prescribed fire, and wildfire, with variations in residual amounts of surface fuels	Vegetation (overstory, midstory and understory) composition and structure, fuel loading, moisture content, fire

Project Name	Lead Investigator(s)	Design Considerations	Treatments Evaluated	Responses Evaluated
	Research Station; Mark Grismer, UC Davis	modeling of fire behavior using FARSITE		hazard/severity, runoff and erosion
Nutrient emissions from prescribed fire	Paul S.J. Verburg, Richard B. Susfalk, and Lung-Wen Antony Chen, Desert Research Institute	Laboratory sampling of forest fuels, spatial modeling of basin-wide fuel loads	Prescribed fire	Potential gas emissions (NH_3, NO, NO_2, CO, O_3, CO_2, H_2O, toxics (e.g., acetaldehyde and formaldehyde) and water emissions (NH_4, NO_3, ortho-P, total P and total N)
Effects of pile burning in the Tahoe basin on soil and water quality	Ken Hubbert and Matt Busse, U.S. Forest Service, Pacific Southwest Research Station; Steve Overby, U.S. Forest Service, Rocky Mountain Research Station	Pre-treatment and two years post-treatment sampling, volcanic and granitic soils, within Stream Environment Zones, will also include modeling using Water Erosion Prediction Project (WEPP) and other tools	Piling and burning with variable pile sizes	Key soil physical, chemical, and biological properties; nitrate and phosphate movement in surface and subsurface runoff
Modeling Projects				
Integrated decision support for cost effective fuel treatments under multiple resource goals	Woodam Chung and Solomon Dobrowski, College of Forestry and Conservation, the University of Montana; J. Greg Jones and William J. Elliot, USDA Forest Service, Rocky Mountain Research Station	Basin-wide, model tools include Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) FlamMap (fire behavior), WEPP and GeoWEPP, MAGIS (economic optimization tool)	Fuels treatments (determined by management agencies) in various areas (WUI vs. non-WUI, treatments, steeply sloped terrain vs. gentle terrain) and arranged in various spatial and temporal patterns	Modeled fire behavior, sediment yield and runoff, crown base height, crown bulk density, reduction in loss caused by potential future wildland fires, habitat for species of concern
Evaluating alternative fuel treatments in the South Shore wildland urban interface area	Morris C. Johnson and Roger Ottmar, Pacific Northwest Research Station	South Shore WUI; Model tools include Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) and Fuel Characteristic	Thinning to various densities + leave, extract, or burn slash	Modeled fire reaction potential, spread potential, flame length potential, canopy base height, canopy bulk density, and fire type (e.g., surface fire,

Project Name	Lead Investigator(s)	Design Considerations	Treatments Evaluated	Responses Evaluated
		Classification System (FCCS)		conditional crown fire, passive crown fire, and active crown fire)
Developing fuel characteristic classification system fuelbeds for the Angora fire region	Roger Ottmar, Pacific Wildland Fire Sciences Lab and Hugh Safford, U.S. Forest Service Pacific Southwest Region	Angora Fire region, using FCCS	Various treatment alternatives considered by the Lake Tahoe Basin Management Unit	Fuelbed structure, fire hazard potentials, modeled flame length and rates of spread, and total carbon
Identifying reference forest conditions	Alan Taylor, Penn State University; Carl Skinner, USFS Pacific Southwest Research Station; Hugh Safford, USFS Region 5	Study of live and dead trees within a 2000 ha unlogged forest in the General Creek watershed, modeling using FVS and FCCS	Mechanical fuel treatments and prescribed burning	Modeled surface and crown fire behavior, and fuel loadings
Sources and transport of fine sediment (WEPP modeling)	William Elliot, USDA–FS Rocky Mountain Research Station; Erin S. Brooks, University of Idaho; Jan Boll, University of Idaho; Joan Wu, Washington State University	Modeling using Water Erosion Prediction Project (WEPP)	Not yet finalized, but may include fuel treatments	Modeled runoff and erosion rates
Predicting nutrient and sediment loading from prescribed fire using WEPP	Drea Traeumer, Em Consulting; Mark Grismer, Integrated Environmental Restoration Services	Modeling using WEPP, calibration using rainfall simulator at sites on volcanic and granitic soils, within and outside SEZs,	Pile burning	Modeled runoff and erosion, phosphorus and nitrogen
Modeling influence of management on wildfire under future climatic conditions	Matthew Hurteau, Northern Arizona University; George Koch, Northern Arizona University	Sampling 80 plots across 8 forest community types (low-mid elevation), modeling tree and stand growth for the Tahoe basin using FVS and SIMPPLLE	Manager-defined forest structural treatments	Modeled stand growth and carbon, fire risk and fire spread

Project Name	Lead Investigator(s)	Design Considerations	Treatments Evaluated	Responses Evaluated
		(landscape modeling)		
Restoration and fuel treatment of riparian forests	Malcolm North, USFS Pacific Southwest Research Station	Sampling 36 stands in non-urban riparian areas, modeling of fire behavior using Fuels Management Analysis (FMA)	Burning	Fire behavior