F.H. STOLTZE LAND & LUMBER COMPANY
Lumber Manufacturers
Box 1429 Columbia Falls, MT 59912
Phone (406) 892-7005 Fax (406) 892-1612
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December 17, 2018

Sandy Mack, Team Leader
Regional Office USFS Northern Region
24 Fort Missoula Road
Missoula, MT 59804

RE: Mid Swan Landscape Restoration & Wildland Urban Interface Project Scoping

Dear Ms. Mack,

Please accept the following comments on behalf of F.H. Stoltze Land & Lumber Co. on the Scoping Document for the Mid Swan Landscape Restoration & Wildland Urban Interface Project.

We are pleased to see a large scale planning area that will take a holistic look at a large landscape. The project should move that landscape towards the Desired Future Conditions outlined in the Forest Plan by implementing a variety of active management treatments. This type of large landscape approach is exactly what is being promoted by USFS Agency leadership as well as local collaborative groups. The efficiencies associated with the large planning area as well as the predictability longer term management planning provides are benefits to the agency and the community alike.

As with all projects, defining the purpose and need is essential to project development and analysis as well as providing a framework for good decision making. While we appreciate the three generalized goals of the project included in the scoping document, we feel it is important to develop more specific and measurable purpose and need statements that can be used by the team in developing the project and the decision maker in crafting a clear and implementable project decision.

While restoring and maintaining aquatic and terrestrial biodiversity is a great goal, it is a very difficult and subjective purpose to define a project around. Your scoping document does a good job of identifying specific actions that will be taken to meet this goal. Specific purpose and need statements need to be developed that are able to be measured and monitored for achievement.

Similarly the goal of reducing the risk of wildfire in the WUI sounds great[1], but I question if that is really the desired outcome? While we can modify fire behavior, increase effectiveness of suppression activities and increase firefighter and public safety through vegetation management

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[1] R5-TP-026a June 2008 *Fuel Treatment Effects on Fire Behavior, Suppression Effectiveness and Structure Ignition, Grass Valley Fire*

and fuel reduction[2], we likely will not, or may not want to, reduce the risk of wildfire in a fire dependent ecosystem such as ours. Being more precise in your purpose and need statements can help focus the effort.

A purpose and need statement of "Provide forest products that contribute to the sustainable supply of timber products from National Forest System (NFS) lands" is essential on all vegetation management projects within the suitable timber base. One of the primary purposes of these public lands is to help meet the societal demand for wood products and fiber in a sustainable manner. Having this purpose and need statement is essential for developing and defending implementation strategies.

37% of the non-wilderness project area acres are being considered for non-fire treatment (only 16% of the entire project area). While it is a good starting point, and higher than many similar projects, it has simply become too easy for the ID team to drop acres from treatment for just about any reason! When there are proposals to drop units or reduce treated acres, the ID team must answer the question of why dropping acres better meets the stated purposed and need for the project than keeping them in treatment. Decisions to drop acres should be documented and defendable. Keeping the acres in analysis, even if marginally economical or feasible, allows for flexibility in implementation and greater acres treated.

One of the reasons commonly given for dropping acres is economic or technological feasibility uncertainty. We encourage the team to engage the knowledge, experience and expertise of the forest products industry in helping to examine feasibility issues or even identify alternative management that may meet the project goals even better. We have talked with Montana Logging Association as well as area mills and all are willing to provide assistance. A few field trips to review specific sites or issues could be very helpful in guiding project development. Early and extensive involvement is essential to improved project development.

When designing the "stormproofing" of your road systems, we encourage you follow the Montana Best Management Practices for Protecting Water Quality guidance. This set of management tools and practices has proven to be extremely effective in mitigating water quality impacts associated specifically with roads and timber harvest[3]. The practices are cost effective and proven to be implementable. There is often a tendency to propose elaborate and expensive engineering solutions to problems that simply need some BMP's applied. We suggest you review the recent study by Brian Sugden[4] on the effectiveness of BMP application on "legacy roads" (copy attached).

We strongly support the proposal to implement vegetation restoration activities within the Inner and Outer Riparian Management Zones. The effectiveness of these expansive vegetative buffers along our riparian areas is dependent on that forested riparian ecosystem being healthy and functional. Disturbance is essential to maintaining resilient and thrifty riparian forest ecosystems. The potential impacts of "controlled disturbance" through either mechanical or prescribed fire treatment are much lower and more predictable than letting Mother Nature take its course. Especially given the generally overstocked and disease ridden state of many of these buffer areas. Once again, the Montana Streamside Management Zone law has proved to be an effective tool in

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[2] *Bioscience* Vol.62 No.6 June 2012 Pg 549-560 Stephens et.al.

[3] *Journal of Forestry* 110(6):328-339 Sept. 2012

[4] *Forest Science* 64(2): 214-224 April 2018

maintaining riparian function while still allowing for judicious management activities to promote vegetative vigor, structure and persistence.

Similarly, in order to maintain a good variety of lynx habitat that is well distributed across the landscape and arranged in a manner that is useable to individual animals, some active management is necessary. The predictability associated with planned active management allows much better habitat efficiency than allowing natural fire and succession to proceed unguided. We can systematically improve habitat now and in the future by planning some disturbance in a controlled manner. We feel the management proposed is consistent with the intent of Lynx management direction and if forest plan modifications are necessary, then they should be pursued.

While designing vegetation treatments in the WUI, we specifically encourage you to consider improvements to primary access routes. The open roads and trails that exist in the project area provide a unique opportunity to address fuel hazard reduction and public safety concerns in a proactive manner. The project should include treatment of all roads and trails with roadside hazard reduction treatments (shaded fuel breaks) for at least one tree length on either side of the road or trail. Increased safety for fire suppression personnel, local residents and recreational users will be gained as well as establishing preexisting suppression control points[5].

Stoltze has undertaken similar treatments on some of our shared use roads or emergency access routes and have found multiple benefits. The obvious and primary benefit is increased safety for use under emergency egress fire situations and as control lines. It is no secret that this is often the first suppression action taken on large project fires by incident management teams. The opportunity to pre-treat this area where there may be an economic return to the USFS rather than extremely high costs associated with emergency treatment under an active wildfire makes good sense.

Secondary benefits include greater public safety due to increased sight distance. We have also experienced greatly reduced road maintenance costs and less spring damage due to the increased sunlight on the road surface allowing quicker drying and shorter “break up” condition periods. Opening up trail corridors would reduce user conflict and unwanted user-wildlife interaction due to increased sight distances. These benefits make sense on open road systems, trails and in front country areas with high levels of public use.

We are pleased to see a variety of silviculture prescriptions being proposed that may be variants of traditional even aged management regimes. Stoltze has long participated in the Kootenai Stakeholders Collaborative and that group has developed a comprehensive set of silvicultural guidelines. These guidelines are areas of agreement and provide general sideboards and best management practices for project design, many of which we see reflected in the scoping document. Generally moving patch size towards what would be seen in the appropriate fire regime for a forest type is important. Decreasing homogeneity and increasing species, age and size class diversity within stands and across landscapes increases overall resiliency. Conserving old growth and improving old growth recruitment through active management rather than non-management is also a good strategy.

Some of the project area was previously industrial timberland. While this land was heavily managed in the past, there are many very productive stands that should continue to be managed.

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[5] *Forest Ecology and Management* 127(2000)55-66 Agee et. al.

The area does not “need to rest”! Conversely, these lands likely need more management, in the form of pre-commercial thinning or commercial thinning to ensure continued stand development and capitalization upon the good silviculture done previously. Similarly the road systems that exist should be maintained, but retained to allow for future management.

We noted the lack of any discussion about public and commercial recreational use within the scoping document. While it may not be a primary management objective, to miss the opportunity to include recreation management in the analysis is not very efficient. Developing integrated projects is how the Agency will become more efficient in their management duties. Undoubtedly, there are recreational improvements or maintenance items that could be incorporated into other management activities, expanding overall accomplishments of the project.

Accurately depicting the no-action alternative is extremely important. Disclosing the impact to the local economy of forgoing management is one essential component. This includes not only the timber products, but also likelihood of closed or unmaintained roads and trails due to unmitigated hazard tree risks and the associated impact to recreation, outfitting and other commercial and noncommercial uses of the forest.

It is also necessary to disclose the impact of the no action to other actions such as climate change response, species viability, reforestation, forest productivity, human safety and accessibility. What will the no action progression towards DFC’s outlined under the forest plan be? What are the costs associated with allowing nature to proceed unchecked? What are the legal, ethical and economic liabilities to adjoining landowners of allowing insect and disease to go untreated or wildland fuels to be unabated?

Based upon review of the initial proposal, the team certainly appears to be on the right track. We look forward to following your analysis and project development process. I want to reiterate our offer of serving as a technical resource on economic and technological feasibility issues related to logging and road systems. Please do not hesitate to contact me if you have any questions about our comments or need clarification.

Sincerely,
Paul R. McKenzie

Lands & Resource Manager

ENC:

United States
Department of
Agriculture

R5-TP-026a

June 2008

Fuel Treatment Effects on Fire Behavior, Suppression Effectiveness, and Structure Ignition

Grass Valley Fire

San Bernardino National Forest

Cover photo by Carlos Chavez, Los Angeles Times. October 22, 2007

Fuel Treatment Effects on Fire Behavior, Suppression Effectiveness, and Structure Ignition

Grass Valley Fire

San Bernardino National Forest

Report submitted to

Randy Moore
Regional Fire Director, Pacific Southwest Region
Vallejo, California

Authors

Gene Rogers
Fire Behavior Analyst, Keno RFPD
Keno, Oregon

Wendel Hann
Fire Ecologist, Washington Office
Fire and Aviation
Leadville, Colorado

Charley Martin
Fire Ecologist,
Bureau of Land Management
Medford, Oregon

Tessa Nicolet
Fire Ecologist,
Lincoln National Forest
Alamogordo, New Mexico

Morgan Pence
Fire Ecologist, Intermountain Region
Moscow, Idaho

Team Oversight, Support and Editing

Tim Sexton
Fire Use Program Manager,
National Interagency Fire Center
Boise, Idaho

Kathy Murphy
Fuels Operations Officer,
Pacific Southwest Region
Vallejo, California

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Executive Summary

The Grass Valley Fire started at approximately 0508 on October 22, 2007 in the mountains of the San Bernardino National Forest in Southern California about 60 miles east of Los Angeles. Weather conditions were warm and dry. Santa Ana winds (strong, dry winds) had been blowing for two days. Live vegetation and dead fuels were very dry.

The fire spread to the south through wildland fuels and then transitioned to urban structural fuels where it destroyed or damaged approximately 199 structures. U.S. Forest Service, state, and local firefighters responded immediately after the initial report. Most of the final fire area burned on the first day. The fire was contained on the 26th of October. According to firefighters, suppression actions were substantially enhanced by fuel treatments in and adjacent to the fire.

A team was formed to assess effects of fuel treatments on:

- ◊ Fire behavior
- ◊ Fire effects
- ◊ Structure ignition
- ◊ Fire suppression
- ◊ Public safety and egress

Key Findings

- ◊ Fire behavior in fuel treatment areas was less rapid and less intense than in adjacent untreated wildland fuel and urban-structural fuel. The reduced spread rate and intensity allowed suppression forces to concentrate on protecting structures and on preventing additional fire spread to the south.

- ◊ Fuel treatments improved visibility enabling firefighters to engage the fire directly in places and to protect homes without jeopardizing their safety.

- ◊ The Mountain Area Safety Task Force coordinates hazard reduction efforts of all the organizations and agencies managing land, infrastructure, and emergency response in the Lake Arrowhead area. Their efforts greatly enhanced the safe evacuation of thousands of people due to previous dead tree removal. Removal of these dead trees reduced the amount of tree fall in roadways along main routes and also reduced ember production and associated spot fires.

- ◊ The Grass Valley Fire burned more intensely within the residential area than in adjacent wildland fuels. Mass ember production from structures ignited adjacent and downwind structures in many cases.

Introduction

The Grass Valley Fire occurred in the mountains just north of San Bernardino in Southern California (Figure 1). Within and adjacent to the fire is a residential area known as Lake Arrowhead. Located approximately 60 miles east of Los Angeles, the area is famous for recreation and destination resorts and contains many year round and vacation homes. The Mountaintop Ranger District of the San Bernardino National Forest administers the core of the mountainous land base. Surrounding foothill lands have intermingled private and government ownership. Many parcels of private land occur within the National Forest. Private lands outside the National Forest contain a dense array of subdivisions.

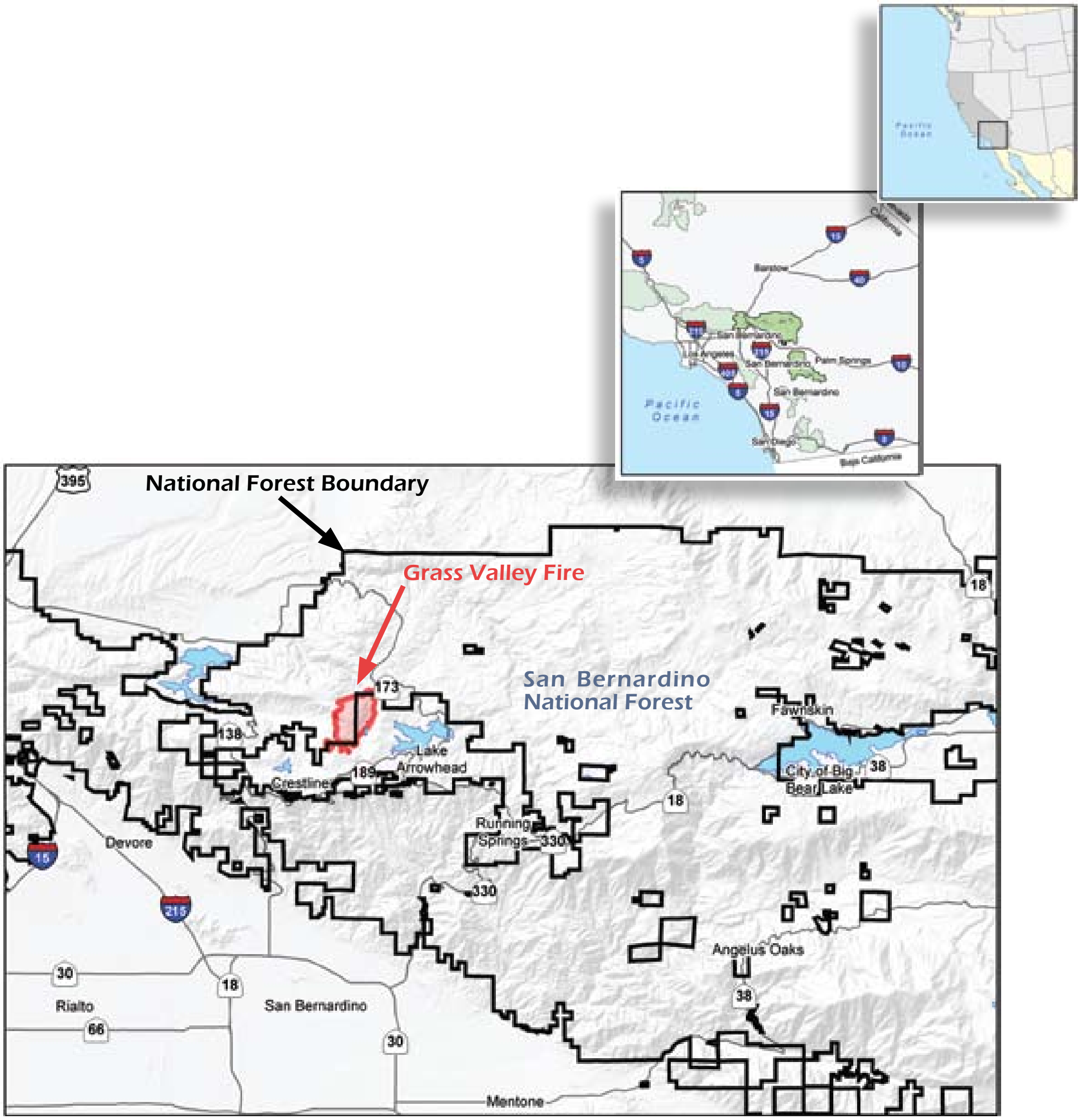


Figure 1. Vicinity map of the Grass Valley Fire.

The fire was reported at about 0508 on the 22nd of October. The fire origin was west of Lake Arrowhead, near Deer Lodge Park off the Grass Valley Road, north of the cul-de-sac on Edge Cliff Drive (Appendix A). The fire was driven to the south by dry Santa Ana winds of 20 to 30 miles per hour (Appendix B). About three fourths of the 1,242 acre fire burned on the first day spreading rapidly to the south through untreated wildland fuels and high density urban structures. Many residents throughout the area were evacuated. Damage in urban areas was extensive with approximately 199 structures destroyed or damaged.

The fire burned onto National Forest System lands where recent hazard fuel treatments had been implemented (Figure 2). Suppression actions contained spread to the east and halted southerly spread by the end of the first day. Low fire intensity and spread rate in treated wildland fuels enabled firefighters to contain the fire north of Fairway Drive and Twin Peaks residential area.

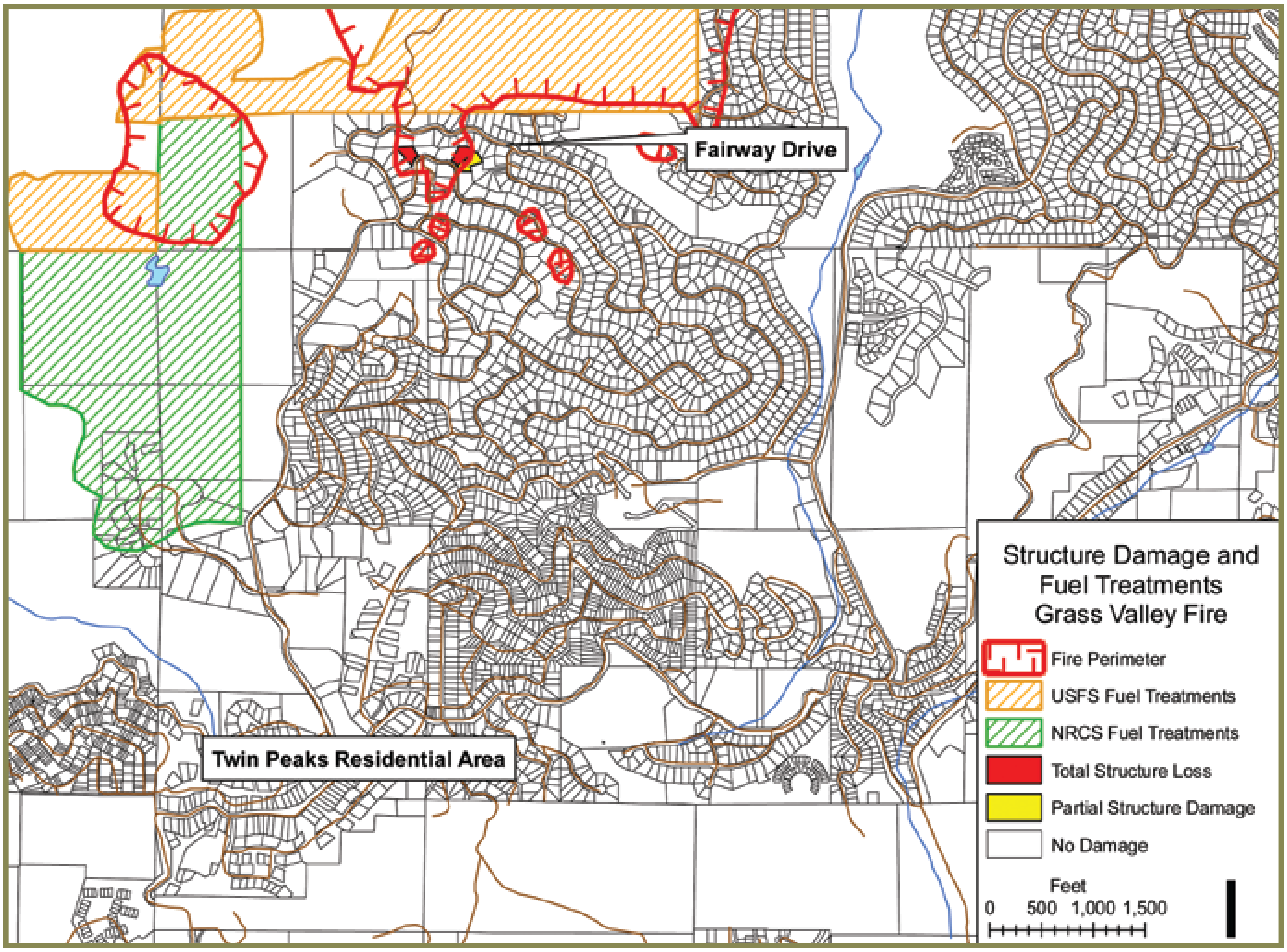


Figure 2. Vicinity map for the southern portion of the fire. Note the location of the fuel treatments and residential areas.

Background

In 2002, major tree mortality broke out caused by a combination of overly dense stands of trees, drought stress, insects, and disease (Figure 3). The Forest Service and other collaborators recognized the need for hazard fuel reduction. Support for this program was greatly enhanced by reaction to the Old Fire, which occurred in October, 2003. This fire occurred in the San Bernardino National Forest including the area surrounding Lake Arrowhead and Crestline and burned 970 structures and 91,281 acres with high intensity fire.

Figure 3. Aerial view of beetle killed trees around Lake Arrowhead in 2003.

The Mountain Area Safety Task Force (MAST) was established to coordinate hazard reduction efforts of all the organizations and agencies managing land, infrastructure, and emergency response in the Lake Arrowhead area and other mountain communities. This group has prioritized hazard fuel treatments, developed grant applications, and commissioned area assessments to determine treatment needs. MAST has emphasized area and linear fuelbreaks adjacent to urban areas in forested fuels. Substantial treatments on private lands have been funded and implemented with emphasis on dead tree removal. MAST continues to collaboratively promote and plan actions to protect communities, evacuation routes, and communication sites.

Assessment Objectives and Methodology

Objectives

Provide a clear description of:

- ◊ Fire environment
- ◊ Fire chronology
- ◊ Fuel treatments implemented prior to the fire

Evaluate the effects of fuel treatments on:

- ◊ Fire behavior
- ◊ Fire effects
- ◊ Structure ignition
- ◊ Fire suppression
- ◊ Public safety and egress

Methodology

Facts and circumstances regarding the Grass Valley Fire were determined by ground and air reconnaissance, photos, videos, interviews, and review of written documentation. Many interviews were conducted with local residents, specialists, and subject matter experts to confirm information. Team members installed plots to gather data for fire behavior, modeling, and analysis used to support conclusions about the effectiveness of fuel treatments.

Description of Fire Environment

Fuel and Topography

Wildland fuel types within and adjacent to the fire perimeter include oak-shrub with surface litter and long and short-needle pine with understory trees. Deciduous black oaks provided a break in canopy continuity of the pine. In addition, a complex fuel mosaic existed within the subdivision areas which included homes and related structures, household items and debris, wildland fuel as described above, and ornamental shrubs. Roughly one fifth of the fire area is within the Forest Service Tunnel 2 fuel treatment. Other fuel treatments were present but much smaller in size (Table 1).

Treated and Untreated Areas Within the Grass Valley Fire Perimeter	Acres
USFS Fuel Treatments (Tunnel 2 and other)	249
USFS Untreated	577
NRCS/San Bernardino County Fuel Treatment (Edge Cliff Dr)	11
NRCS Fuel Treatment (California Fish and Game)	20
NRCS Fuel Treatment (Krause-Hall)	68
Forest Care Fuel Treatment (Deer Lodge Park)	15
Untreated Private	302
Total	**1,242**

Table 1. Fuel treatments and acres

The layers of vegetation in the forest/woodland types created a continuous fuel ladder from surface into canopy fuel (Figure 4). The overstory consists of sparse black oak and a mix of Coulter, sugar, and Jeffery pine, with big-cone Douglas fir in the lower elevations and drainages. The understory consists mostly of dense suppressed white fir. Interior live oak and incense cedar were scattered throughout the fire area. Additionally, there were areas of chaparral with manzanita as the dominant species.

Figure 4. Typical conditions in stands which had not received fuel treatment.

Where vegetation and fuel management activities have been implemented, trees and shrubs were less dense (Table 2). These areas were dominated by large over-story oak and pine with smaller areas of widely-spaced chaparral.

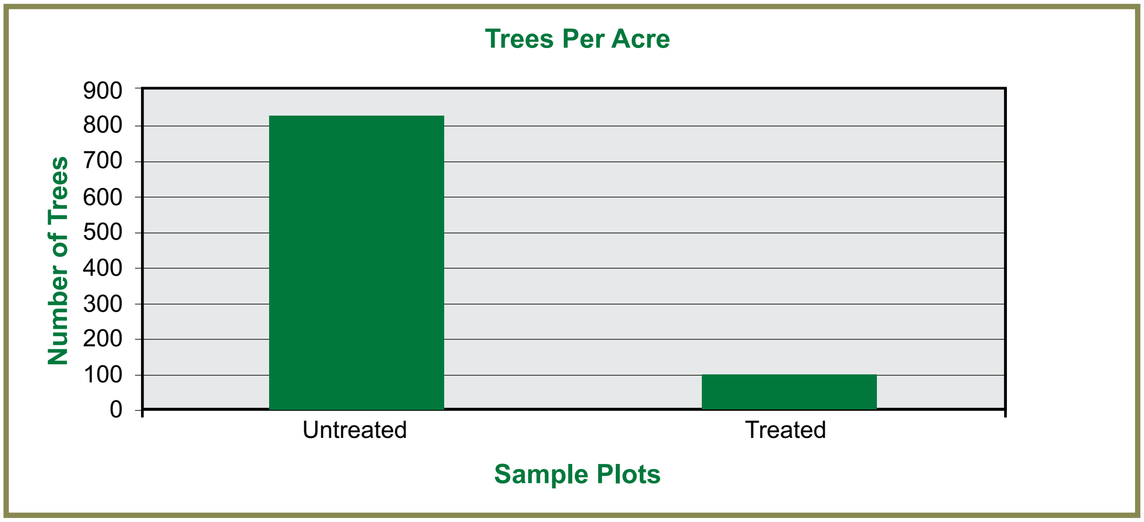


Table 2. Trees per acre in treated and untreated areas based on sample plots taken immediately after the fire within the fire perimeter. This quantifies the difference in tree density between treated and untreated areas.

Surface fuel in the managed stands consisted of pine needles and oak leaves with light to moderate loading (Figure 5). The topography within the fire perimeter varies from gentle (<10%) to steep (>60%).

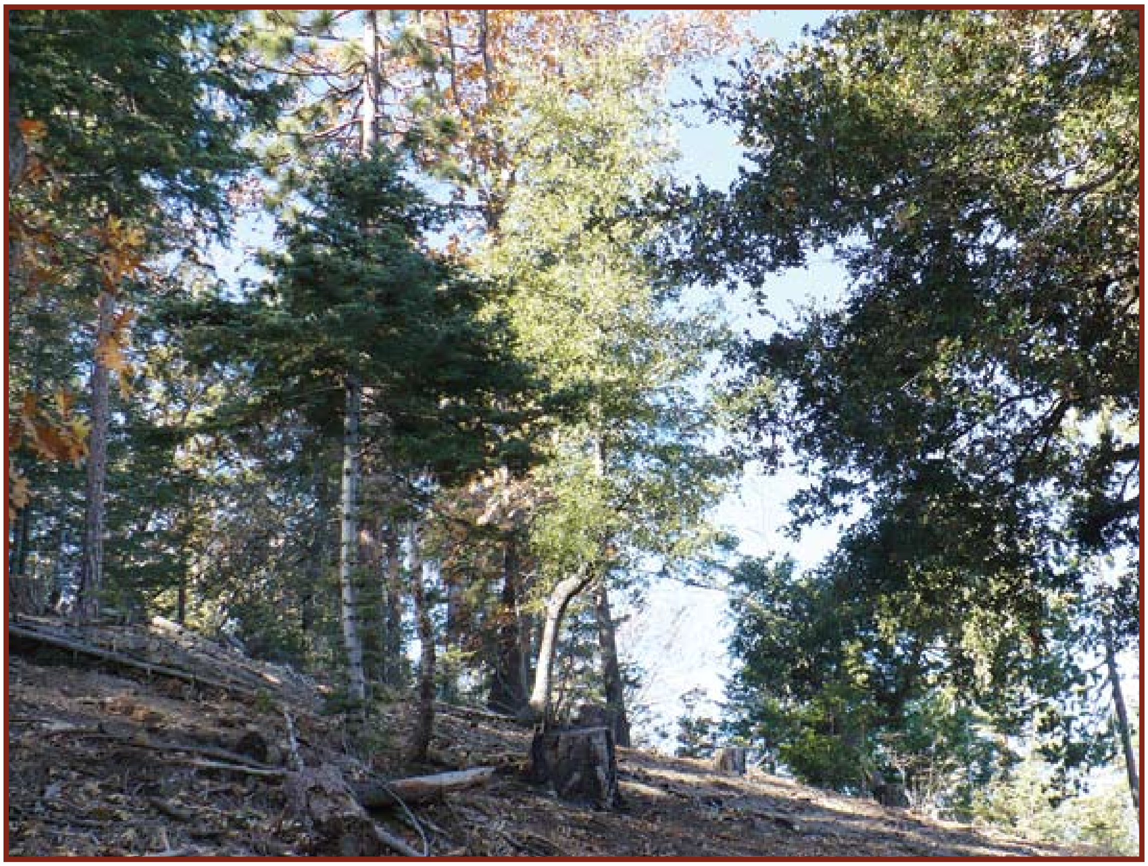


Figure 5. Typical conditions in stands which had received fuel treatment.

Fire Weather and Fire Danger

The Lake Arrowhead vicinity is typically warm and dry during the summer and fall months. October of 2007 was unusually dry, as recorded by the four Remote Automated Weather Stations (RAWS) in the area. The large dead fuel moisture (3"-9" diameter) was 8% and the live woody fuel moistures were 56% which further indicates a very dry season. On October 22nd, the minimum relative humidity was 8%, one of the lowest recorded for the 2007 fall season. The Rock Camp RAWS, located approximately 1/2 mile northeast of the ignition point, recorded average northerly wind speeds of 18 mph with gusts up to 34 mph (Appendix B). October 22nd set a record for the highest wind speeds during the month of October over the past 13 years. Firefighters observed winds in the fire area gusting in excess of 40 mph.

Fire Behavior Chronology

The fire started October 22, 2007 at approximately 0508 in grass and brush. The Rock Camp RAWS recorded a north wind averaging 18 mph with gusts up to 29 mph for the first hour of initial attack (Appendix B).

Strong northeast winds pushed the fire down and cross-slope into the Grass Valley Creek drainage. According to dispatch logs, the first engine on scene, USFS E-11, reported 5 acres and moderate rate of spread at 0526 and a need for law enforcement to initiate evacuation.

At 0534, the Initial Attack Incident Commander, Randy Clauson, requested a mandatory evacuation of Deer Lodge Park, reporting the potential of a fire larger than 1,000 acres. "One of my worst fears was a north wind fire in the Grass Valley Creek drainage" (Randy Clauson, Initial Attack Incident Commander).

Firefighters on scene reported that spotting contributed to fire spread in the wildland fuels. Wildland firebrands consisting of leaves, needles, and small twigs which ignited from surface fire, were lofted into the air by convection and transported down wind where they landed and ignited new fires in advance of the main fire.

According to dispatch logs and interviews with firefighters, the first home to burn on the east flank of the fire occurred on the north end of Brentwood Drive. This home was located directly above a steep south facing slope.

Shortly after the first home ignition, the fire burned into a dense residential area at Trinity Drive and the streets above. The close proximity of homes to one another, along with wind and slope alignment, contributed to rapid fire spread from house-to-house. At 1141, the Incident Commander notified dispatch that approximately 75 to 100 structures were destroyed.

Figure 6. Typically in the subdivisions, the homes were burning and the adjacent vegetation was not. (Photo by Brett Snow, San Bernardino Sun)

Once a home ignited and was fully involved, it exposed other adjacent structures to damaging radiant and convective heat (Figures 6 and 7). Burning homes also produced a tremendous amount of embers which were lofted and carried downwind.

Figure 7. Flammable roofs were vulnerable to embers. (Photo by Eric Reed, San Bernardino Sun)

Wood decks, overhanging vegetation, firewood, lumber, and other flammable material located immediately adjacent to houses ignited readily when embers landed on them (Figure 8). Small spot fires in these materials spread quickly to the adjacent house.

Figure 8. Spot fire igniting flammable material on deck of a structure. (Photo by Eric Reed, San Bernardino Sun)

Structure firefighting efforts were difficult due to dense smoke, house-to-house ignitions, limited access, and other unsafe conditions as homes were burning on both sides of roads simultaneously.

By 1300, David Kelly, Initial Attack Operations Section Chief, was able to get out to the Tunnel 2 fuelbreak to check the fire behavior through the treated area. At that time it was a very low intensity surface fire with predominately two foot flame lengths. According to Kelly, "It was a relief to see the type of fire behavior in the fuelbreak so our fire resources could concentrate on the east side in the community."

By 1500, the fire had moved into the south end of the Tunnel 2 fuel treatment area. By 1700, the fire had burned to its final perimeter (Figure 9) to the south along the boundary of the Tunnel 2 fuel treatment area. A retardant line and helicopter drops secured the southwest portion of the fire at the edge of the Tunnel 2 fuel treatment area.

A spot fire about one-third of a mile to the southwest of the main fire was detected about 2200 on 10/22/07. Action was deferred until the next day because the spot was in a treated area and exhibited very low fire intensity. In addition, priority for firefighting resources was in the residential area. The west flank of the fire exhibited low intensity spread on the 24th and 25th. Indirect lines were constructed and burned out to establish the final fire perimeter on the west.

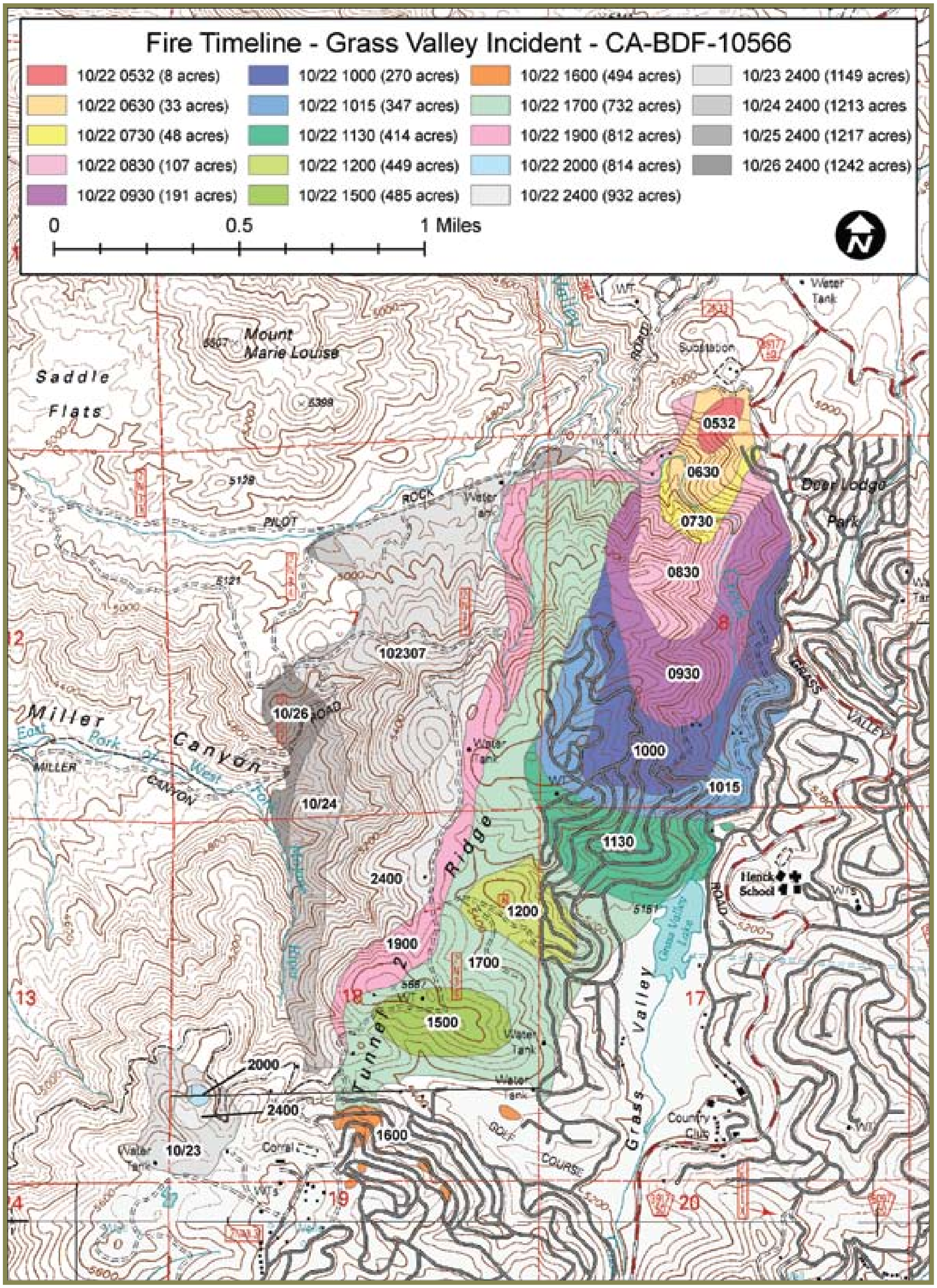


Figure 9. Approximate progression of the Grass Valley Fire (as recalled by firefighters) from its start in the northeast corner on October 22nd to the final expansion of the perimeter on the west, ending on October 26th at 2400.

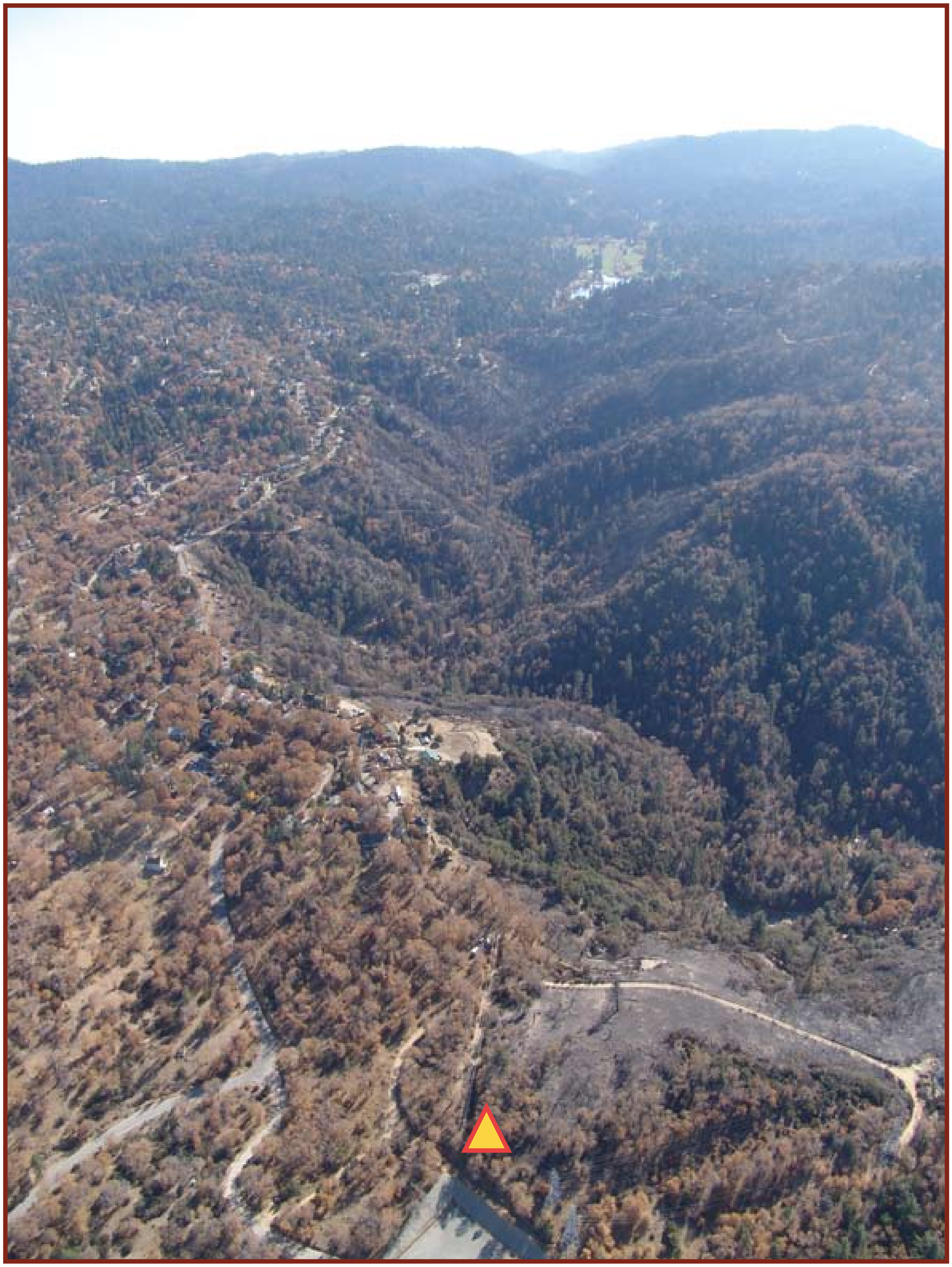


Figure 10. View from area of origin (yellow triangle) looking south into the Grass Valley drainage. Note minimal crowning on north aspects.

Figure 11. Grass Valley Creek drainage, looking north. Note the fully consumed tree crowns on south and southeast facing slopes. Triangle is approximately the point of origin.

Some of the homes on Trinity Drive and Merced Lane received embers or direct flame contact and radiant heat from wildland fire. These homes were on a north facing aspect in the path of the fire, located on a steep slope above untreated private land. The area below these streets had substantially higher tree densities than treated areas. Fuels directly below these homes had continuous vertical and horizontal arrangement of white fir with tight canopy spacing (Figure 13).

Figure 12. Consecutive burned homes where streets were aligned with the wind are indicated by the arrow.

Figure 13. Typical fuels below homes on Trinity Drive and Merced Lane.

On the ground inspections revealed that pieces of sheathing, siding, and other burning matter were carried downwind. Firebrand production from burning structures was substantial in both quantity and size (Figure 14).

Figure 14. Large firebrand that drifted onto a resident's property.

Post-fire visual examination indicated a lack of substantial fire effects on the vegetation and surface fuels between burned homes. Lack of surface fire evidence in surrounding vegetation provides strong evidence that house-to-house ignitions by airborne firebrands were responsible for many of the destroyed homes. Much of the tree canopy burned only in the area directly adjacent to the burning homes. This was the result of radiant and convective heat from burning structures. See Cohen and Stratton (2008) for a detailed explanation of home ignition and spread on the Grass Valley Fire.

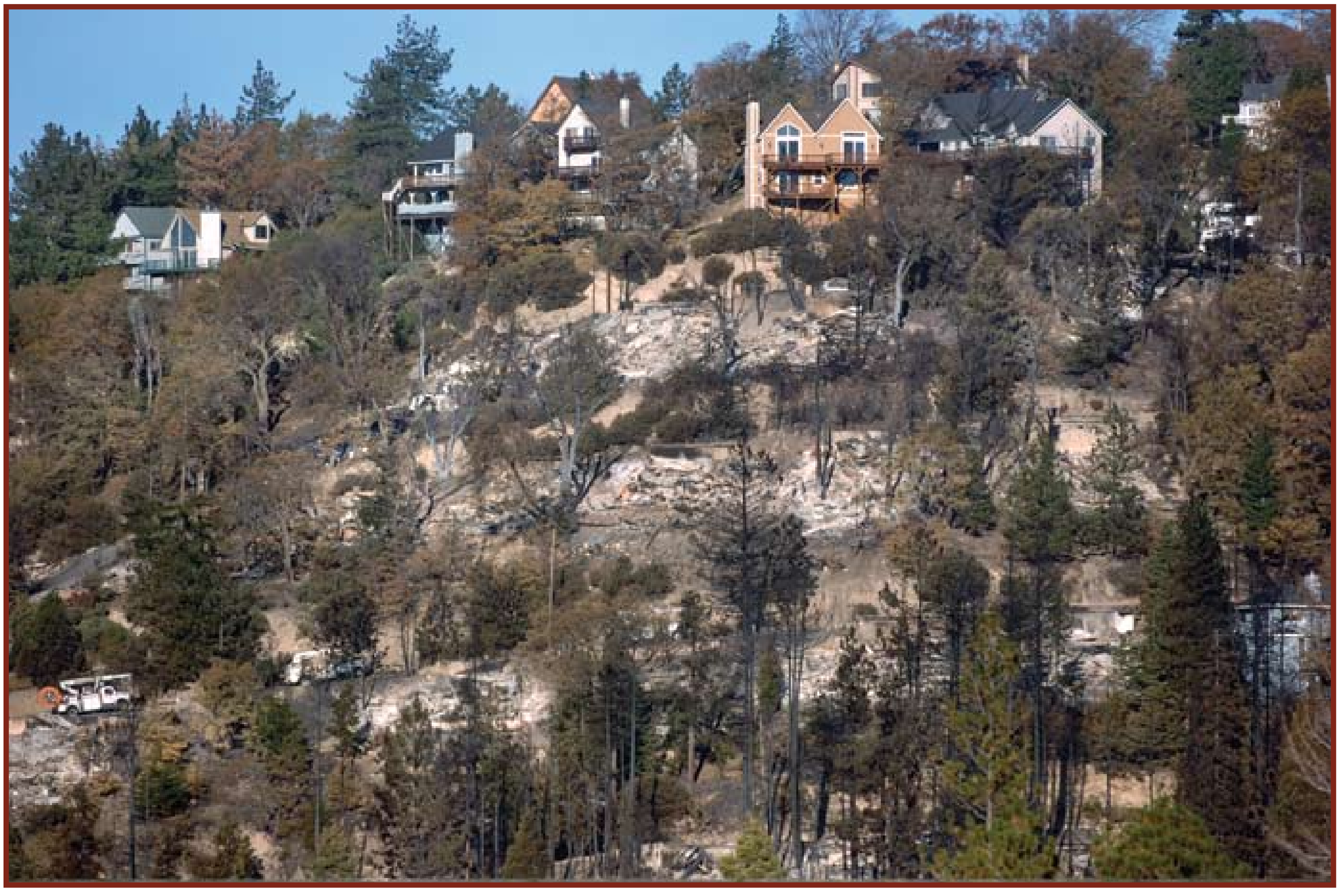


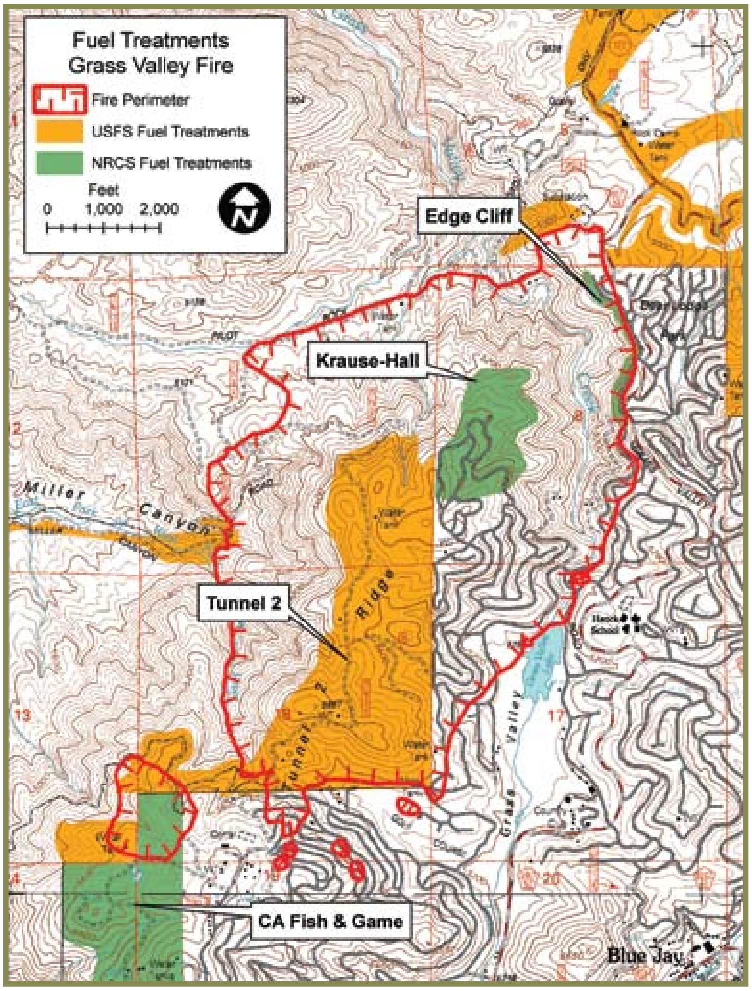
Figure 15. Trees directly adjacent to homes were burned, while trees more distant from homes were not burned. This indicates that homes, not the vegetation, were the primary fuel by which the fire spread. (Photo by Eric Reed, San Bernardino Sun)

Figure 16. Note the unburned vegetation adjacent to the burned structure. The scarring on the tree indicates the tree caught fire from the structure and not the reverse.

Fuel Treatments

USFS Tunnel 2 Fuel Treatment

The Mountaintop Ranger District of the San Bernardino National Forest in collaboration with MAST, recognized the need for forest health improvement and fuel treatments. In response to this need, a hazard fuel reduction plan was developed. The treatment plan for the National Forest was developed by taking a district wide look at the forest and woodland areas adjacent to urban and other facilities. Sites were selected where high fuel hazards existed and where an area fuel treatment could be implemented that would be large enough to change fire behavior from crown fire to surface fire, reduce flame lengths, spotting, and improve forest health. The largest of the Forest Service area treatments was Tunnel 2. Other Forest Service treatments were located in smaller areas along community boundaries in the area. (Figure 17)



Local managers recognized the critical importance of prioritization and location of fuel treatments. Planners considered the hazard reduction effect of recent wildfires which had burned about 25% of the area. They also recognized that, in the short term, given the operational and funding capabilities, treatments could only reduce hazard on a small portion of the other 75% of the area. The Tunnel 2 treatment was located on the National Forest boundary area between the high density wildland urban communities of Lake Arrowhead and Twin Peaks. These communities were embedded in very hazardous fuels adjacent to Forest Service lands to the northwest (Figure 18).

Figure 17. Fuel Treatment Map

Figure 18. Home embedded in dense vegetation in the Lake Arrowhead area.

Managers defined acceptable fire behavior for this area as "flame lengths of four feet or less under 90th percentile weather conditions."[1] Flame lengths of four feet or less are generally recognized as safe for direct attack by firefighters on the ground (Andrews and Rothermel 1982). Areas treated to the "four foot flame length" standard have proved to be effective in changing fire severity and increasing effectiveness of fire suppression resources. In many cases, fire behavior has been observed to transition from a crown fire to a surface fire when the fire entered the treatment area (Murphy, Sexton, and Rich 2007; Finney, McHugh, and Grenfell 2005).

Fire behavior modeling and expert judgment provided estimates of surface fuel, ladder fuel, and tree canopy conditions which would result in the desired level of fire behavior (Appendix C). Treatment actions which achieved this objective included removal of dead, dying, and diseased trees, thinning, pruning, chipping, and burning to reduce surface litter and woody fuel loading as well as ladder and canopy fuel. More conifers than oaks were removed and more understory trees than overstory trees were removed. This left widely spaced oak-dominated woodland with discontinuous surface fuels.

Figure 19. Crews working in Tunnel 2 fuelbreak.

It should be recognized that Tunnel 2 fuel treatment prescription did not seek to stop fire spread. The treatment objectives were to reduce crowning potential and ember production. A prescription designed to stop fire spread would have directed the removal of almost all trees and shrubs for at least 1/2 mile (spot fires were observed on the Grass Valley Fire that originated from embers lofted 1/4 to 1/2 mile upwind) and all surface fuel for as much as 100 yards.

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[1] 90th percentile weather conditions occur on ten percent of the days of the fire season and are the top ten percent for severe fire danger.

Fuel Treatments on Private Lands

Natural Resources Conservation Service (NRCS) and San Bernardino County Fire accomplished many hazard reduction projects on private land including Krause-Hall and Edge Cliff Drive. Forest Care, a program that assists homeowners in reducing fire risk, helped many landowners reduce fuels on their property. Forest Care is administered by the non-profit San Bernardino National Forest Association. The program is offered through the cooperation of the California Department of Forestry and Fire Protection and is funded through a U.S. Forest Service grant. Through Forest Care, homeowners are offered assistance in thinning trees and removing undergrowth to make their property more fire resistant while meeting state and local regulations for fire clearances.

In addition, Southern California Edison began a program to remove dead, dying, and diseased trees in 2003. By October of 2007, more than 186,000 trees had been removed. The primary objective for these private land treatments was to remove hazard trees associated with the 2002 beetle kill outbreak.

Figure 20. Large dead tree removal on private property.

These dead trees posed a risk of falling on roadways, homes, power lines, and other structures. In addition, once ignited they cast embers to ignite spot fires in wildland fuel and structures. Removal of these trees lessened the risk to firefighters working in and around the structures.

Some of these private land treatments also disposed of small trees, shrubs, and surface fuels in order to reduce potential fire intensity and spread rates. One worker described conditions on Edge Cliff Drive as 6 to 10 foot manzanita with 10-12 inch bases, scrub oak, full oak trees, downed pine, and a fuel load so heavy you couldn't walk through it (Figure 21). Treatments placed along roadways such as Edge Cliff, were intended to make public evacuations safer while improving visibility and access for firefighters. This was accomplished by cutting some of the trees and shrubs and disposing of some of the surface fuels. Some of this material was burned, some was chipped and scattered to inhibit post-treatment herbaceous fuel growth and some was hauled off-site.

Figure 21. Conditions in Edge Cliff fuelbreak before treatment.

Fire Behavior in Fuel Treatments

USFS Tunnel 2 Fuel Treatment

Fire behavior within the Tunnel 2 treatment area during the Grass Valley Fire exhibited lower flame lengths, slower rate of spread, less transition to crown fire, and less spotting than outside the treatment area. Fire personnel noted that the reduced fire behavior allowed fire resources to concentrate on evacuating other sides of the fire.

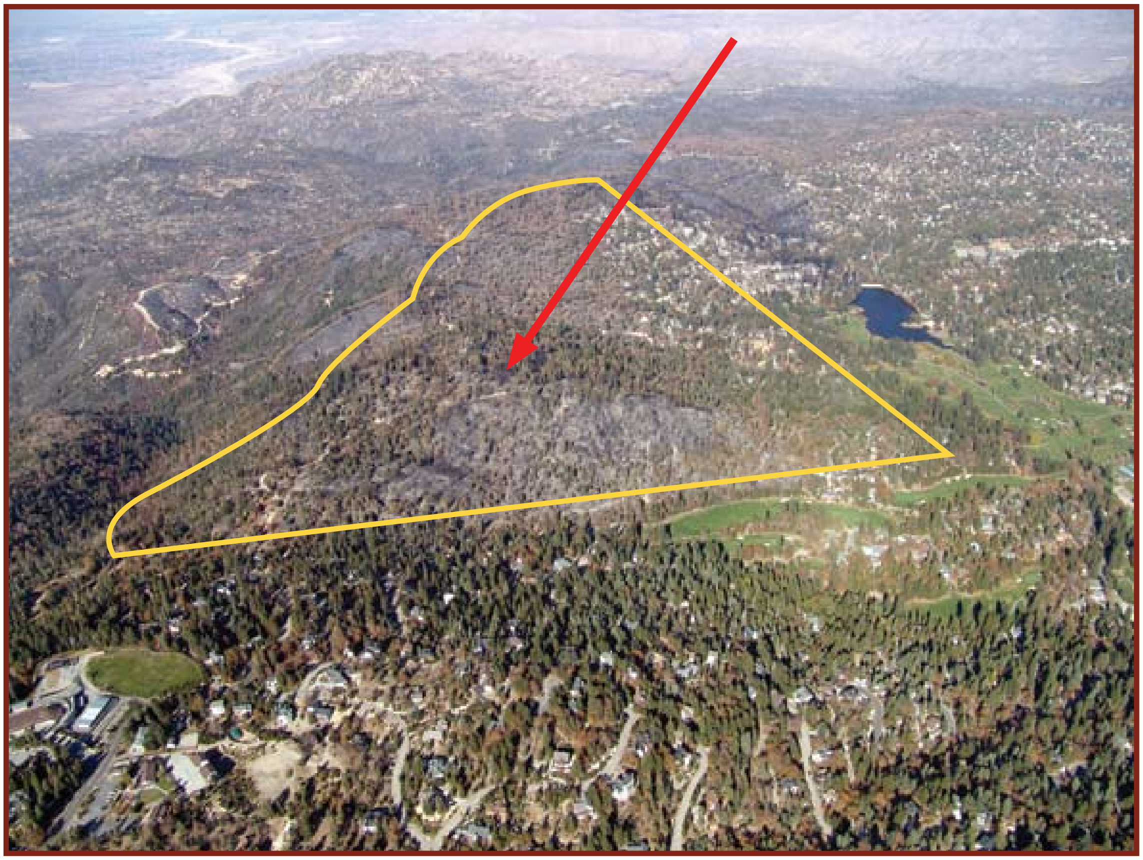

Figure 22. Tunnel 2 Fuel Treatment – aerial view, looking north. Yellow line depicts approximate unit boundary. Red arrow indicates direction of wind and fastest fire spread.

Figure 23. Tunnel 2 fuelbreak with low scorch heights and patches of unburned fuel.

Post-fire examination of incomplete litter and duff consumption, observations of patches of unburned fuel, and comparatively low scorch heights on trees (Figure 23) supported the firefighter accounts.

Insect and drought stress caused tree mortality after Tunnel 2 treatment was completed resulting in small concentrations of standing dead and down fuel. Due to these conditions, there were isolated areas within the Tunnel 2 project where torching occurred.

Included in a portion of the Tunnel 2 fuel treatment was a portion of a Spotted Owl Protected Activity Center (PAC). Fuel treatment occurred in this area (Appendix C). This portion of the PAC experienced surface fire due to a combination of factors, including fuel treatment, high wind, and moderate slope, which kept the fire on the ground until it hit the top of the slope where it entered the tree crowns. The rest of the untreated PAC, which was on private property, received almost complete mortality from crown fire.

Figure 24. Tunnel 2 treatment area boundary is shown in white. Portions of the treatment area burned with higher intensity (in yellow oval).

Fuel Treatments on Private Lands

Observations from home owners and initial attack resources describe fire behavior in the area of the county hazard fuels reduction project along Edge Cliff Drive as a low intensity surface fire. Post-fire photos and interviews support these conclusions (Figures 25 and 26. "The Edge Cliff fuel break definitely saved lives" (Peter Brierty, San Bernardino County Fire Department). "It is my opinion that the lives of my children and husband, as well as our many neighbors, were saved by the intended practical application of this fuels reduction treatment" (Ginny Jablonski, resident, Edge Cliff Drive). It is clear that the residents and local firefighters believed the treatments provided a margin of safety in this fire situation.

Figure 25. Note location of Edge Cliff Drive (red arrow) and the fuel break below the road (white polygon).

Figure 26. Hazard fuel reduction project along Edge Cliff Drive. Note limbed trees.

Figure 27. Krause-Hall treatment area burned with low intensity due to flat terrain, open roads, and a driving wind.

Krause-Hall and California Fish & Game Treatments

The primary objective for both the Krause-Hall and California Fish and Game area fuel projects were removal of dead, down, and diseased trees. A secondary effect from this treatment was reduction of surface fuels and removal of some small groups of trees on the skid trails in these areas. However, throughout the majority of these areas there was little change in live tree canopy characteristics. Fire burned through the Krause-Hall treatment area (Figure 27) at approximately 1000. This area was relatively flat with discontinuous fuel due to many open skid trails and roads. Post-fire photo observations indicate low fire intensity as the fire moved through this treatment area.

Figure 28. California Fish and Game treatment area, where a spot fire occurred. Notice shorter clumps of white fir are scorched, while large over-story fuel remained un-scorched.

Fire spotted into the California Fish and Game treatment area and was first discovered around 2200. The spot burned with low intensity and severity, creating a patchy surface fire, where short dense clumps of white-fir varied from little to full scorch. Evening burning conditions and flat terrain reduced fire intensity. Most of the overtory vegetation remained unscorched (Figure 28). Action on this spot was deferred until the next morning because it exhibited very little fire behavior and suppression priorities were higher elsewhere. Interviews with fire personnel, photos, and observations support these conclusions.

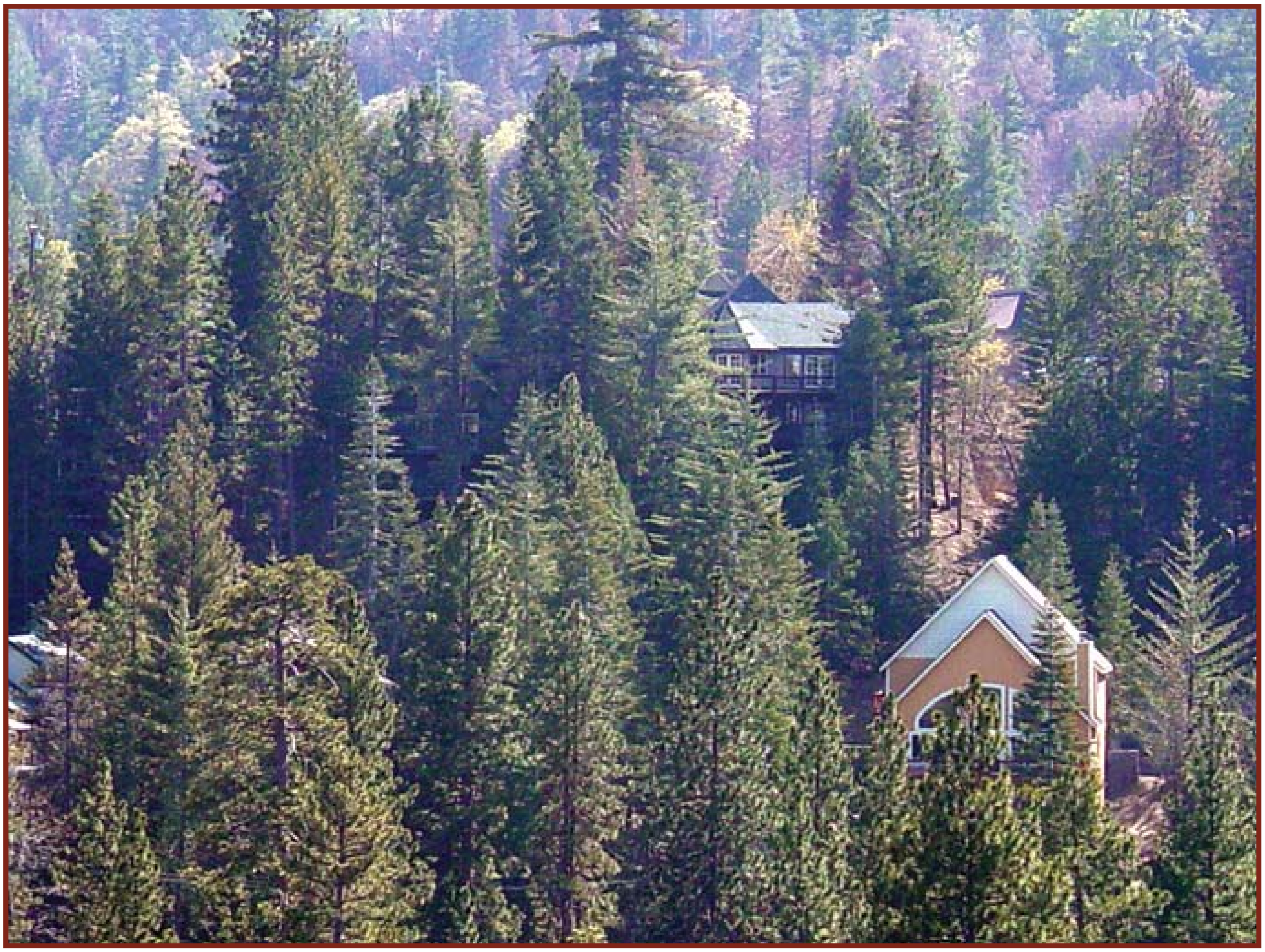

Figure 29. Typical conditions with high density fuel on steep slopes with intermingled homes. Look closely behind the trees to see more homes.

Fuel Treatments on Private Lands

The reduction of large diameter dead trees from urban lots did little to reduce fire behavior once homes ignited. Many homes within the fire perimeter were less than fifty feet apart. Homes were built on steep slopes, many were 3 storied with multiple levels of wooden decks (Figure 29).

Fire Suppression Effectiveness, Structure Ignitions, and Public Safety/Egress

USFS Tunnel 2 Fuel Treatment

The effectiveness of initial attack on the Grass Valley Fire was improved by the Tunnel 2 fuel treatment area. When the fire moved into that treated area, the fire behavior shifted to a low intensity surface fire. Surface fire and low flame lengths, two feet or less, were observed by the Operations Section Chief. This allowed firefighting resources to concentrate on the protection of structures and secure a control line on the east flank of the fire.

Firebrands, lofted by an area of crown fire activity, resulted in many spot fires from south of the fuel treatment boundary. The spot fires were contained by rapid suppression actions. Slower fire spread in the treatment area allowed more time for public evacuations.

The location of the Tunnel 2 treatment area reduced fire behavior as the fire spread south-southwest, allowing suppression forces time and safety to contain spot fires before they were able to spread throughout the homes southwest of Fairway Drive.

Fuel Treatments on Private Lands

These areas received substantial spotting and direct surface fire when the fire came out of the Grass Valley Creek drainage. Private land treatments added to the effect of the Tunnel 2 fuel treatment area in slowing the fire spread and intensity and allowing suppression resources to focus attention elsewhere of higher priority.

Fire personnel noted that visibility was improved where trees and brush had been removed. Improved visibility enabled firefighters to observe the fire location and intensity in relation to egress and values at risk. The treatments allowed fire fighters to enter residential areas that otherwise would have been avoided due to safety concerns. Treatments also reduced fire intensity and spread rate allowing fire fighters to more rapidly suppress ignitions.

Significantly fewer trees fell on roadways and powerlines because of the fuel treatments which had removed hazard trees before the Grass Valley Fire. Reduced treefall enabled rapid safe public evacuations and firefighter access. The Southern California Edison dead tree removal program was specifically credited by firefighters with improving access for fire suppression forces, especially those that arrived later in the day.

Summary

The Grass Valley fire spread to the south, driven by strong winds aligned with the canyon in extremely dry untreated wildland fuels that crowned and spotted until it transitioned to urban structure fuels.

Fire spread rates through area wildland fuel treatments on private and Forest Service was comparatively slower than on untreated lands. Greater density of trees on steeper south facing slopes had stand replacement fire behavior. Structure fires, driven by winds aligned with the streets, spread more rapidly than adjacent wildland fuels, producing mass ember spotting and intensity that ignited other structures.

People throughout the area were evacuated more safely due to previous dead tree removal coordinated by MAST. Fire spread was slower through wildland fuels that had been treated on Forest Service lands. Suppression actions contained spread to the east and by the end of the first day had essentially stopped further southerly spread. Due to the low fire intensity in the wildland fuels that had been treated to the west, fire spread was stopped with just a dozer line connecting roads on the western flank of the treated area.

Fire spread was less intense in the Tunnel 2 fuel treatment area allowing suppression forces to concentrate on controlling the spread of fire in urban areas.

Three factors contributed most to treatment effectiveness:

1. Placement and prioritization was based on an integrated landscape look at hazardous fuels and terrain, fire weather and history, access, egress, and communities at risk.
2. Effective treatments were planned and implemented on specific fire behavior objectives.
3. Treatments along roads, power lines, and urban areas all contributed to enhancing suppression actions and enabling safe evacuation of the public.

Older homes in the Lake Arrowhead area are constructed of flammable materials including wood shake roofs. Dense vegetation often surrounds many of these older homes. These structures are not only at risk from wildfire, but are at risk for house-to-house ignition. Where trees and shrubs were removed prior to the fire, suppression forces were able to engage the fire and protect homes. In some places where vegetation had not been removed, suppression forces were unable to safely engage the fire or protect structures.

Southern California Edison had done work along its power lines to remove dead trees and top live trees to keep them away from the lines. This had two benefits during the Grass Valley Fire. First, the removal and trimming lowered the probability of tree damage to the lines which could have blocked or slowed evacuations. Second, the power service remained on to the community through the incident.

Recent collaborative fuel treatments reduced fire behavior, specifically rate of spread and intensity, allowing residents to evacuate and firefighters to enter the initial attack area. Other fuel treatment areas encountered by the fire allowed fire fighters to concentrate on perimeter containment and structure protection.

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Carlos Chavez, Los Angeles Times

Brett Snow, San Bernardino Sun

Eric Reed, San Bernardino Sun

USFS Pacific Southwest Region

Bernard Bahro

Hugh Safford

Jerry McGowan

Mario Chocooj

USFS Adaptive Management Services Enterprise Team

Dave Kerr

Scott Dailey

San Bernardino County Fire Department

George Corley

Peter Brierty

Scott Turknette

Daniel Elliot

Others

Northern California Team 2

Dr. Jack Cohen
USFS Rocky Mountain Research Station

Brett Fay
USFS Intermountain Region

Tom Iraci
USFS Pacific Northwest Region

Rick Stratton
Systems for Environmental Management

Glenn Barley
Cal Fire-Forest Care

Jim Williamson
Local resident

Ron Bench
Local resident

Ginny Jablonski
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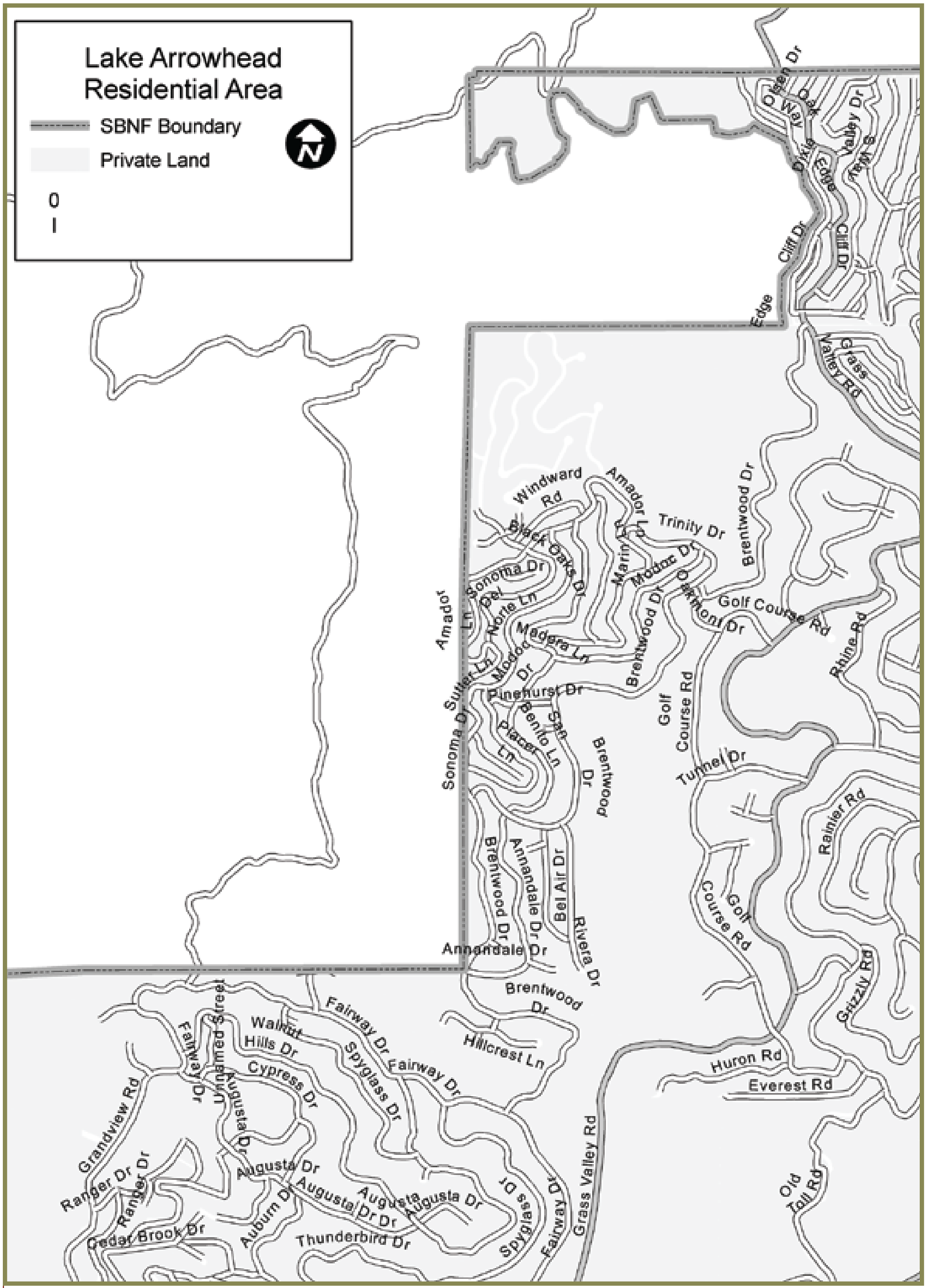
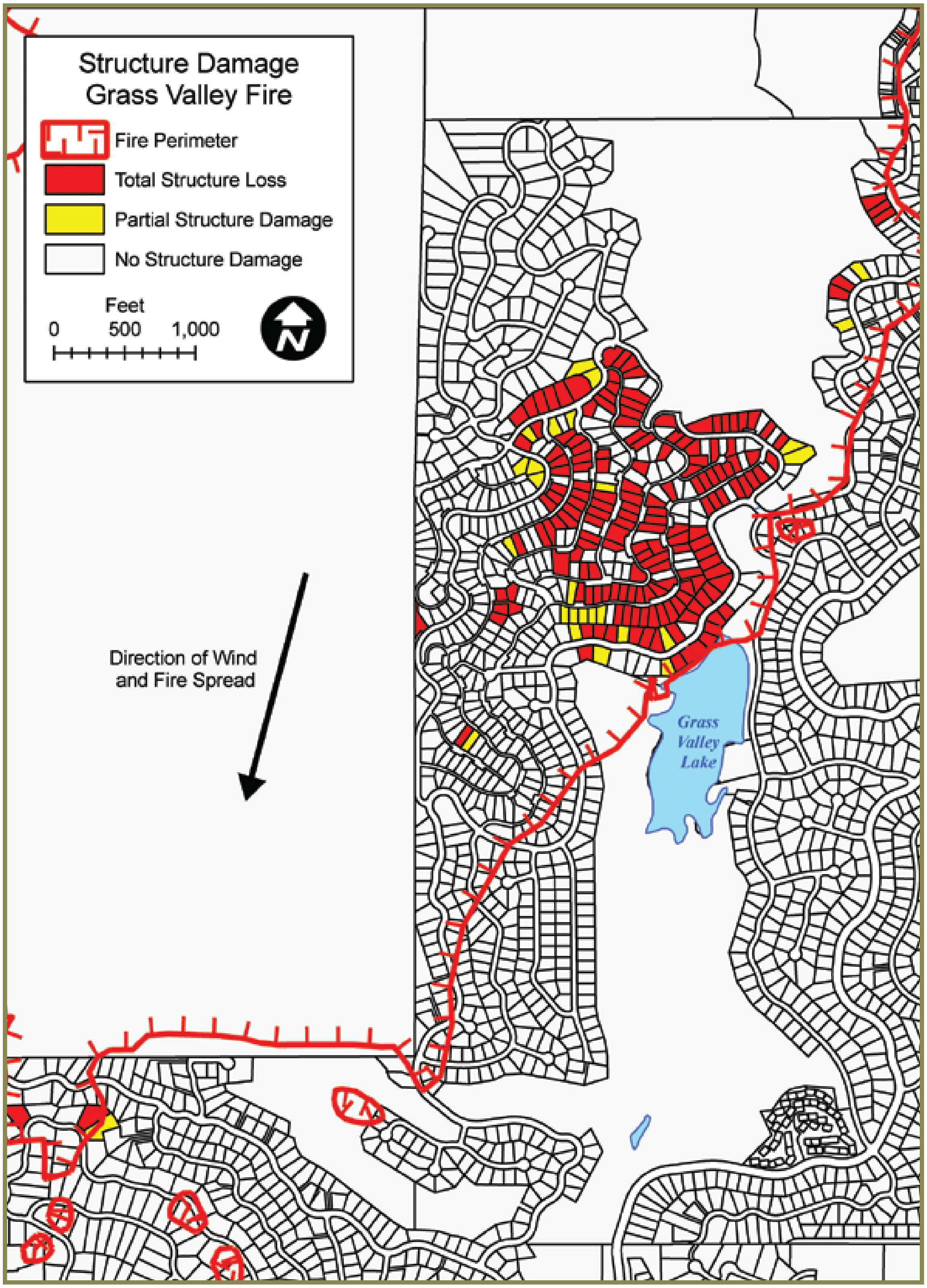
Appendix A: Maps

Lake Arrowhead Residential Area



Structure Damage Grass Valley Fire



Appendix B: Fire Weather/Fire Danger

Wind and Gust Speeds and Direction

	October 22nd			October 23rd		
Time	Average Wind Speed MPH	Gust Speed MPH	Direction Degrees	Average Wind Speed MPH	Gust Speed MPH	Direction Degrees
1:00 AM	16	33	15	10	23	336
2:00 AM	18	33	7	9	19	336
3:00 AM	16	32	14	11	21	357
4:00 AM	16	31	12	9	19	351
5:00 AM	18	27	8	11	19	5
6:00 AM	18	29	13	13	20	9
7:00 AM	16	29	13	11	21	8
8:00 AM	16	29	7	12	20	352
9:00 AM	18	30	2	10	22	342
10:00 AM	17	29	10	13	23	351
11:00 AM	14	34	341	12	23	330
12:00 AM	12	28	345	12	24	343
01:00 PM	13	26	342	12	24	1
02:00 PM	15	27	331	12	24	348
03:00 PM	13	32	336	12	21	331
04:00 PM	12	24	318	9	21	338
05:00 PM	10	19	352	7	18	325
06:00 PM	11	24	12	3	12	327
07:00 PM	10	20	3	4	11	3
08:00 PM	13	22	3	5	9	350
09:00 PM	14	24	349	5	8	50
10:00 PM	12	25	0	7	13	327
11:00 PM	11	20	4	3	8	192
12:00 PM	9	20	7	5	9	189

Appendix C: Forest Service Fuel Treatment Prescriptions

Fuels Reduction Treatment Level Guidelines and Desired Condition

Arrowhead and Big Bear Ranger Districts, San Bernardino National Forest

Treatment Level 1

This treatment level was applied adjacent to urban development and on roads/ridges at a width of approximately 100 feet.

Fuels Reduction Objective:

- ◊ Four foot or less flame length under 90th percentile weather conditions.

Desired Condition:

- ◊ Twenty foot spacing between crowns of individual or clumps of trees.
- ◊ Canopy base height averages 15 feet or greater.
- ◊ Twenty percent or less shrub canopy cover.
- ◊ All recent dead standing and down trees are removed.
- ◊ Litter and fine fuel loading less than 1-3 tons per acre.

Treatment Level 2

This treatment level was applied adjacent to level one treatments at a width of approximately 200 feet.

Fuels Reduction Objective:

- ◊ Eight foot or less flame length under 90th percentile weather conditions.

Desired Condition:

- ◊ Ten to twenty foot spacing between crowns of individual or clumps of trees.
- ◊ Canopy base height averages 10 feet or greater.
- ◊ Thirty five percent or less shrub canopy cover.
- ◊ All recent dead standing and down trees are removed within 100 feet of level 1 areas. All recent dead standing and down trees are removed beyond 100 feet of level 1 areas except those needed to minimally meet Forest Plan Standard for snags and down logs.
- ◊ Litter and fine fuel loading less than 3-5 tons per acre.

Spotted Owl Protected Activity Center Treatment Level

This treatment level was applied in this Spotted Owl Protected Activity Center, which was within the Tunnel 2 fuelbreak

- ◊ Remove all standing dead.
- ◊ Remove trees less than 10” DBH that provide ladder to the overstory canopy.
- ◊ Leave all live trees greater than 10” DBH
- ◊ Prune all remaining trees to approximately 8’ above the ground
- ◊ Pile and burn slash from activity fuels
- ◊ Desired condition for litter and fine fuel loading is 5-7 tons/acre

The Effects of Forest Fuel-Reduction Treatments in the United States

SCOTT L. STEPHENS, JAMES D. McIVER, RALPH E. J. BOERNER, CHRISTOPHER J. FETTIG, JOSEPH B. FONTAINE, BRUCE R. HARTSOUGH, PATRICIA L. KENNEDY, AND DYLAN W. SCHWILK

The current conditions of many seasonally dry forests in the western and southern United States, especially those that once experienced low- to moderate-intensity fire regimes, leave them uncharacteristically susceptible to high-severity wildfire. Both prescribed fire and its mechanical surrogates are generally successful in meeting short-term fuel-reduction objectives such that treated stands are more resilient to high-intensity wildfire. Most available evidence suggests that these objectives are typically accomplished with few unintended consequences, since most ecosystem components (vegetation, soils, wildlife, bark beetles, carbon sequestration) exhibit very subtle effects or no measurable effects at all. Although mechanical treatments do not serve as complete surrogates for fire, their application can help mitigate costs and liability in some areas. Desired treatment effects on fire hazards are transient, which indicates that after fuel-reduction management starts, managers need to be persistent with repeated treatment, especially in the faster-growing forests in the southern United States.

Keywords: fire surrogates, wildfire, fire ecology, forest management, forest conservation

For several millennia, frequent, low- to moderate-intensity wildfire has sculpted seasonally dry forests in the southern, eastern, and western United States. Low- to moderate-intensity fires reduced the quantity and continuity of fuels and discouraged the establishment of fire-intolerant species (Agee and Skinner 2005). Yet fire suppression, the preferential harvest of large-diameter trees, and land conversion over the past 150 years have changed fuel conditions over millions of hectares (ha) of forests (Stephens and Ruth 2005) such that recent wildfires have tended to be larger and more severe, and this trend may continue in some forests as climates continue to warm (McKenzie et al. 2004). Given this scenario, it is easy to see why tools such as prescribed-fire and *mechanical* (i.e., manual removal; e.g., thinning) fuel treatments are increasingly used by managers in an effort to change the only factors in the fire behavior formula they can: the quantity and continuity of fuel.

There is increased recognition that most low- to moderate-intensity fire regimes in US forests included some patchy high-severity fire (Hessburg et al. 2007, Beaty and Taylor 2008, Perry et al. 2011). Fire is an inherently complex landscape process, both within individual fires and among multiple fires over time. This complexity is driven by heterogeneity in vegetation and fuel, topography, and local weather for individual fires and by variability in the timing, effects, and extents of multiple fires (Collins and Stephens 2010). Patchy, high-severity fire provides opportunities for early seral habitat development and the production of deadwood resources from tree mortality that are important to many wildlife species (Hutto 2008, Kennedy and Fontaine 2009). As such, forest fuel treatments should not attempt to eliminate all high-severity fire, but most patches should be relatively small, as is the case in upper mixed-conifer forests in the Sierra Nevada, where the median high-severity patch size was approximately 2 ha (Collins and Stephens 2010). Current wildfire high-severity patch sizes and areas in many forests that once burned frequently with low- to moderate-intensity fire regimes are well outside historical conditions and this may increase as climates continue to warm (Miller et al. 2009).

As a fuel-reduction practice, prescribed fire (figure 1) is an attractive alternative to large, high-intensity wildfires, because it is thought to best emulate the natural process that it is designed to replace (Schwilk et al. 2009). However, forest managers have been so substantially constrained by social, economic, and administrative issues that prescribed-fire use is low, especially in the western United States. Therefore, fuel-reduction surrogates, such as forest thinning and mastication (figure 1), have become more attractive, especially when forest managers can use such treatments to accomplish

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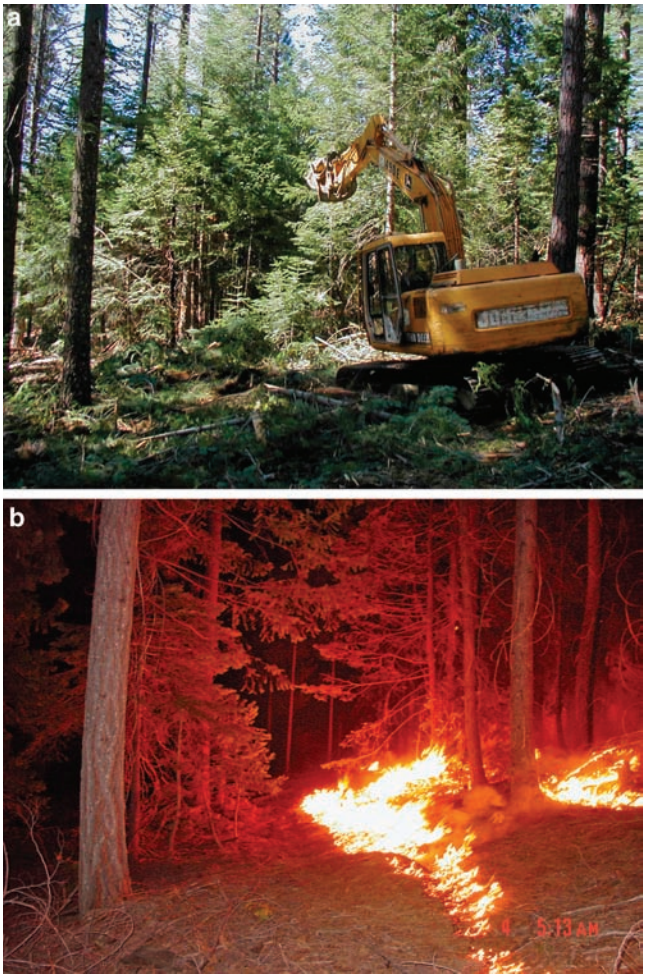

Figure 1. Examples of fire and fire-surrogate treatments applied in order to reduce fire hazards in mixed-conifer forests in the central Sierra Nevada, California. (a) Mechanical fuel treatment using a rotary masticator mounted on an excavator. (b) Prescribed fire at night. Photographs: Jason Moghaddas.

stand-structure goals similar to those obtained by prescribed fire. Until recently, however, we knew little about the possible unintended consequences that might arise from widespread application of fire-surrogate treatments in seasonally dry forests.

The principle question addressed in this article is misleadingly simple: What components or processes are changed or lost, and with what effects, if fire surrogates such as cuttings and mechanical fuel treatments are used instead of fire or in combination with fire? To answer this challenging question, in this article, we summarize diverse research (including the national Fire and Fire Surrogate [FFS] Study and the broader literature) related to fuel treatments from multiple perspectives, including fuels and potential fire behavior, vegetation, soils, wildlife, bark beetles, carbon sequestration, and costs and utilization. This information is targeted toward scientists, policymakers, and managers of forests that were once dominated by frequent, low- to moderate-intensity fire regimes.

Fuels, fire behavior, and wildfire surrogates

A brief introduction of wildland fuels and their characteristics is necessary to understand the factors and processes important to achieving reductions in wildfire severity through the application of fuel-reduction treatments (Stephens and Ruth 2005). Wildland fuels can be classified into four groups: ground, surface, ladder, and crown; each of these has a different potential to influence fire behavior. *Ground fuels* include the duff (the O_i soil horizon) on the soil surface and generally do not contribute to wildfire spread or intensity. *Surface fuels* include all dead and down woody materials, litter, grasses, other herbaceous plant materials, and short shrubs, which are often the most hazardous fuels in many forests. This is particularly true in seasonally dry forests, where vegetative species composition, density, and structure have been influenced by decades of fire suppression and harvesting (Fulé et al. 2001, Agee and Skinner 2005). *Ladder fuels* are small trees or tall shrubs that provide vertical continuity from surface fuels to the crowns of tall trees and are generally the second-most-hazardous fuel component. *Crown fuels* are those in the overstory and are a small component of fire hazards in these forests (Stephens et al. 2009).

The potential for *passive crown fires* (initiated by the torching of a small group of trees) is reduced most efficiently by the reduction of surface fuels followed by a reduction of ladder fuels. Reducing surface fuels by prescribed fire is a very effective treatment for reducing the potential for passive crown fires. The potential for *active crown fires* (fire spreading in crown and surface fuels simultaneously) is reduced most effectively by a combination of mechanical and prescribed-fire treatments, because these treatments can target ladder and surface fuels and intermediate-size trees. However, prescribed fire alone can greatly increase the wind speed needed to initiate a passive crown fire, which effectively reduces stand vulnerability to torching and the transition to active crown fire (Stephens et al. 2009). This result is not only supported by modeling of fire behavior but by empirical studies of wildfires burning through treated stands (Ritchie et al. 2007).

The results of mechanical treatments alone are mixed regarding their ability to reduce potential fire severity (Agee and Skinner 2005, Stephens et al. 2009). In this regard, whole-tree-removal systems are one of the most effective mechanical systems and may be preferred where wood-chip or biomass markets are available. Where trees are too small (less than 20 centimeters [cm] in diameter) for sawn products and cannot be economically chipped and transported to a processing facility, subsidizing treatment or hauling costs should be considered if the corresponding decrease in fire hazard warrants the additional expenditure. Whole-tree-removal systems are also advantageous when forest managers plan to apply prescribed burns after harvesting, because this creates minimal logging debris, and therefore, only surface fuels existing prior to treatment need to be consumed.

An important difference between prescribed-fire treatments and combined mechanical and prescribed-fire treatments is the amount of residual dead material left standing after treatment, which is higher after prescribed-fire treatments (Stephens et al. 2009). This material, killed by the fire, will eventually fall to the ground and can exacerbate fire effects when the site burns again. Although the addition of this woody material may increase wildlife habitat value or may stabilize erosive soils, it will increase future surface-fuel loads and shorten the longevity of the fuel treatment. We expect that several fire-only treatments (two or three during a 10–20-year period) would be needed to achieve the management objective of reducing potential fire behavior and effects in the forests studied.

In many forest ecosystems, logistical constraints restrict fire prescriptions to cooler and milder conditions than those under which wildfires historically occurred (Fulé et al. 2004). Burning in the spring results in the fewest significant changes to stand and fuel structures, and spring burning results in greater retention of large woody debris, which could be desirable in some cases, including the retention of microhabitat features required by many wildlife species (Knapp et al. 2009, Fettig et al. 2010). Our analysis supports the assertion that a lack of treatment or passive management (Stephens and Ruth 2005) perpetuates the potential for extensive high fire severity in forests that once burned frequently with low- to moderate-intensity fire regimes. Retaining larger dominant and codominant trees in the residual stands also increases a forest's resistance to fire (Agee and Skinner 2005). Conversely, thinning from above, or overstory removal of dominant and codominant trees, decreases fire resistance (Stephens and Moghaddas 2005).

The net treatment costs and reduction in fire risk are critical considerations when determining the feasibility of any fuel treatment (Hartsough et al. 2008). The effectiveness of mechanical thinning for reducing passive and active crown fire potential is largely dependent on the type of harvest system used—particularly, whether the harvest system leaves logging debris within treated stands. Creating forest structures that can reduce fire severity at the landscape level may decrease the need for an aggressive suppression response and could eventually reduce the costs of fire suppression.

Vegetation

One of the primary concerns with prescribed fire as a management tool is its application outside of the historical fire season (Knapp et al. 2009). It is reasonable to assume that the seasonality of fire might interact with vegetative species' phenologies, but experimental results have been mixed. Early-growing-season burns occur at the beginning of the annual growth period, when plants are most susceptible to heat damage and when carbohydrate reserves are at their lowest levels. Burns implemented during the growing season may result in greater tree mortality than those implemented during the dormant season and may also cause greater damage to fine roots, particularly in old growth stands of ponderosa pine (*Pinus ponderosa*; Swezy and Agee 1991). Conversely, late-growing-season or dormant-season prescribed fires are likely to be of greater intensity and to entail greater fuel consumption and have been reported by some authors to result in greater amounts of tree mortality than early-season prescribed fires (e.g., Thies et al. 2005). Comparing early- and late-season prescribed fires, Schwilk and colleagues (2006) reported that the levels of tree mortality were related to fire intensity rather than to seasonality and tree phenology in California mixed-conifer forests. In eastern hardwood and southeastern pine forests, growing-season fires were the historical norm, but dormant-season burns have been used successfully (Glitzenstein et al. 1995, Brose and Van Lear 1998).

Mechanical fuel treatments can be successful surrogates for fire in modifying forest structure but are variable in their effects on understory plant communities because of large differences among treatments and the variation in understory vegetation composition and productivity among forest types. Although most studies of mechanical fuel treatments have been focused on their efficacy for reducing crown-fire hazard, in several recent investigations, the impacts of such treatments on plant communities have been measured (e.g., the FFS Study; Schwilk et al. 2009).

The mechanical fuel treatments implemented as part of the FFS Study proved more variable in their effects on understory vegetation than on stand structure (Schwilk et al. 2009). Mechanical treatments can vary widely, but there are several general ways in which mechanical fuel treatments may not act as surrogates for fire. Such treatments may disturb or add to organic material on the forest floor and may lack the heat required to kill fire-sensitive tree and shrub species or to cue seed germination in some fire-dependent species. Harvesting equipment may result in damage to nontarget species. However, mechanical fuel treatments, like fire, open the canopy and provide increased light to the understory and decreased competition among overstory trees. Therefore, a general pattern observed following mechanical fuel treatments is an increase in understory production and diversity similar to that seen following low- to moderate-intensity fire (Bartuszevige and Kennedy 2009).

Increases in understory vegetation richness tend to be greatest in closed-canopy forests that have the lowest understory component prior to treatment. In more open forests, the effects on understory species composition may take years to emerge, even when understory production increases rapidly following treatment (Laughlin et al. 2004). Both prescribed-fire and mechanical fuel treatments can increase the abundance of exotic species, and this increase is generally greatest with combined mechanical and prescribed-fire treatments (e.g., Bartuszevige and Kennedy 2009, Schwilk et al. 2009). Tree seedling recruitment is particularly sensitive to variation in mechanical treatment techniques, potentially as a result of variation in soil disturbance, compaction, and the amount of bare soil exposure (Schwilk et al. 2009), or this sensitivity to treatment may represent large, natural interannual variation in recruitment (League and Veblen 2006). Mechanical fuel treatments alone fail to mimic fire in systems containing species with fire-cued recruitment. This failure, combined with the increase in surface woody material common to many mechanical treatments, may explain a lack of shrub recruitment following mechanical treatments (e.g., Perchemlides et al. 2008). Across ecosystems in which such treatments are most commonly used (i.e., forests that historically experienced low- to moderate-intensity fire regimes), fire-surrogate treatments have not been shown to produce dramatic negative impacts on plant communities (table 1). There has been increased interest, however, in the application of both prescribed-fire and mechanical fuel treatments in communities that historically experienced infrequent crown fire, such as subalpine forests or shrublands. In these crown-fire systems, the lessons learned concerning vegetative responses from other forest types may be misleading (Schoennagel et al. 2004). Fire treatments have been successfully used in Florida scrub communities that contain fire-dependent species (Menges et al. 2006), but in shrub communities with many species sensitive to immaturity risk, frequent fire or mechanical disturbance can result in ecosystem degradation and local extirpation (Keeley 2002).

Soil properties

The literature indicates that the FFS Study is the most comprehensive study conducted on the effects of fuels treatments on soils, and we therefore rely most heavily on that study in this synthesis. The soils underlying the 12-site FFS Study network were very diverse and included six soil orders and more than 50 named soil series. Across their network, pretreatment soils varied in pH from less than 4 to more than 7 and exhibited ranges of 2 times in bulk density, 4 times in soil organic carbon content, 10 times in total inorganic nitrogen, and 200–1000 times in extractable base cations, such as calcium and potassium (Boerner et al. 2009).

Fuel-reduction treatments that include prescribed fire, alone or in combination with mechanical treatments, generally result in short-term losses of forest-floor organic layers, resulting in greater mineral soil exposure (figure 2; Boerner et al. 2009). Although considerable mineral soil exposure may be observed in skid trails and other areas of intensive vehicle activity during mechanical treatments, such treatments typically had an impact on less than 2% of the forest floor, and therefore had little effect on soil exposure. In the FFS Study, increases in mineral soil exposure persisted through later years (to the second or fourth year, depending on the site) only after the prescribed-fire-only treatment.

Soil bulk density (as a measure of soil compaction) was not affected significantly by any of the fuel-reduction treatments at the FFS Study–network scale, a result that is consistent with other studies (e.g., Moehring et al. 1966). Stand-replacing wildfires can result in considerable erosion because of processes that result from mineral soil exposure and, in some ecosystems, the development of hydrophobicity (e.g., overland flow, slope failure), and such impacts may be exacerbated by logging (Ice et al. 2004). However, the effects on soil physical properties regarding fire severity and harvest levels that characterize typical fuel-reduction treatments are relatively modest, and therefore, the potential for significant erosion or other hydrological impacts is small.

There was considerable within- and among-site variability in soil pH both before and after treatment in the FFS Study. Despite this variability, at the network scale, soil pH was significantly higher in soils of the combined mechanical and fire treatment than in untreated control soils during the first posttreatment year but not during the later sampling year (figure 2). Neither prescribed fire alone nor the mechanical treatment alone had a significant effect on soil pH at the FFS Study–network scale during either sampling year (figure 2). Within- and among-site variability in extractable base cation content was even more variable than was soil pH, with the result that there were no significant network-scale effects of the manipulative treatments on either extractable calcium or extractable potassium (Boerner et al. 2009).

Table 1. Prescribed-fire and mechanical fuel treatment use across several US forest types.

		Risks of prescribed fire		Risk of mechanical treatments		
Forest type	**Management goals**	**Overstory**	**Understory**	**Overstory**	**Understory**	**Seasonality risk**
Mixed-conifer forest	Restoration or hazard reduction	Low	Low	Low	Medium (exotic species)	Low
Ponderosa pine forest	Restoration or hazard reduction	Low	Low	Low	Low or medium (exotic species)	Low
Subalpine forests and boreal forests	Hazard reduction	Medium	Medium	High	Medium	Medium
Southeastern pine forests or savannas	Restoration or hazard reduction	Low	Low	Low	Low	Low or medium
Eastern deciduous hardwood forest	Restoration	Low	Low	Low	Low	Low

Note: The "Seasonality risk" column indicates the estimated risk of treatments outside of the historical fire season.

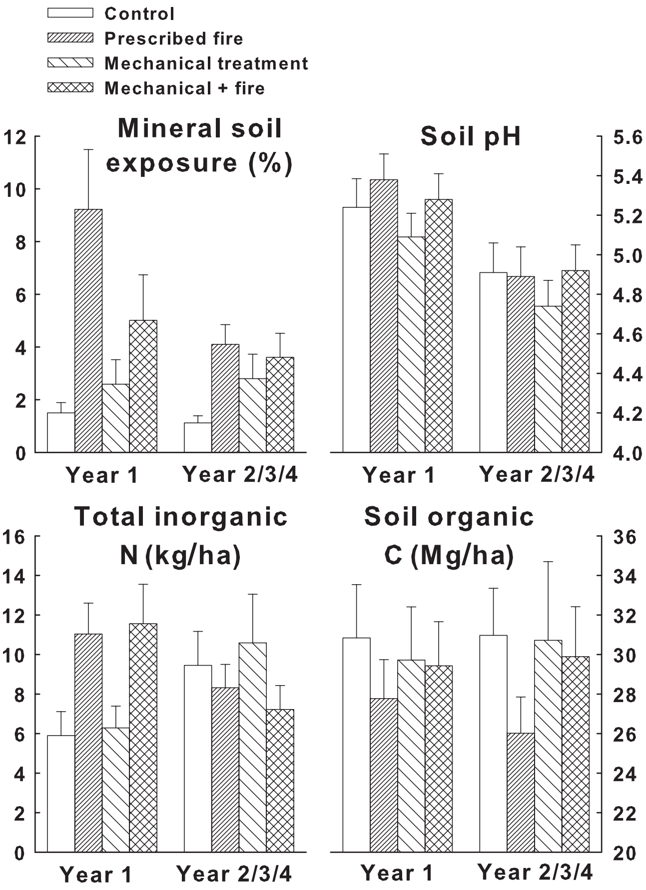

Figure 2. Trends for mineral soil exposure, pH, inorganic nitrogen (N), and organic carbon (C), in response to fire and fire-surrogate treatments measured across a national network of 12 research sites in the United States (part of the national Fire and Fire Surrogates Study). These four variables were selected to represent some of the most important in characterizing soil treatment effects. The values presented are means, and the error bars represent the positive standard error of the mean. Abbreviations: ha, hectares; kg, kilograms; Mg, megagrams.

At the FFS Study–network scale, total inorganic nitrogen increased significantly during the first posttreatment year after all manipulative treatments, but this effect did not persist to the later sampling year (figure 2). Once again, this result is consistent with those of previous studies demonstrating that the increases in dissolved, inorganic nitrogen commonly observed after fire are short lived (Covington et al. 1991, Covington and Sackett 1992). Soil organic carbon content was not significantly affected by any of the treatments during the first posttreatment year and was only marginally reduced by prescribed fire alone during the later sampling year (figure 2; Boerner et al. 2009). Johnson and Curtis (2001) evaluated the effects of various disturbance modes, including fire and logging, on soil carbon, and concluded that the impact of prescribed fire on soil carbon was typically small, whereas Eivazi and Bayan (1996) concluded that no net increase in total soil carbon resulted from more than 40 years of prescribed fire in an oak forest in Missouri. Similarly, neither FFS Study–network scale nor individual-site total soil carbon was affected significantly by any of the manipulative treatments in either sampling year (Boerner et al. 2008a). Overall, the network-wide effects of the FFS Study treatments on soil properties appear to have been modest and transient. Given the scale of the FFS Study and the results from previous research, we expect similar minimal effects on soils properties when areas are treated with fire or mechanical fuel treatments in forests that historically experienced frequent, low- to moderate-intensity fire regimes.

Wildlife

In addition to its use in managing wildfire hazards, the application of prescribed-fire and fire-surrogate treatments is frequently motivated by wildlife–habitat objectives (Yager et al. 2007, Kennedy and Fontaine 2009, Roberts et al. 2010). Research on fire and its effects on terrestrial vertebrates (wildlife) has been conducted since the early 1900s, beginning with research showing the negative effects of fire exclusion in longleaf pine (*Pinus palustris*) forests on northern bobwhite (*Colinus virginianus*; Stoddard 1931). Since then, a large body of work has been developed, particularly in the last 10–15 years (Kennedy and Fontaine 2009), which has shown that many wildlife species depend on fire-maintained habitats or pyrogenic structures, such as the snags, shrubs, and bare ground created by fires of varying severity (Hutto 2008).

Increased applications of fuel-reduction treatments, public scrutiny of land management agencies, and a growing scientific literature on the topic motivated a recent comprehensive review and meta-analysis of the fire–wildlife literature from forests dominated by low- to moderate-intensity fire regimes (Kennedy and Fontaine 2009, Fontaine and Kennedy 2012). On the basis of the characteristics of the available literature, fuel-reduction treatments and high-severity fire were considered at 0–4 years posttreatment. A lack of published longer-term (more than 5 years) studies precluded any analyses of longer-term effects. Importantly, the only thinning treatments included in this analysis were those conducted for fuel reduction, which is generally a lower-intensity treatment (e.g., the median reduction in basal area for the FFS Study was 30%; Schwilk et al. 2009) than those implemented for other silvicultural objectives (see Vanderwel et al. 2007 for a detailed meta-analysis of avian responses to a broader range of thinning intensities). The data from low- and moderate-severity fires were pooled, because neither of these treatments resulted in a large canopy loss (less than 50% canopy mortality, less than 25% in almost all cases), and there are insufficient studies of mixed-severity fire to warrant separation. These categories allowed for a comparison of vertebrate responses (mean abundance, density, and vital rate in treated and reference conditions) to fire surrogates combined with fire, as well as differing levels of fire severity (measured by overstory tree mortality). Data were more abundant for birds than for any other taxon

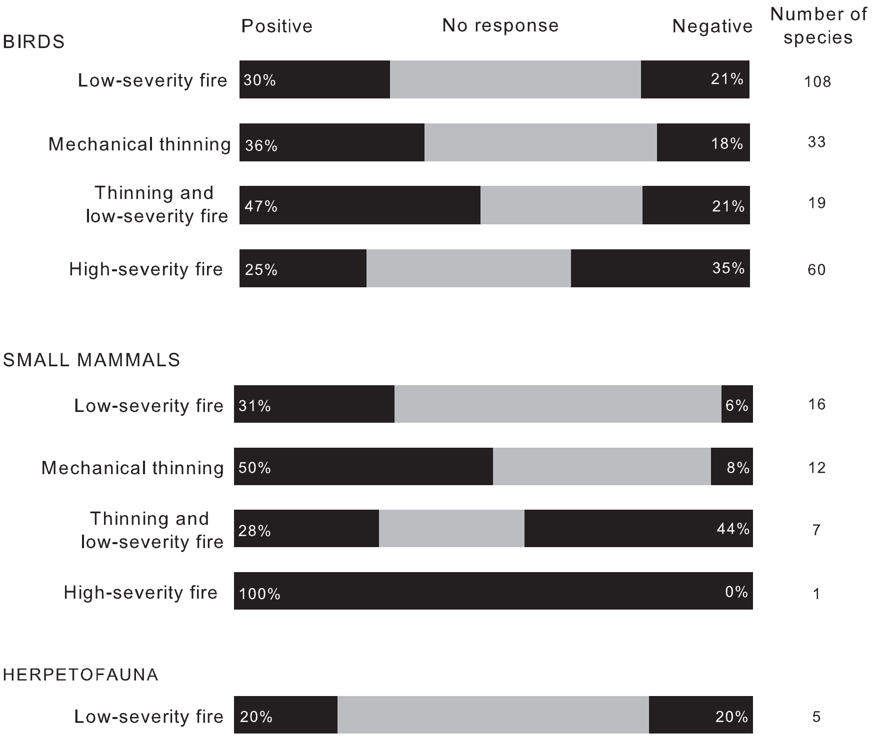

Figure 3. The responses (positive, neutral, and negative; number of species with sufficient data) of birds, small mammals, and herpetofauna to fire and fire-surrogate treatments 0–4 years after fire treatment in seasonally dry forests of the United States. The response classification was based on a meta-analysis of the existing literature and the generation of cumulative effect-size estimates and their 95% confidence intervals with overlap (neutral) or not (positive, negative) with zero.

(figure 3), which underscores a need for further work on other wildlife taxa—particularly herpetofauna, which reside primarily on the forest floor.

One of the most interesting results was the similarity in the pattern of responses between thinning and low- to moderate-severity prescribed fire (figure 3). Across all species of birds, the proportions of species with negative, neutral, and positive effects were quite similar. Thirty percent to 36% of the birds responded positively to low-severity fire and mechanical thinning, with smaller negative responses of 21% and 18%, respectively (figure 3). The sample of small mammals was smaller but with similar response patterns for low-severity fire and an increased positive response for mechanical thinning, probably reflecting some species' negative response to consumption of the litter layer. Combined mechanical thinning and low-severity fire led to an increased positive response in birds (47%) but a decrease in small mammals (28%; figure 3). When responses of the same species were compared between mechanical thinning and low-severity fire (reported in Fontaine and Kennedy 2012), 42% of the birds ($n = 31$) and 54% of the small mammals ($n = 13$) showed no change in response. A comparison of fire severity suggested clear differences among treatments for birds (decreased neutral response to high-severity fire; figure 3). Data for only five species of herpetofauna (four amphibians and one turtle) were available for the low-severity fire treatment, and most species did not respond to the treatment.

This similarity in the responses of birds and small mammals to thinning and low-severity prescribed fire suggests that, at the stand scale and in the short term (0–4 years), thinning may adequately mimic low-severity fire in terms of its effects on these taxa. The levels of regeneration of vegetation, fuel dynamics, and nutrient cycling following prescribed fire and following thinning differed substantially (Boerner et al. 2009, Schwilk et al. 2009), but thinning or low-severity prescribed fire have the potential, in the short term, to create forests with similar structure and with habitat conditions favored by many wildlife species. Therefore, the results suggest that the use of thinning in lieu of prescribed fire may be warranted for birds and small mammals, particularly in areas in which the implementation of prescribed fire is problematic. However, the long-term effects of these two treatments on wildlife require further investigation before these results can be fully integrated into management.

Research illustrates that these fuel treatments do not create conditions suitable for all species (see the negative responses in figure 3). Additional analyses demonstrate that low- to moderate-severity surface fire (and presumably its thinning surrogate) does not mimic the early successional habitat conditions created by high-intensity, patchy, stand-replacing fires. When it is feasible, managers may aim for patchy high-intensity prescribed fire to mimic the effects of wildfire (Fulé et al. 2004). In short, there is no one-size-fits-all prescription when it comes to incorporating disturbances into land management (i.e., there is a need for the presence of all successional stages within a forested landscape in order to maximize wildlife diversity; Fontaine et al. 2009).

Bark beetles

Bark beetles are recognized as important tree-mortality agents in the coniferous forests of the southern and western United States. Fuel-reduction treatments may influence the amount and distribution of bark-beetle-caused tree mortality at various spatial and temporal scales (e.g., Fettig and McKelvey 2010, Fettig et al. 2010). For example, these treatments may affect the health and vigor of residual trees; the size, distribution, and abundance of preferred hosts;

and the physical environment within forest stands (Fettig et al. 2007). Carelessly implemented treatments may result in physical damage to residual trees, soil compaction, and increased rates of windthrow, which would increase the likelihood of tree colonization by bark beetles, other subcortical insects, and root pathogens. Furthermore, tree volatiles released during harvest operations and the application of prescribed fire are known to influence the physiology and behavior of bark beetles and the colonization rates of trees by bark beetles (Fettig et al. 2006).

The levels of tree mortality following prescribed fire depend on numerous factors, including tree species; tree size; phenology; the degree of fire-caused injuries; initial and postfire levels of tree vigor; the postfire environment; and the frequency and severity of other predisposing, inciting, and contributing factors (Fettig and McKelvey 2010). Bark beetles may attack and kill trees that were injured by fire but that would otherwise have survived. These trees may then serve as a source of beetles and attractive semiochemicals (i.e., host volatiles and aggregation pheromones produced by many bark beetle species during host colonization) that attract other beetles into the area, which would result in higher levels of tree mortality. The propensity for many species of bark beetles to attack fire-injured trees—particularly in the western United States—has stimulated much research on the effects of fire surrogates on the amount and distribution of bark-beetle-caused tree mortality. In most studies, short-term increases have been reported in bark-beetle-caused tree mortality. However, the rates of tree mortality are generally low (less than 5% of trees) and are concentrated in smaller-diameter trees for most bark beetle species (figure 4). However, there are important exceptions, such as when delayed mortality occurs in the larger-diameter classes (Fettig and McKelvey 2010). In the longer term, thinning has been shown to reduce stand susceptibility to bark beetle attack in many seasonally dry forests (Fettig et al. 2007).

A common management concern is that fire-injured trees may serve as breeding substrates for bark beetles, which later attack adjacent trees at elevated levels, but this has not been well documented. Large numbers of severely stressed trees could provide abundant host material, and once this resource has been exhausted (e.g., within 1–2 years following prescribed burns), bark beetles may attack and kill trees that might otherwise have survived. However, Breece and colleagues (2008) reported that 80% of all bark-beetle-attacked trees were colonized during the first year following the application of prescribed fire. Fettig and colleagues (2010) reported that, in the central Sierra Nevada, California, 38%, 42%, and 20% of bark-beetle-caused tree mortality occurred during the first, second, and third years following prescribed fire, respectively.

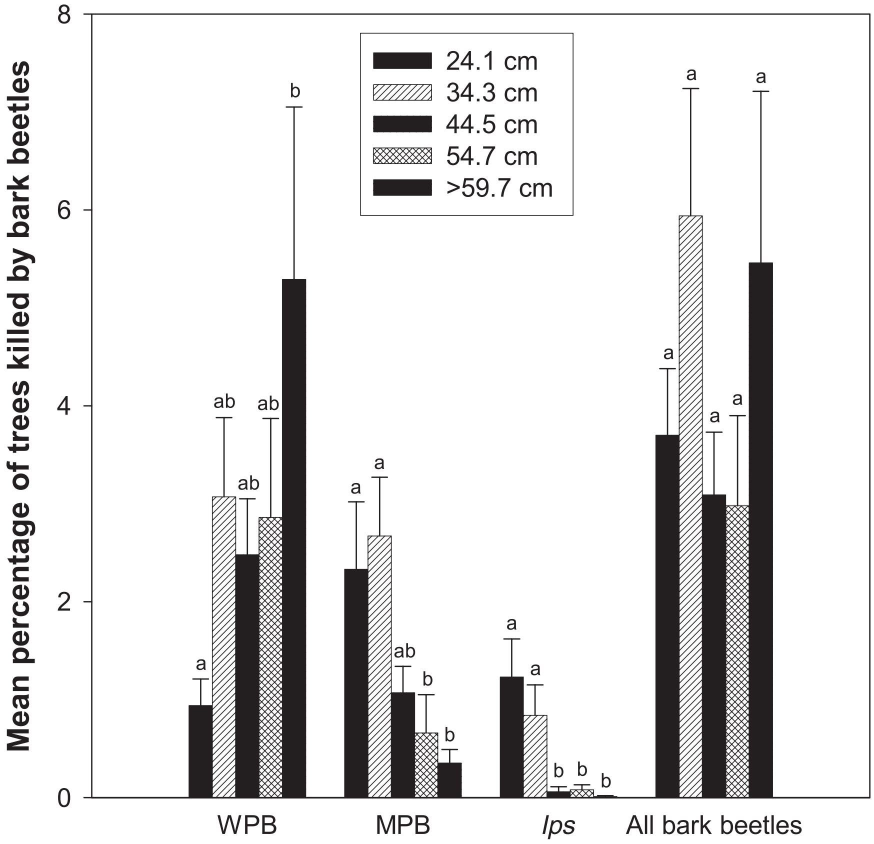

Figure 4. Mean bark beetle colonization rates of available pines among diameter classes on burned split plots for the western pine beetle (WPB), the mountain pine beetle (MPB),* Ips *spp. (*Ips*), and all bark beetle species combined during a five-year period following a prescribed fire. The means marked with the same letter within a group are not significantly different (Tukey's HSD) from one another. The error bars represent the positive standard error of the mean. Source: Adapted from Fettig and McKelvey (2010).

Although it appears that most of the delayed mortality attributable to bark beetle attacks occurs during the first few years following prescribed fire within the treated area, this may not be the case for adjacent untreated areas. For example, Fettig and McKelvey (2010) reported large increases in bark-beetle-caused tree mortality on unburned split plots relative to adjacent burned split plots 3–5 years after the application of prescribed fire at Black Mountain Experimental Forest, California. This is likely because of unburned areas' not benefiting from the positive effects of prescribed fire (e.g., increased growing space) that affect tree vigor and, therefore, susceptibility to bark beetle attack (Fettig et al. 2007). Interestingly, Fettig and colleagues (2006) observed a similar effect for mechanical fuel treatments involving chipping of sub- and unmerchantable trees, whereby chipping increased the plots' risk of bark beetle attack in the short term through the production of large amounts of attractive monoterpenes. In the longer term, however, this treatment decreased the hazard through an increase in the amount of growing space allocated to each residual tree by reducing stand density through thinning. Surveys along the perimeter of chipped plots revealed large numbers of recently attacked trees in untreated areas that did not benefit from the positive effects of thinning but that suffered a level of risk similar to that associated with high levels of monoterpenes beneath the forest canopy (Fettig et al. 2006).

In some areas, forest managers are concerned about potential increases in the amount of tree mortality—both direct and delayed tree mortality attributable to bark beetle attacks during and immediately following early-season burns. Schwilk and colleagues (2006) found that the probability of bark beetle attack (several species) on pines did not differ for early- and late-season prescribed fires, whereas the probability of attack on firs (*Abies* spp.) was greater following early-season burns. Although more research is needed, it appears that there may be fewer meaningful differences in the levels of tree mortality attributable to bark beetle attack observed between early- and late-season burns than was previously thought (Fettig et al. 2010). Finally, when bark beetles contribute to short-term increases in the levels of tree mortality, the results of this increase may not be entirely negative. Tree mortality after prescribed fires can contribute to important habitat features for wildlife, such as snags and downed logs (Kennedy and Fontaine 2009), which in turn may attract and sustain populations of many vertebrate species.

Carbon sequestration

To assess the potential impact of fuel treatments on forest carbon inventories and sequestration rates in the FFS Study, pretreatment standing stocks of carbon in vegetation, on the forest floor, in dead wood, and in mineral soil were analyzed at 12 sites, using a combination of direct measurements (soil, forest floor, and downed dead wood) and dimension regressions (standing dead wood and biomass). An estimation of the rates of change due to the application of the fuel-reduction treatments over the first posttreatment year and on an annual basis over the following 1–3 years was also performed (Boerner et al. 2008b). Prior to the application of the FFS Study treatments, the total carbon storage across the network averaged 185 megagrams (Mg) of carbon per ha, of which 45% was in vegetation, 38% in soil organic matter, 10% in the forest floor, and 7% in dead wood; the western US forest sites averaged 171 Mg of carbon per ha; and the eastern sites averaged 196 Mg of carbon per ha (Boerner et al. 2008b). In contrast, Heath and colleagues (2003) estimated that the total amount of carbon in US forested ecosystems averaged approximately 203 Mg of carbon per ha (193 Mg of carbon per ha for the western forests and 210 Mg of carbon per ha for the eastern forests). These estimates were probably greater than those reported by the FFS Study, because Heath (2003) included soil carbon to a depth of 1 meter, whereas the FFS Study estimates were based only on the top 30 cm. The amount of carbon stored in vegetation was not significantly affected by prescribed fire but decreased by about 30 Mg per ha as the result of mechanical or combined mechanical and prescribed-fire treatment. In contrast, the amount of forest-floor carbon storage was reduced by about 1–7 Mg per ha by fire or combined mechanical and fire treatment but was unaffected by mechanical treatment alone (Boerner et al. 2008b).

The superficial (O_i) layer of the forest floor is among the most dynamic of forest carbon pools (Yanai et al. 2003) and is also the pool most susceptible to loss from fire (Page-Dumroese et al. 2003). Hall and colleagues' (2006) results suggest, however, that this carbon pool returns rapidly to prefire conditions unless vegetative biomass is reduced for extended periods of time. The reductions in carbon in vegetation produced by modest mechanical fuel treatments are considerably smaller than those that one would expect from commercial harvesting practices (North et al. 2009), and therefore, forest-floor carbon stocks are likely to be rebuilt to pretreatment levels shortly after a prescribed fire, with or without mechanical treatment.

Neither dead-wood carbon nor soil organic carbon was significantly affected by the FFS Study treatments, although changes in these two carbon stocks were highly variable (Boerner et al. 2008b). Furthermore, Boerner and colleagues' (2008b) results suggest that dead-wood carbon stocks will approach pretreatment magnitudes within 2 years after treatment, except in the combined mechanical and prescribed-fire treatment. These results contrast strongly with those of studies of stand-replacing wildfires, in which dead-wood carbon can continue to accumulate for decades (Hall et al. 2006), reflecting the lower intensity of fires used for ecosystem restoration and fuel reduction.

At the FFS Study–network scale, total ecosystem carbon was not significantly affected by prescribed fire, although four individual sites did exhibit significant carbon losses to prescribed fire. Mechanical treatment, with or without prescribed fire, produced significant reductions of 16–32 Mg of carbon per ha during the first posttreatment year, but this was partially balanced by an enhanced net uptake of about 12 Mg of carbon per ha during the subsequent 1–3 years (Boerner et al. 2008b). In terms of carbon storage and uptake, western US coniferous forests responded differently to the FFS Study treatments than did eastern US deciduous, coniferous, and mixed forests, which suggests that the optimal management for fire, harvesting, and carbon sequestration differs between these regions. The greater loss of forest-floor and, to a lesser extent, dead-wood carbon in western US forests, as well as their slower rate of recovery from disturbance, suggests that management strategies for carbon storage will differ.

Costs and utilization

The costs of wildfire suppression in the United States from 1994 to 2004 averaged over $400 per ha burned (Perlack et al. 2005). In addition, associated costs, including the loss of forest products, other values and resources, and personal property, may total several thousand dollars per ha for large fires (e.g., Lynch 2004). The costs of fuel reduction (ignoring any revenues from the materials removed) may range from $100 to several thousand dollars per ha, with mechanical treatments generally being more expensive than prescribed fire (Hartsough et al. 2008). The key factors affecting treatment costs include the amount and type of material to be treated, terrain and weather conditions, and the size of the treatment unit and its proximity to residential or other developments (Fight and Barbour 2005).

Although fuel reduction is focused primarily on small trees and down woody materials, which are expensive to collect or treat, much of the volume to be removed may be in the boles of trees with a 15–20-cm diameter at breast height or larger. These materials have commercial value to sawmills and other conventional processing facilities, and the value may more than cover the costs of their removal. In the FFS Study, for example, product values exceeded the total costs of treatment by averages of nearly $3000 per ha on some western sites but were less than the costs in other locations (Hartsough et al. 2008). The net financial results for similar stands may vary dramatically, depending on the treatment prescription and markets (Hartsough 2003). Studies of various conventional mechanized treatment systems have shown that it is most efficient to handle trees and their residues as few times as possible. For example, whole-tree harvesting systems are usually less expensive than cut-to-length harvesting (Hartsough et al. 1997), especially when it is desirable for fuel-reduction objectives to remove logging debris (activity fuels) from the site.

Although mechanical treatments are the only means of rapidly and predictably removing trees that form ladder fuels, prescribed fire is an effective and relatively inexpensive way of reducing surface fuels and ladder fuels (Agee and Skinner 2005). The combined mechanical and prescribed-fire treatment is quite effective in reducing fire hazards, especially where adjacent residential or other property does not increase the costs of fire management. Mechanical treatment of smaller material has two obvious advantages over prescribed fire: It cannot escape to cause damage to neighboring property, and it can produce material to be utilized in place of nonrenewable fuel sources. The US Department of Energy and the US Department of Agriculture estimate that over 50 million oven-dry metric tons of smaller material could be recovered in fuel treatments across the United States for biomass energy (Perlack et al. 2005).

For mechanical treatment to become widespread, further research is needed on the effectiveness of these treatments to handle small trees and some surface fuels. Although the use of downsized equipment for smaller trees or small treatment units may seem like a worthy idea, it has consistently produced costs per ha and per metric ton of biomass that are substantially higher than those of conventional equipment operating under good conditions (e.g., DeLasaux et al. 2009). Promising efforts are under way to reduce costs through processing and handling small materials in bulk, such as with a masticator that collects the comminuted biomass (Roise et al. 2009). It is substantially more expensive (per megajoule-kilometer) to transport woody biomass by truck than it is to move coal, oil, or natural gas by rail, ship, or pipeline. As a result, the economics of biomass utilization are strongly influenced by the proximity of conversion facilities to the forest (Hartsough et al. 2008).

Conclusions

When they are applied, both prescribed fire and its mechanical surrogates are generally successful in meeting short-term fuel-reduction objectives and in changing stand structure and fuel beds such that treated stands are more resistant and resilient to high-intensity wildfire. Although the numbers of exotic plants tend to increase with levels of treatment disturbance, overall understory species richness also increases (Schwilk et al. 2009), especially that of fire-adapted plants and those plants that are favored by more xeric forest-floor conditions. Although mineral soil exposure, pH, and exchangeable cations respond to treatment in the short term, initial changes tend to disappear after only a few years. Other soil variables, including bulk density, soil carbon, dead-wood carbon, and soil nitrogen exhibit extremely subtle responses to treatment (Boerner et al. 2009). The wildlife literature, which is dominated by studies on birds and small mammals, demonstrates that in the short term and at the stand scale, fire-surrogate forest-thinning treatments effectively mimic low-severity fire, whereas low-severity fire is not a substitute for high-severity fire (Kennedy and Fontaine 2009). Although bark beetles often take advantage of fire-damaged trees—particularly in the western United States—the overall responses by bark beetles tend to be relatively short lived and concentrated in the smaller-diameter classes. In the longer term, thinning effects (e.g., on tree vigor and microclimate) have been shown to reduce stand susceptibility to bark beetle attack (Fettig et al. 2007).

We recommend that a full suite of alternative fuel treatments be implemented in appropriate forests, including prescribed fire, mechanical thinning, and combined mechanical and prescribed fire treatments, and also support the expanded use of managed wildfire (Collins et al. 2009, Collins and Stephens 2010) to meet management objectives. These fuel treatments can be used in combination across a landscape to mimic the landscape heterogeneity characteristic of low- to moderate- and mixed-severity fire regimes (Collins et al. 2011, Perry et al. 2011). Although mechanical treatments cannot serve as complete surrogates for fire, their application can help mitigate costs and liability in some areas, such as the wildland–urban-area interface. Current research has shown that not all fuel treatments are being applied in high-priority forest types in the western United

States, which suggests that some managers may need additional information on local fire regimes to help prioritize restoration activities (Schoennagel and Nelson 2010).

Effective managers should consider the landscape context of their particular area when planning fuel-management strategies. Finney and colleagues (2007) compared the effectiveness of different rates of treatment over several decades in the western United States. Their findings indicated that treatment rates beyond 2% of the landscape per year, based on optimized treatment placement, yielded little added benefit. This figure includes both the maintenance of previously treated units and the installation of new treatments, both of which are critical for a successful strategy. Implementing optimized fuel-reduction treatments in appropriate forest types will allow more of the forest to survive when it burns during wildfires.

Designing more fire-resistant stands and landscapes will likely create forests that are more resistant and resilient to the changes imposed on them by climate change. For this reason, it is more appropriate to design and test a range of specific forest structures in order to learn about their resistance and vulnerabilities rather than trying to restore an ecosystem to presettlement conditions that may not be appropriate for the future (Millar et al. 2007). Most available evidence suggests that fuel-reduction objectives are typically accomplished with few unintended consequences, because most ecosystem components (vegetation, soils, wildlife, bark beetles, carbon sequestration) exhibit very subtle effects or no measurable effects at all; similar results were found in Western Australia forests and shrublands that were repeatedly burned over 30 years (Wittkuhn et al. 2011). The results presented in this article are for forests that once burned frequently with low- to moderate-intensity fire regimes; other ecosystems adapted to different fire regimes would probably exhibit different responses to fuel treatments.

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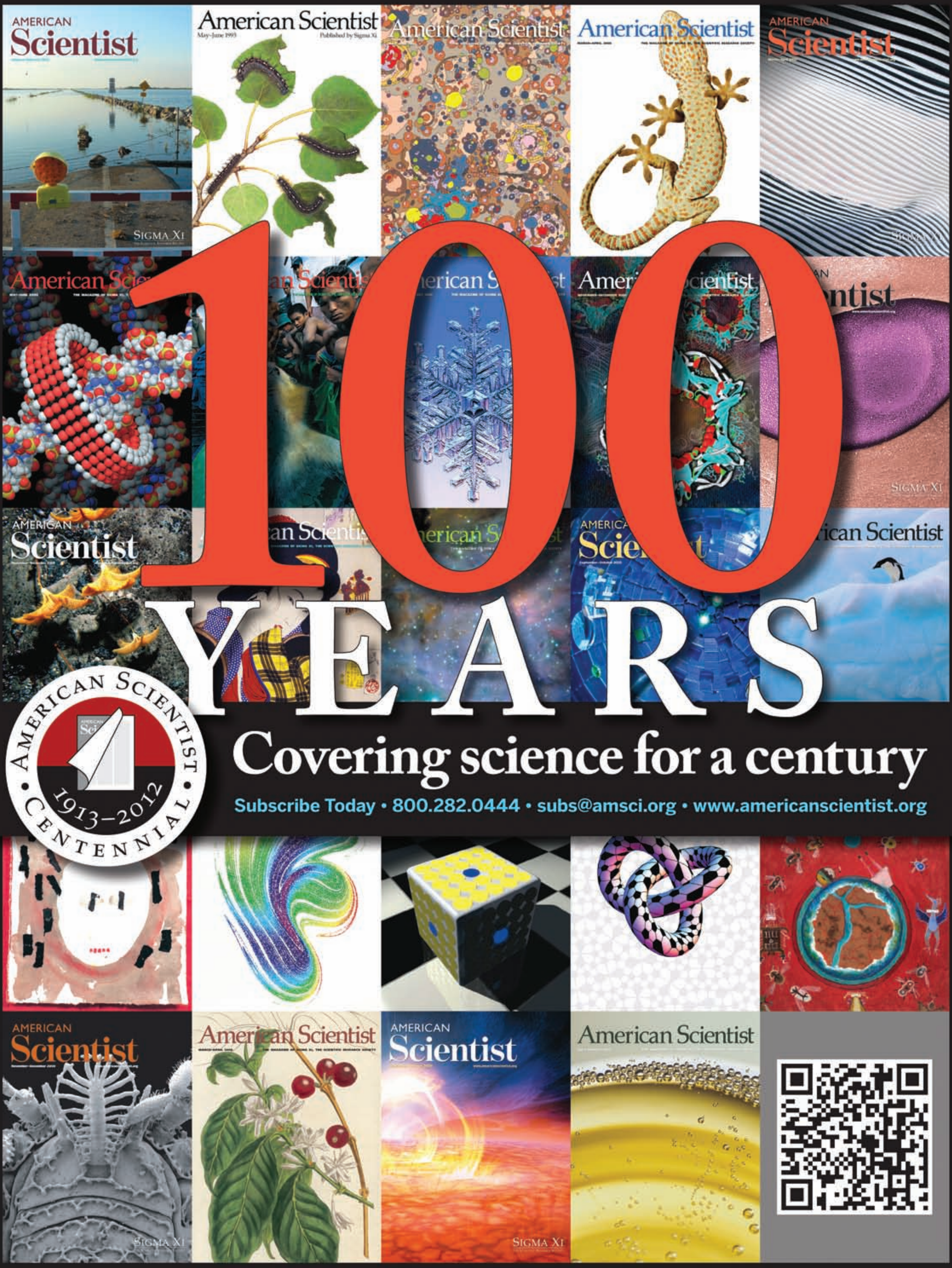
Scott L. Stephens (sstephens@berkeley.edu) is affiliated with the Department of Environmental Science, Policy, and Management at the University of California, Berkeley. James D. McIver is affiliated with the Oregon Agricultural Research Center, at Oregon State University, in Union. Ralph E. J. Boerner is affiliated with the Department of Evolution, Ecology, and Organismal Biology at The Ohio State University, in Columbus. Christopher J. Fettig is affiliated with the US Department of Agriculture Forest Service's Pacific Southwest Research Station, in Davis, California. Joseph B. Fontaine is affiliated with the School of Environmental Science at Murdoch University, in Perth, Australia. Bruce R. Hartsough is affiliated with the Department of Biological and Agricultural Engineering at the University of California, Davis. Patricia Kennedy is affiliated with the Eastern Oregon Agricultural Research Center and with the Department of Fisheries and Wildlife at Oregon State University, in Union. Dylan W. Schwilk is affiliated with the Department of Biological Sciences at Texas Tech University, in Lubbock.



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Montana's Forestry Best Management Practices Program: 20 Years of Continuous Improvement

Brian D. Sugden, Robert Ethridge, George Mathieus, Patrick E.W. Heffernan, Gary Frank, and Gordy Sanders

Under the federal Clean Water Act, states have developed nonpoint source control programs for forestry that range from voluntary to regulatory approaches. Nationally, management of runoff from forest roads is currently under scrutiny by courts, the US Environmental Protection Agency, and Congress. This article describes Montana's "blended" program of voluntary forestry best management practices (BMP) for roads and upland practices, and a Streamside Management Zone Act, which regulates operations near streams. Biennial audits over the past 20 years have shown continuous improvement, with BMP implementation rates increasing from 78% in 1990 to 97% in 2010. Observed water quality impacts have declined from an average of eight per harvest site in 1990 to less than one in 2010. Activities and culture that have promoted an effective program include regular compliance monitoring, customized landowner and logger education programs, strong buy-in from the forestry community, and program coordination by a statewide stakeholder group.

Keywords: water quality, best management practices, BMP, nonpoint source, stormwater

In the 40 years since passage of the federal Clean Water Act (CWA), states have taken a variety of approaches to address water quality impacts from forestry activities (Ice et al. 2010). The amendments to the CWA in 1987 added Section 319, which required states to assess what categories of nonpoint sources were most important and develop effective control strategies. It was left to states to decide if regulatory or nonregulatory (i.e., voluntary) approaches would be adopted. Nationally, 16 states have adopted programs that are regulatory, 22 have nonregulatory approaches, and the remainder have elements of both, which could be termed "blended" or "quasi-regulatory" (Schilling et al. 2009).

Currently, forest roads are under scrutiny by courts, the US Environmental Protection Agency (USEPA), and Congress as to whether they should be reclassified as point sources, because some roads have ditches and other runoff control measures that discharge pollutants to waters of the United States. This is in response to a Ninth Circuit Court of Appeals decision in *Northwest Environmental Defense Center versus Brown* (Ninth Circuit 2011). If the Ninth Circuit decision stands and there are no statutory or administrative remedies enacted, landowners and loggers may be required to obtain stormwater discharge permits for roads from USEPA or states under Section 402 of the CWA (USEPA 2012). For most states, movement to a fully regulatory permit-based approach to forest road management would be a significant departure in how forest roads have been managed for decades under established best management practice (BMP) programs. Montana has experiences with both regulatory and nonregulatory approaches to forest water quality protection that can inform the current national dialogue over classification and regulation of runoff from forest roads.

During the 1970s and 1980s, there was significant pressure by environmental inter-

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Affiliations: *Brian D. Sugden (brian.sugden@plumcreek.com) is forest hydrologist, Plum Creek Timber Company, PO Box 1990, 500 12th Avenue West, Columbia Falls, MT 59912. Robert Ethridge (rethridge@mt.gov) is chief, Forestry Assistance Bureau, Montana Department of Natural Resources and Conservation, 2705 Spurgin Road, Missoula, MT 59804. George Mathieus (gemathieus@mt.gov) is administrator, Planning, Prevention and Assistance Division, Montana Department of Environmental Quality, 1520 E. Sixth Avenue, Helena, MT 59620-0901. Patrick E.W. Heffernan (patrick@pafti.com) is president, PAFTI, Inc, PO Box 190161, Hungry Horse, MT 59919. Gary Frank (gfrank@mt.gov) is resource management supervisor, Forest Management Bureau, Montana Department of Natural Resources and Conservation, 2705 Spurgin Road, Missoula, MT 59804. Gordy Sanders (gsanders@pyramidlumber.com) is resource manager, Pyramid Mountain Lumber, Inc, 379 Boy Scout Road, Seeley Lake, MT 59868.*

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est groups to regulate forest practices in Montana. Over several legislative sessions, bills were introduced to enact a comprehensive state forest practice act modeled after other western states. The 1987 amendments to the CWA requiring nonpoint source planning added a further impetus. Although comprehensive forest practices legislation was never enacted, the 1987 Montana legislature passed House Joint Resolution (HJR) 49, which mandated a study of logging practices on water quality. The results of this study (Montana Environmental Quality Council 1988) led to the adoption of several targeted laws and voluntary programs to improve implementation of forestry BMPs in Montana. These included (1) formation of a multistakeholder BMP Working Group coordinated by the Montana Department of Natural Resources and Conservation (DNRC) in 1988, (2) development of a consistent set of voluntary BMPs for Montana in 1989, (3) adoption of a state Streamside Management Zone (SMZ) Act in 1991 that regulated timber harvest and other activities in a 50- to 100-ft zone on each side of streams (Montana Code Annotated [MCA] 77-5-301), (4) adoption of a state law in 1989 requiring landowners to notify DNRC in advance of conducting forest practices (MCA 76-13-420), and (5) legislative direction for DNRC to coordinate monitoring of BMP implementation, with biennial reports to the Environmental Quality Council (EQC) of the state legislature.

Montana's blended program of regulatory and nonregulatory approaches has been largely unaltered since 1991. This article presents results and lessons learned over 20 years of implementing the program.

Montana Forestry BMP Program

Montana's forestry BMPs were formally adopted in 1989 and are the consensus product of a BMP technical committee formed during the HJR 49 study. The BMPs comprise over 100 individual practices related to road and timber harvest planning and design; road and skid trail drainage, construction, and maintenance; slash disposal and site preparation; stream crossings; and more (Montana DNRC 2011).

The 1988 EQC report designated DNRC as the lead agency to develop educational programs for landowners and loggers, monitor BMP implementation, and work with landowners on adapting the BMPs over time. To enable stakeholder collaboration on these activities, a working group was created and facilitated by DNRC. The BMP Working Group today includes approximately 25 participants from state and federal public land-management agencies, Montana Department of Environmental Quality, industrial forest landowners, conservation organizations, private landowners and landowner groups, Montana State University (MSU) Extension Forestry Service, the Montana Wood Products Association, and the Montana Logging Association (MLA). The Working Group provides oversight of audits, approves modifications to the state BMPs, and makes recommendations on logger and landowner education programs. There are no defined terms for participants, and new organizations and individuals that have expressed interest in the group have been welcomed by DNRC and others.

Table 1. Number of audit sites by ownership category for each audit year.

Ownership	1990	1992	1994	1996	1998	2000	2002	2004	2006	2008	2010
State	5	5	5	5	5	5	5	4	5	6	6
Federal	16	16	14	12	12	9	5	9	5	8	16
Industrial private	16	16	14	14	18	18	21	19	22	17	15
Nonindustrial private	7	9	13	13	12	10	12	7	12	11	8
Total	44	46	46	44	47	42	43	39	44	42	45

Methods

Audits are conducted every other year and cover all forested regions of Montana, including federal and nonfederal lands. To qualify for the state BMP audit, harvest units must have been logged in the previous 3 years, undergone at least one spring runoff cycle, and meet several minimum criteria (Ziesak 2010). These include a harvest area of 5 ac or more, the harvest must be conducted within 200 ft of a stream (or contains an access road that crosses a stream), and must have a minimum average timber volume removal per acre (currently 3,000 bd ft/ac in western Montana and 1,500 bd ft/ac in eastern Montana). The purpose of the minimum criteria is to focus the audit on sites that have a greater potential to impact water quality (USEPA 1997). During the winter preceding an audit year, public land-management agencies and industrial private landowners provide DNRC a list of all sites that meet the selection criteria. Qualifying nonindustrial private harvest sites are identified by DNRC based on site criteria contained in harvest notifications.

Harvest units meeting the minimum selection criteria are stratified by ownership category and region. Ownership categories include federal (US Forest Service and Bureau of Land Management), state, nonindustrial private, and industrial private. Regions include Northwest, West, and Central–Eastern (Ziesak 2010). Within these strata, the population is ranked for site attributes, including new road construction or reconstruction, harvest within an SMZ, and new stream crossings installations. Sample sites are distributed across ownerships and regions in approximate proportion to the statewide harvest. A systematic sample is randomly generated, with a higher sample intensity of sites with more site attributes. The intent of this is to achieve a good distribution of sample sites across the state in proportion to ownership category and amount of harvest and maximize the number of BMPs evaluated at a given site (USEPA 1997). The number of audit sites statewide has averaged 44 since 1990 and ranged from 39 to 47 in any given audit year. Table 1 shows the distribution of sample sites by ownership category by year. This sample of harvest sites represents 1–3% of the statewide total and up to 5% of higher-risk sites.

Management and Policy Implications

States currently have wide latitude in how they address water quality impacts from forestry activities under the federal CWA. There is intense debate underway about whether runoff from forest roads should be more tightly regulated. Should this change occur, it is expected to have significant implications on the forestry sector. This article describes 20-year results of Montana's program of voluntary BMPs for roads and upland harvest activities and a regulatory SMZ Act. Montana's experience shows that a cost-effective voluntary program, if properly constructed and implemented, can dramatically reduce water quality impacts and achieve compliance rates that are comparable with states with fully regulatory programs.

Table 2. Definitions for BMP and SMZ application ratings.

Application rating	Definition
5	Operation exceeds requirements of BMPs
4	Operation meets requirements of BMPs
3	Minor departure from intent of BMPs
2	Major departure from intent of BMPs
1	Gross neglect of BMPs

Table 3. Definitions for BMP and SMZ effectiveness ratings.

Effectiveness rating	Definition
5	Improved protection of soil and water resources over preproject condition
4	Adequate protection of soil and water resources
3	Minor and temporary impacts on soil and water resources
2	Major and temporary or minor and prolonged impacts on soil and water resources
1	Major and prolonged impacts on soil and water resources

Adequate, small amounts of material eroded; material does not reach draws, channels, or floodplain.
Minor, some material erodes and is delivered to draws but not to stream.
Major, material erodes and is delivered to stream or annual floodplain.
Temporary, impacts lasting 1 year or less; no more than one runoff season.
Prolonged, impacts lasting 1 year or more.

Figure 1. BMP teams inspect road drainage and erosion control on a bridge approach during a calibration exercise before the 2004 audit. (Photo provided by Brian Sugden.)

Three audit teams are organized to conduct harvest site inspections, with each assigned a geographic region. Teams are comprised of experts from seven disciplines: forestry, engineering, hydrology, soils, fisheries, conservation, and a logger or nonindustrial private landowner. Team members volunteer from state and federal agencies, landowners, consulting firms, and nonprofit organizations. For many positions, an alternate team member is also designated. A small stipend is available for volunteers not supported by an employer. Counting alternates, statewide participation on teams is about 50 people.

Not all of Montana's BMPs are likely to affect water quality or are applicable during a postharvest review. A total of 50 individual practices contained in the BMPs are audited by teams in the field. These include practices rated to road planning, location and design (8 BMPs), road construction and drainage (13 BMPs), road maintenance (5 BMPs), timber harvest design (3 BMPs), harvest skid trails and landings (5 BMPs), slash treatment and site preparation (5 BMPs), and 11 BMPs related to stream crossing design and installation. Rated and reported on separately are 13 practices related to the state SMZ law. In reviewing each site, the team observes any erosion rills or gullies, sediment plumes or pathways, and any road cut slope sloughing. For each individual practice, a rating is made for both application and effectiveness on a scale of 1 to 5 (Ehinger and Potts 1990). If a BMP is fully met, an application rating of 4 is given. Operations exceeding the required BMP are given a rating of 5. Departures from BMP application range from 3 to 1, depending on severity (Table 2).

BMP effectiveness is rated based on observed erosion and downslope sediment movement (Table 3). An effectiveness rating of 4 indicates the BMP was effective at controlling impacts (e.g., surface erosion, downslope sediment movement, and more). A rating of 5 indicates improved protection of soil and water resources over preproject conditions. Effectiveness ratings of 3 and lower correspond to varying levels of duration and impact to soil and water resources. Ratings of 3 or lower are reported as not effective. This approach is believed to be conservative, in that a small amount of sediment delivery is treated the same as a large volume of delivery.

Before each audit cycle, a quality control calibration meeting is held in which all teams participate (Figure 1). The objectives of this session are to orient new members to the process, calibrate the teams to rate practices consistently, discuss important interpretation issues, and visit a field site that can generate discussion among teams. A postaudit meeting of team members is also held to discuss any unusual situations or consistency questions encountered during the audit. These points are discussed among the teams and have resulted in adjustments to ratings.

Audits are conducted in July and early August, and individual teams typically visit two harvest sites in a day. Audits are attended by the landowner or landowner representative and often by the operation forester and logger. Before coming onto the site, the team discusses whether the entire harvest area, SMZ, and road network can be inspected in the allowable time frame of 2–3 hours. If the area is too large to be visited entirely, a subsample of the site will be inspected. In these cases the teams identify higher-risk portions of harvest units and road systems to inspect based on a map review. The audit team walks (and drives) the site as a group (Figure 2), inspecting road drainage and erosion control on new or reconstructed roads, stream crossings, skid trails, landings, SMZs, and more. The intensity of the survey is variable and depends on the size of the harvest area and allowable time. Where available, teams typically inspect several miles of access road, three to five stream crossings, a quarter mile of SMZ, and several skid trails and landings. During the site inspection, BMP concerns are discussed by the team along the way. Some limited measurements are made, such as soil type, average slope, SMZ width, stream width and classification, number dimensions of any erosion features, and fish passage parameters at culverts. The audit concludes by rating and recording all applicable BMPs on the audit form in the presence of the landowner, logger, and any other observers. Audit scores are determined using a consensus process but will be resolved with a majority vote if consensus can not be reached. The landowner being audited is allowed to answer questions of the team but otherwise reserves comment until the audit is completed. Other observers are encouraged to attend.

Key metrics generated from the audit are the percentage of individual rated practices that meet or exceed BMP requirements, the percentage of practices that provide adequate or improved protection of soil and water resources, and the observed water quality "impacts" per site, which are defined as BMP effectiveness ratings of 1, 2, or 3. Results are reported by ownership category.

Results

Eleven audits have been held in Montana since 1990 (on even-numbered years) with results published before the biennial state legislative session. Audit reports have been prepared by Schultz (1990, 1992), Frank (1994), Mathieus (1996), Fortunate et al. (1998), Ethridge and Heffernan (2000), Ethridge (2002, 2004), Rogers (2006a), and Ziesak (2008, 2010). The most recent monitoring report and executive summary is posted on the DNRC website (Ziesak 2010).

Statewide BMP application rates (i.e., the percentage of total practices rated statewide that met or exceeded BMP requirements) increased from 78% in 1990 to 97% in 2010 (Figure 3, blue bars). Most of this improvement came in the 1990s, and results have been maintained at a high level over the past 10 years. Improvement in BMP application rates have been observed across all ownership categories (Figure 4).

Figure 2. West audit team inspecting a SMZ and harvest in 2008. (Photo provided by Brian Sugden.)

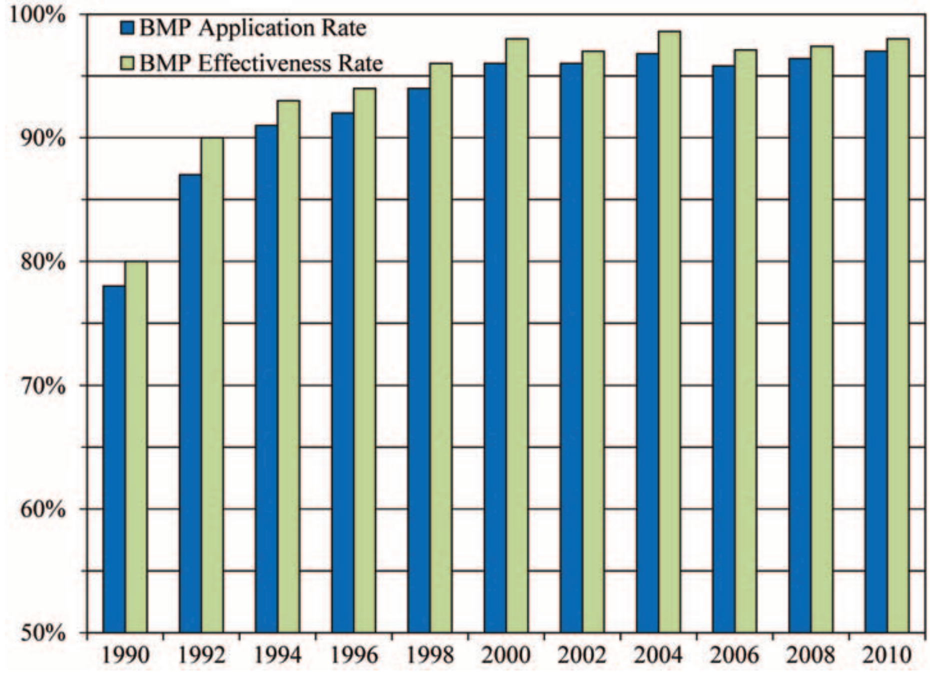

Figure 3. Percentage of rated BMPs that met or exceeded requirements across Montana (blue bars), and the percentage of rated BMPs determined to provide adequate or improved protection of soil and water resources (green bars).

In the vast majority of cases, if BMPs are applied properly they are also found to be effective at controlling rill or gully erosion and sediment delivery to streams (Figure 3, green bars). As such, the trend in effectiveness rates mirrors that for application, although the effectiveness rating is slightly higher. In some cases, impacts are not observed even if BMPs have not been fully applied (i.e., rating of a 3 on application and a 4 on effectiveness). An example of this is inadequate application of road draining BMPs where sediment deposits on the hillslope below the road and does not enter a nearby stream. In only rare circumstances in Mon-

Figure 4. Percentage of rated BMPs that met or exceeded requirements by ownership category.

tana is a BMP practice met but found to be ineffective at preventing impacts (i.e., rating of 4 on application but a 2 or 3 on effectiveness). When encountered, these become a continuing improvement discussion item by audit teams and the BMP Working Group. We note, however, that our effectiveness observations represent postharvest impacts after one to three runoff seasons, so sites may not have been subjected to large stressing storms. Longer-term effectiveness was validated during the 1998 audit and is discussed later in the article. The average number of observed impacts per site (BMP effectiveness ratings of 3, 2, or 1) has declined ninefold between 1990 and 2010 (Figure 5).

Rates of SMZ law implementation during the period 2000–2010 (Figure 6) are about a percentage point higher than the voluntary BMP application rate during this period. Seventy percent of SMZ departures are rated as minor and are usually related to improper SMZ boundary marking and/or minor equipment encroachment into the SMZ.

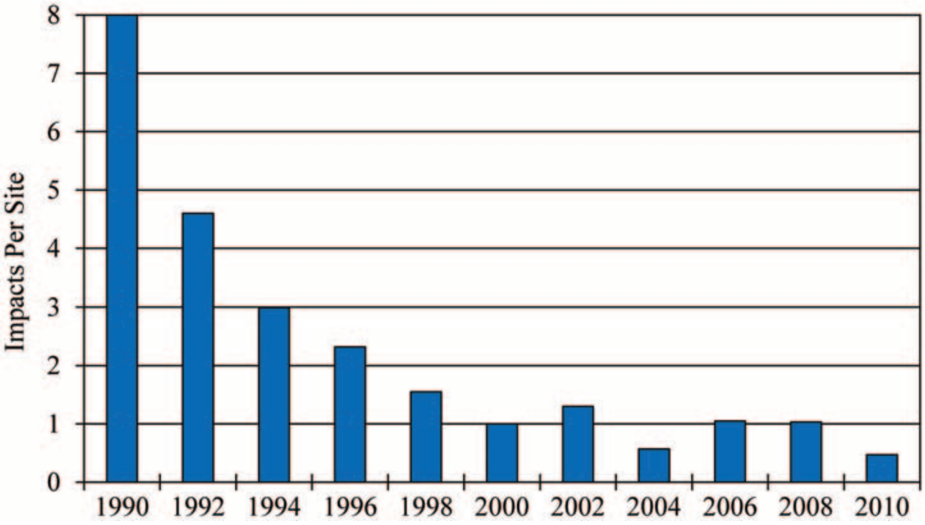

Figure 5. The average number of observed impacts per audit site.

Discussion

After adoption of forestry BMPs in 1989, DNRC collaborated with the MLA and MSU Extension Forestry to develop education programs for landowners, loggers, and foresters. In 1990, classroom BMP sessions for loggers were initiated, with instruction provided by DNRC and MLA staff. In addition, since 1995, more detailed BMP/SMZ workshops (with both classroom and field instruction) have been held annually across Montana (typically five to nine towns and cities). At about this same time, industrial landowners began requiring foresters and contractors to attend workshops, and the MLA developed its Accredited Logging Professional (ALP) program. To date, BMP/SMZ training workshops have reached a cumulative audience of approximately 3,500 people. The BMP audit results have proven helpful in focusing logger education efforts over time.

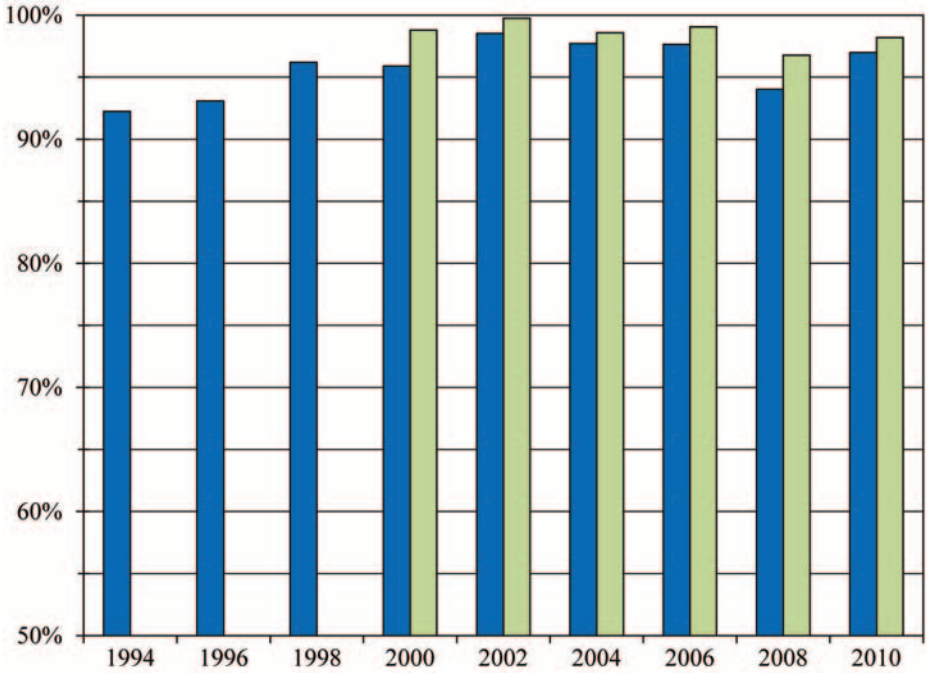

Figure 6. Percentage of rated SMZ practices that met or exceeded SMZ regulations across Montana (blue bars), and the percentage of rated SMZ practices determined to provide adequate protection of soil and water resources (green bars). SMZ effectiveness was not compiled in audit reports before 2000.

MSU Extension Forestry developed a forest stewardship program targeting nonindustrial private landowners. This program teaches landowners about forestry and other natural resources and is completed when a landowner develops a stewardship plan for their property. Between 1991 and 2011, there were 136 forest stewardship workshops held, with 3,189 participants. The program has yielded 2,054 stewardship plans encompassing 1.1 million ac (Cindy Bertek, pers. comm., MSU Extension Forestry, Mar. 15, 2012). Education has evolved even further over the past 10 years with the ongoing development of the ALP program and requirements for logger training and BMP/SMZ implementation under the Sustainable Forestry Initiative and other forest certification programs.

Easy to understand education materials have been developed and are central to all training workshops. Color booklets containing photographs and other illustrations to better communicate BMPs to landowners and loggers were published (Logan and Clinch 1991, Logan 2001). DNRC also developed color guides to the SMZ law and rules (Fortunate 1994, Rogers 2006b).

BMP implementation rates today are uniformly high but vary among ownership categories (Figure 4). State and industrial private lands have reached a very high level of compliance, averaging 98% over the past five audit cycles dating back to 2002. This is significantly higher ($P < 0.05$) than federal and nonindustrial private ownership categories during this time frame. On average, audits on these ownerships observe less than one BMP departure per site, and these are typically minor.

BMP application rates on nonindustrial private lands have improved by 36 percentage points since 1990 (averaging 93% since 2002). This represents the largest increase of any ownership category. This improvement is attributed to several factors. Montana DNRC provides educational materials to nonindustrial private landowners on notification of forest practices and makes DNRC service foresters available for landowner assistance. However, it is challenging to achieve very high rates of compliance on nonindustrial private ownerships that may only harvest timber once every 20 years. There is also a constant influx of new private landowners that may have not had any exposure to previous forest management or training. Finally, nonindustrial private landowners do not necessarily have the technical resources that agencies and timber companies have. Audit teams must obtain permission from nonindustrial private owners to come onto their property to perform the review, and there have been instances that permission has not been granted. In many cases this is simply because an absentee landowner can not be on site during the audit time frame. But there is occasionally resistance to providing access. DNRC has worked through this by using the log purchaser, consulting forester, or contract logger as a liaison to allay concerns. We estimate that audit teams have not been able to visit 25% of selected nonindustrial private sample sites over the past 20 years. Overall, we believe this has had a minimal effect on results from this ownership category, but it is an uncertainty.

BMP application rates on federal lands have improved by ten percentage points over the 20-year period (averaging 94% since 2002) but slightly lag application rates observed on state and industrial private ownerships. The reason for this has been extensively discussed by audit team members over the years. The authors believe there are a number of contributing factors, including initial resistance by engineers to lower-standard and lower-impact roads, different people being involved in different phases of the project (e.g., harvest unit layout, roads, contracting, administration, and reforestation, to name a few), and a timing disconnect between available funding for road BMP upgrades and timber harvest projects. State and industrial private harvests are typically the responsibility of a single person who sees the project through the entire process, from conception to implementation. This increases ownership, accountability, and clear communication on the project.

These results are believed to be reflective of BMP application rates across Montana. The minimum site selection criteria have been set at levels where at least one-third of the harvest area in Montana is eligible for the audit. The sites that do not meet the minimum criteria represent a lower risk to water quality, because there is either no harvest close to streams or low timber volume per acre removed. Our experience suggests that BMP application rates on nonqualifying lands are not appreciably different from what has been measured at qualifying sites.

A key factor in the success of Montana's audit program has been continuity of audit team member participation over time. Average tenure for team membership is more than five audit cycles (10 years), and several have participated for the entire 20 years. Because of this continued participation and teams having learned to work together, group consensus is reached in the vast majority of ratings. Only a few scores each year come down to a vote. It is also a fairly manageable program for people to commit time to. Team member involvement is capped at 10 days biennially, and in some cases, this time is divided with an alternate. There has been a declining trend in involvement among conservation/environmental interests in the state BMP program, both at the working group level and as participants on audit teams. In the most recent cycle, conservation representative slots were vacant on two of three teams despite recruiting efforts by DNRC. The reason for this lack of recent participation is unknown.

Montana's observational approach for evaluating BMP effectiveness does not physically measure water quality or biological response to timber harvest. However, it is believed to be a valid way to evaluate environmental success of the program, particularly with regard to impacts such as erosion and sediment delivery to streams. In a study in northeast Washington State, Corner et al. (1996) were able to detect sediment delivery from timber harvest operations using observational approaches that was not measurable with instream sampling. An observational approach was used by Litschert and MacDonald (2009) in the Sierra Nevada and Cascade Mountains of northern California. They inspected skid trails on 200 recent harvest units and found six instances of hillslope rills delivering sediment to streams (several where BMPs were not fully applied). Rivenbark and Jackson (2004) also used observational methods to determine locations where concentrated flow paths moved across SMZs and delivered to streams. Advantages of this approach include timely information, cost-effectiveness, and providing direct feedback on effectiveness of specific practices. A disadvantage is that erosion features and sediment movement are dependent on the occurrence of testing storms, and some observations are transient, such as road surface erosion features that may be masked by recent road grading. Although we believe the observational approach is powerful, it is important to complement these with instream monitoring projects to get a full picture of BMP effectiveness. These research efforts are underway across the United States to validate instream effectiveness of BMP and streamside practices (Ice and Schilling 2012). This includes research and monitoring undertaken in Montana in support of fisheries Habitat Conservation Plans (Plum Creek 2000, Montana DNRC 2012).

The BMP audit program has also created an opportunity for supplemental questions to be asked regarding the BMP program. In 1996, e.g., fisheries biologists involved with bull trout restoration in Montana asked the BMP Working Group if BMPs were effective over time (i.e., beyond our 2-year audit window). This was evaluated during the 1998 audit (Fortunate et al. 1998) by revisiting 11 sites previously assessed during the 1994 or 1996 audit cycles. These revisits found that BMPs were durable and effective over time when properly designed and implemented. Another supplemental question implemented in 2000 related to road BMP improvements that landowners were making in conjunction with projects. The supplemental question asked, "Did the project include improvements to the existing road system that reduced overall sediment delivery to streams?" This question was asked on 244 harvest units between 2000 and 2010 and was answered "yes" for 161 harvests (66%). The implication is that there is extensive watershed restoration being undertaken in conjunction with ongoing management. The percentage of harvests with "yes" to this question has declined in recent audit cycles because landowners have already upgraded much of the older road network to modern BMP guidelines. More recently, the BMP Working Group and a fish passage subcommittee developed an approach to evaluate fish passage at new stream crossing installations. The method needed to be easily incorporated into audits but yield reliable results. A fish passage "questionnaire" was pilot tested during the 2004 and 2006 audits. To allow time for landowner and logger education, it was not formally included in the BMP audits until the 2010 cycle.

The Montana Legislative Audit Division reviewed the BMP program during the 2006 audits (Montana Legislative Audit Division 2007). The conclusions of the report were as follows:

1. Partnerships and education have enhanced the implementation of sound forest practices.
2. Onsite inspections of forest practices and landowner consultations help compliance with BMPs.
3. BMP audits are an essential component for DNRC to evaluate if forest practices were conducted responsibly.
4. Voluntary BMPs are used in a high percentage of time near water.
5. Use of BMPs to protect water is part of forest practices culture.
6. Montana's current process of regulating forest practices, via a mostly voluntary process, appears to be achieving similar results in protecting water resources as states using a more regulation-oriented structure.

The report had one recommendation, which was to "… expand BMP audit selection criteria prior to the 2008 BMP audit cycle to audit/monitor a broader spectrum of timber harvest sites." The BMP Working Group had mixed feelings about this. Although it would be good to have a more complete assessment of BMP implementation across a wider range of sites, limited audit resources suggest choosing sites with streamside harvesting and other risk factors. The BMP Working Group resolved this by changing the selection process to require that two-thirds of audit sites are pulled from a higher-risk selection pool and one-third be pulled from a lower-risk pool. These changes were incorporated into the 2010 audit cycle.

The national average BMP implementation rate (weighted by state timber harvest volume as a percentage of the national total) is 89% (Ice et al. 2010). Montana's "blended" program has achieved an average voluntary BMP implementation rate of 96% over the past 10 years and an average regulatory SMZ application rate of 97% during this period. As reported by Ice et al. (2010), Montana's BMP implementation rate is very similar to compliance rates observed in other western states with comprehensive forest practices acts, including Idaho (96%), Oregon (96%), and California (94%). In addition, Montana's rate is higher than Washington (80%) and Alaska (89%). It is noted that caution must be exercised when comparing results among states, because monitoring methods differ.

The cost of the biennial monitoring program for the state of Montana is not substantial. Because of the strongly volunteer nature of the program, the DNRC role largely involves logistics and reporting. No full-time employees have been added to implement this program. It is estimated that one employee focuses about 4 months of scattered time over a 2-year period to coordinate the audit and that the cost for team member stipends and travel during the audits is approximately $6,000.

Montana DNRC has 16 service foresters dedicated to landowner assistance and forest practices implementation, with a recent statewide timber harvest of 197,903,000 ft^3 (Smith et al. 2009). Much of this service forester time is spent with nonindustrial private landowners answering questions about BMPs, SMZs, and slash fire hazard abatement and providing technical assistance to landowners in the management of their forests. No more than 10% of each service forester's time is directly tied to the BMP program.

MLA and DNRC staff teaching BMP/SMZ workshops have emphasized the opportunity to embrace BMPs on voluntary terms, and the commonsense approach the state has developed has resonated with loggers and landowners. However, cultural change truly came when BMP implementation became a source of pride among loggers, and there was a "specter of defame" for noncompliance. With this culture shift and a strong commitment to environmental compliance by landowners, Montana's voluntary BMPs are not really viewed as discretional today.

Montana's program has served as a model both nationally and internationally. Our user-friendly color BMP booklet was among the first of its type in the country and was the model used by several other states. A Spanish language version was developed for the country of Chile. Our program has also caught the interest of the Rights and Resources Initiative (RRI), which is an organization working toward forestland tenure and policy reforms in developing countries. For the past 2 years, the RRI has convened a 5-day workshop titled "Rethinking Forest Regulation" at the University of Montana's Lubrecht Experimental Forest. The purpose of this project is for Montana to share its experiences in voluntary forestry BMPs, logger training, auditing, forest stewardship, and more. This workshop has been attended by individuals from throughout the world.

The experience of Montana's blended program of voluntary and regulatory practices designed to protect water quality is particularly pertinent as the courts, USEPA, and Congress consider the classification of forest roads as point or nonpoint sources of pollution under the CWA. This classification could affect program approaches used to protect water quality. Forest road networks are extensive and may have regular or only periodic use. Practical approaches, such as effective BMPs with high implementation rates, and visual audit methods that provide affordable assessments of water quality protection, will need to be part of any forest road pollution control program. Montana's success shows the importance of a culture of BMP implementation and water quality protection. Evidence of practices going beyond the BMP guidelines and improved protection of soil and water, especially for forest roads, shows how maintaining a viable forest products industry can lead to improved watershed protection under the right conditions.

Conclusion

The CWA has allowed states to tailor nonpoint forestry programs to their unique needs. Montana's blended approach of voluntary BMPs with regulatory SMZs has yielded above-average BMP implementation rates nationally (Ice et al. 2010). Education efforts that empower logging professionals and landowners to make harvest management and road planning and design decisions and a full commitment to BMPs by agencies and industrial landowners have been key elements in improving the protection of soil and water resources in Montana. Among loggers, the BMP program is viewed as a commonsense approach, and there is very strong buy-in. The cooperative attitude of Montana DNRC leadership and staff has also been a defining factor in the success of the program. There has also been tremendous support for the program among the natural resource professionals and others who volunteer for audit teams. They are proud of the changes they have seen over their time and are tremendous advocates for the program.

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APPLIED RESEARCH

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soils & hydrology

Estimated Sediment Reduction with Forestry Best Management Practices Implementation on a Legacy Forest Road Network in the Northern Rocky Mountains

Brian D. Sugden

This study modeled changes in sediment delivery to streams in response to systematic Best Management Practice (BMP) upgrades to a 28,000 km forest road network in western Montana and northern Idaho. Key BMPs applied included installing more frequent road drainage features to disperse runoff entering streams, managing public road access to reduce the need for ongoing maintenance, increasing road surface vegetative cover, and installing supplemental filtration near streams. The Washington Road Surface Erosion Model (WARSEM), with locally validated model assumptions, was used to estimate fine sediment delivery before and after BMP upgrades. Results from 10 repeated watersheds (inventoried and modeled before and after BMPs) estimated that sediment delivery (weighted by watershed road length) was reduced by 46% (watershed range: –84% to +57%) over a 10–15-year period. Delivery rates from these watersheds were similar to an additional 22 watersheds that were inventoried after BMP upgrades had been completed. Road sediment delivery from surface erosion estimated by WARSEM in BMP-upgraded watersheds represented less than a 5% increase above background erosion rates in this region.

Keywords: legacy forest roads, sediment, surface erosion, Best Management Practices, road runoff, road erosion control

Introduction

Forest roads that are improperly located, constructed, or maintained can deliver sediment-laden stormflow into streams, with negative effects on water quality and aquatic ecology. Comprehensive reviews of these impacts are provided by Furniss et al. (1991), NCASI (2001), and Endicott (2008). A leading cause of stream impairment nationally is sediment (USEPA 2017), and roads can increase sediment delivery to streams from erosion of road surfaces (Megahan and Kidd 1972, Reid and Dunne 1984, Bilby et al. 1989, Luce and Black 2001), mass erosion generated by landslides, or stream crossing failure (Sidle and Ochiai 2006, Furniss et al. 1991).

Best Management Practices (BMPs) for forest roads have been developed over the past half-century to minimize these impacts (Ice et al. 1997). Road BMPs exist for design, placement, construction practices, maintenance, temporary decommissioning, and complete decommissioning/reclamation (NCASI 2009). Recent literature reviews suggest that implementation of BMPs can reduce the impacts of forest roads on water quality and ecology (Ice and Schilling 2012, Cristan et al. 2016). Examples of modern BMPs include:

- Minimize the road density and area of road prism.
- Locate roads away from streams [i.e., outside Streamside Management Zones (SMZs)] unless stream crossings are required.
- Install road drainage features at regular intervals to reduce erosion and divert overland flow from roads onto undisturbed hillslopes to promote water infiltration.
- Ensure road runoff is disconnected from streams toward filtration areas.
- Re-vegetation and ground cover establishment on disturbed areas near streams (cutslopes, fillslopes, and road ditches).
- Gravel surfacing on highly erodible soils or when wet weather use is required.

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Affiliation: *Brian D. Sugden (Brian.sugden@weyerhaeuser.com), Forest Hydrologist, Weyerhaeuser Company, 2050 US Highway 2 West, Kalispell, MT 59901.*

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- Install supplemental filtration for suspended sediments where needed to prevent direct sediment delivery to streams. This includes slash windrows, silt fences, straw bales, etc.
- Install appropriately sized stream crossing structures that allow passage of flood flows, sediment, wood, and minimize disruptions to aquatic species movement.
- Manage/restrict seasonal road access to vehicles as needed to prevent rutting, and perform any necessary maintenance (grading) through time.
- Consider road closure or decommissioning of unneeded roads.

To address documented impacts to salmon habitat, states in the Pacific Northwest adopted regulatory BMP programs by the mid-1970s through state-legislated Forest Practices Acts (Ice et al. 2004). The 1987 reauthorization of the federal Clean Water Act further promoted state nonpoint source pollution planning through Section 319. It is up to states to select regulatory, non-regulatory (voluntary), or quasi-regulatory approaches to address nonpoint source pollution (Ice et al. 1997, Cristan et al. 2017). Montana adopted statewide voluntary BMPs in 1989, and a regulatory Streamside Management Zone (SMZ) Act passed the state legislature in 1991 (Montana Code Annotated 75-5-301). Today, all states have adopted BMP programs or forest practices acts for forest management activities, including roads (Cristan et al. 2017).

Nationally, state monitoring of BMP implementation shows high levels of compliance with forestry BMPs, regardless of whether state programs are regulatory or voluntary (Cristan et al. 2017). But recently, the US Environmental Protection Agency (USEPA) has expressed concern about "legacy roads" that were constructed prior to state adoption of BMP programs, and whether or not these roads are being effectively addressed (USEPA 2016). In some cases, older roads were not sited properly, are inadequately drained, and deliver significant quantities of fine sediment to streams (Ice and Schilling 2012). USEPA intends to facilitate information exchange on the impacts of legacy roads and their management (USEPA 2016).

In 2000, Plum Creek Timber Company (PCTC) owned 590,600 ha of forest land in western Montana and 16,300 ha in northern Idaho[1] (Figure 1). This land base was accessed by a 28,000 km forest road network, which included roads on the ownership, as well as jointly managed roads leading to the ownership. It is estimated that 85–90% of this road length was built prior to Montana's adoption of forestry BMPs in 1989 and passage of the Idaho Forest Practices Act in 1974. In steeper terrain, old mainline roads accessing watersheds often were built along watercourses (i.e., stream-adjacent roads), contrary to contemporary forestry BMP standards. In more gently sloping glaciated terrain, watersheds were accessed by fewer stream-adjacent roads. Original culverts on legacy roads in this region often only accommodated a 5–10-year flood event, rather than being designed to meet or exceed the current BMP standard of a 25-year event in Montana and a 50-year event in Idaho. Old roads were constructed with inadequate surface drainage by today's BMP standards. Water would often be routed hundreds to thousands of meters down roads (in roadside ditches or in tire depressions/ruts in the road surface) and deliver directly to streams.

PCTC began upgrading legacy roads by the early 1990s in conjunction with ongoing forest management activities under Montana's voluntary BMP program. In 1994, PCTC enrolled its lands in the Sustainable Forestry Initiative (SFI™), which requires adherence to state BMPs as a condition of certification (SFI 2015). In November 2000, PCTC entered into a 30-year Native Fish Habitat Conservation Plan (NFHCP) agreement with the US Fish and Wildlife Service (USFWS) to protect and restore streams on this ownership (USFWS et al. 2000). Under the plan, PCTC had 10–15 years (depending on watershed priority) to upgrade legacy roads to current BMP standards. All new roads were constructed following BMPs.

This study was undertaken to help address a critical information gap on the effectiveness of state BMP programs at addressing legacy roads. Specific objectives were to: 1) Estimate landscape-scale reductions in sediment delivery to streams from road surface erosion with BMP upgrades in sample watersheds; 2) Compare post-BMP upgrade estimates of sediment delivery with background watershed erosion rates; and 3) Examine patterns in sediment delivery to help inform ongoing road management.

Study Area

The study area is in the Northern and Middle Rockies Ecoregions of western Montana and northern Idaho (Omernik 1987). The climate is continental-maritime, with annual precipitation on PCTC lands averaging 750 mm (Table 1). Typically, 50–70% of annual precipitation falls as snow. Rainfall erosivity in this area is among the lowest in the nation (Renard et al. 1997). This is due to the small fraction of total annual precipitation in the summer, when higher-intensity convective storms occur. Stream densities in study watersheds based on the National Hydrography Dataset (NHD) average 2.0 km/km^2 (Table 1).

Most of the study area is underlain by metasedimentary Precambrian rocks of the Belt Supergroup, which is primarily composed of argillites, quartzites, and limestones (Ross 1963). In northwestern Montana, approximately 75% of the landscape is covered by tills that were deposited following retreat of Quaternary continental and alpine glaciers (Johns 1970). Tills are primarily derived from Belt Supergroup parent materials. The Hydrologic Soil Group classifications for study area soils are dominated by Groups A and B (USDA 2007). These groups have low-to-moderate runoff potential, with saturated hydraulic conductivities greater than 3.6 cm/hr. Roadbed soil textures for both tills and residual soils formed in the

Management and Policy Implications

Many forest roads were constructed prior to state adoption of forestry BMP programs, and these legacy roads can contribute significant quantities of sediment to streams. Over time, forest landowners and agencies are upgrading legacy roads to current BMP standards. But no previous estimates of landscape-scale benefits of such BMP implementation exist for this region. Our repeated road inventories and modeling estimates that sediment delivery from road surface erosion was reduced by 46% during a 10–15-year period of systematic BMP upgrades. This research also highlights the importance of field inventories, which can identify the minority of crossings that contribute the majority of sediment to streams. While there are other mechanisms for road sediment to enter streams, such as landslides and stream crossing failures, our results suggest that road surface erosion with BMP implementation can be managed to contribute a small fraction of watershed sediment loading rates in this region.

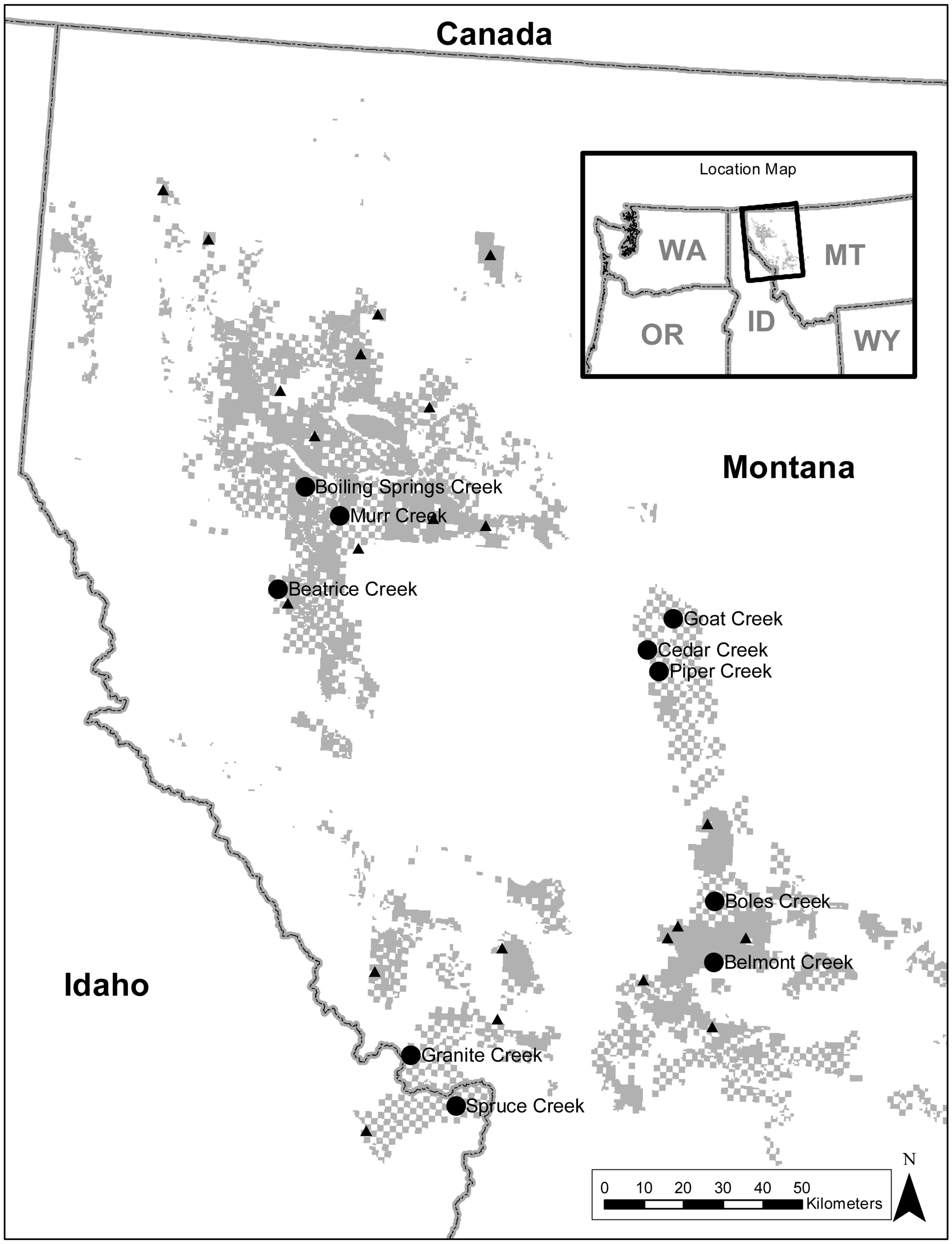

Figure 1. Locations of ten repeated-inventory road sediment delivery study watersheds (circles), and 22 post-BMP upgrade study watersheds (triangles). Plum Creek Timber Company (PCTC) ownership (as of 2000) is in gray shade.

Belt Supergroup tend to be very or extremely gravelly sandy or silt loams (Packer 1967, Sugden and Woods 2007). The distribution of soil types on PCTC land in the study area is: glacial till (45%), residual soils in Belt Supergroup (34%), granitic (2%), and other types (e.g., alluvial, lacustrine, and volcanic) based on mapping compiled by Ford et al. (1997).

Road grades in the study area average 6.9% (Standard Deviation 3.7%) in Belt geology and 5.1% (Standard Deviation 3.0%) in tills (Parker 2005). With this precipitation regime and rocky soils, most study area roads are un-ditched and the running surface outsloped, with additional drainage provided by drivable drain dips (also commonly referred to as broad-based, rolling, or grade dips). These dips are excavated into the road running surface and convey water off the road and onto the hillslope below. They are permanent structures, and can be negotiated by log trucks. Drivable drain dips have more diffuse lead-outs than ditch relief culverts, and less concentrated flow, so sediment travel distances are substantially shorter than below relief culverts (Megahan and Ketcheson 1996, Woods et al. 2006). Because of the predominance of gravelly glacial till and residual soils, most roads in this area are native-surfaced. However, this type of surfacing requires attention to wet weather haul conditions and frequent road surface drainage (Packer 1967). Ditched roads are estimated to comprise about 20% of study area roads, with the road running surface generally constructed with a crown.

Methods

Road sediment delivery to streams was estimated using the Washington Road Surface Erosion Model (WARSEM) (WFPB

Table 1. Attributes of 10 repeated-inventory watersheds, 22 post-BMP upgrade watersheds, and the entire PCTC ownership in the study area.

Watershed name	Assessment year(s)	Geologic type(s)	Watershed area	Mean annual precipitation	Total road length	Watershed stream density	Number of inventoried delivery locations following upgrades	Road hydrologic connectivity before and (after) upgrades
Replicated inventory watersheds			*km² (%PCTC)*	*mm*	*km (%PCTC)*	*km/km²*	*Count*	*%*
Beatrice	1997, 2005, 2010	Belt, Till	26.6 (47%)	984	97.6 (65%)	2.5	38	8.2 (5.9)
Belmont	1994, 2005, 2010	Belt	77.2 (83%)	734	324.1 (85%)	2.3	109	15.4 (6.0)
Boiling Springs	1997, 2005, 2010	Till	22.2 (85%)	736	85.2 (91%)	1.9	24	2.5 (1.6)
Boles	1998, 2005, 2010	Till, Belt	53.6 (37%)	904	128.9 (76%)	1.9	27	1.6 (1.8)
Cedar	1997, 2005	Till	77.5 (29%)	1021	91.6 (78%)	1.9	14	3.5 (2.0)
Goat	1996, 2005, 2010	Till	91.0 (25%)	1188	147.0 (74%)	2.3	20	1.4 (1.2)
Granite	1998, 2005	Granite	53.8 (33%)	1155	139.1 (62%)	2.3	81	8.6 (8.3)
Murr	1997, 2005, 2010	Belt	80.6 (49%)	867	208.8 (90%)	1.4	53	1.8 (1.3)
Piper	1996, 2005	Till	32.1 (21%)	1096	36.8 (82%)	1.9	11	2.7 (1.6)
Spruce	1996, 2005	Belt, Other	65.1 (37%)	1178	69.3 (95%)	0.8	89	17.8 (11.2)
Totals			580 (43%)	986 (Mean)	1328 (80%)	1.9 (Mean)	466	6.4% (4.1%) Mean 3.1% (1.9%) Median
Un-replicated post-BMP upgrade watersheds								
Albert	2007	Belt	36.9 (42%)	835	79.9 (71%)	2.5	11	(1.5)
Ashby	2006	Belt, Other	49.7 (62%)	534	154.6 (89%)	2.5	51	(2.0)
Barnum	2006	Till, Belt	29.7 (78%)	874	73.5 (95%)	1.7	29	(2.1)
Bear	2005	Belt	28.5 (21%)	898	49.2 (66%)	1.9	8	(7.5)
Bear 2	2007	Belt	12.2 (75%)	983	58.1 (97%)	2.4	27	(3.3)
Big Rock	2008	Belt, Till	85.4 (31%)	942	154.8 (84%)	2.2	70	(3.2)
Blanchard	2005	Belt, Till	71.5 (88%)	676	260.5 (91%)	2.2	59	(4.0)
Blue	2009	Till, Belt	24.7 (85%)	970	73.9 (69%)	2.0	39	(3.1)
Brush	2003	Till, Belt	24.5 (39%)	782	51.8 (68%)	1.9	49	(8.9)
Cow	2003	Till, Belt	42.5 (29%)	835	94.0 (60%)	1.9	28	(4.8)
Fish	2007	Till, Belt	7.2 (34%)	808	24.2 (68%)	0.9	9	(3.6)
Freeland	2004	Till, Belt	32.1 (74%)	788	130.6 (89%)	2.3	41	(1.8)
Johnson	2004	Belt, Till	22.6 (37%)	797	31.9 (94%)	1.9	18	(6.8)
Jungle	2002	Till, Belt	22.2 (68%)	927	105.4 (82%)	2.1	25	(1.0)
Lazy-Swift	2010	Till, Other	62.0 (100%)	698	180.7 (100%)	1.2	24	(0.6)
Little Meadow	2009	Till, Belt	69.0 (93%)	680	267.9 (87%)	2.2	32	(1.2)
Little Wolf	2006	Till, Other	98.8 (70%)	683	276.9 (83%)	1.9	72	(2.1)
Parachute	2002	Belt, Other	10.5 (51%)	1152	49.0 (84%)	1.9	15	(1.5)
Upper Gold	2009	Till, Belt	74.8 (55%)	912	185.0 (94%)	2.0	46	(2.0)
Upper Pipe	2010	Till, Belt	24.2 (49%)	1013	83.4 (66%)	1.9	19	(1.2)
WF Clearwater	2008	Till	87.3 (57%)	1072	267.2 (94%)	1.7	133	(2.9)
WF Gold	2006	Till, Belt	52.0 (59%)	865	125.3 (95%)	2.0	53	(2.2)
Totals			968 (62%)	858 (Mean)	2778 (86%)	2.0 (Mean)	858	3.0% (Mean) 2.1% (Median)
Entire PCTC ownership in study area (year 2000)		Till (45%) Belt (34%) Granitic (2%) Other (19%)	6073	750	28,000	1.6		

1993). The method relies on field observations of stream crossings and stream-adjacent/parallel road segments to populate a simple empirical model, which estimates long-term average amounts of sediment for roads with similar conditions (Dubé et al. 2004). Roads are carefully inspected, and at each delivery location, the road area that contributes sediment to streams is measured. This area (length and width) is measured separately for each road prism component: cutslope, fillslope, and tread (WFPB 1993). A base erosion rate per unit area of contributing road is assigned based on the local geologic type. WARSEM provides default literature base erosion rates where local data are not available. The base rate is then modified for the traffic level on the road, presence and depth of gravel surfacing, vegetative cover, and precipitation. Modifications to the base erosion rate are derived from literature values contained in WARSEM or other available documented sources. Additional supporting documentation on the methodology is provided by Dubé et al. (2004).

While widely applied across the Pacific Northwest, WARSEM performance at a watershed scale has had limited direct validation. Surfleet et al. (2011) evaluated WARSEM in an Oregon and California watershed, and found that predictions were substantially improved with local field measurements of runoff and sediment. With field calibration, WARSEM predictions were within 50% of measured yields. Dubé et al. (2011) also found that field calibration is essential for empirical road erosion models like WARSEM if absolute values are needed.

For this study, base erosion rates were obtained from erosion plot data for PCTC roads in the study area in Belt Supergroup and glacial till soils (Sugden and Woods 2007). In each soil type, 10 road plots were selected based on a stratified random sampling of the PCTC road network. Each plot was measured for three years, and a regression model was fit to the data. The model explained 68% of the variability in sediment yield. Based on the regression model, a WARSEM base erosion rate for each soil type was calculated for a 7% roadbed slope that is annually maintained by road grading. Base erosion rates were 1.0 Mg/ha/yr for roads in Belt Supergroup soils, and 4.3 Mg/ha/yr in glacial till soils (Sugden and Woods 2007).

A second key model assumption in WARSEM is the fraction of total erosion from the inventoried contributing area that delivers to streams (i.e., the delivery ratio or percentage). In cases of direct sediment delivery to streams via a gully or ditch, 100% delivery was assumed per the standard methodology (WFPB 1993). Other drainage features within 60 m of streams were evaluated for indirect (overland) delivery. To do this, the surveyor walked downslope of drainage feature outfalls, following visible sediment flow paths to their end. Observations were made on slope steepness, sediment deposits, hillslope obstructions such as down logs and vegetation, distance from the sediment flow path terminus to the stream, and any designed mitigations in place (such as slash filter windrows). Based on these observations, the surveyor assigned an indirect delivery percentage ranging from zero (no delivery) to 100%. If a visible sediment flowpath ended more than 10 m from the stream, zero delivery was assigned. Sediment flowpaths terminating closer to the stream than 10 m were generally assigned 10 to 50% delivery, based on field observations of the sediment plume and travel distance, and guided by sediment plume volume versus distance relationships for granitic soils developed by Megahan and Ketcheson (1996). Overland sediment flowpaths reaching the stream were generally assigned a delivery rate of 75–100%. Unless the stream was located very close to the erosion source, this delivery ratio is conservatively high (Megahan and Ketcheson 1996, Ward and Jackson 2004, Lakel et al. 2010). Subsequent to the majority of these road inventories being completed, sediment travel distance below drivable drain dips in the study area was evaluated for glacial till and Belt Supergroup soils (Parker 2005, Woods et al. 2006). They found mean travel distances (as measured from the toe of fillslopes) of 4.0 m for tills and 3.2 m for Belt Supergroup geology. Dimensionless curves of sediment plume volume versus distance from source in tills and Belts were similar to those developed by Megahan and Ketcheson, though slightly more linear. This is likely explained by the finer soil textures in the study area.

Between 1994 and 1998, PCTC did a road inventory and estimated road sediment delivery with WARSEM for 10 watersheds in the study area prior to most BMP upgrades being undertaken (shown as circles in Figure 1). Six study watersheds in the Swan and Thompson River Basins were selected to represent variation within these basins and across the company's larger western Montana ownership. The other four study watersheds were selected because of perceived sediment delivery impacts, or to support environmental assessments for federal land access. These 10 baseline assessments from the 1990s were repeated in 2005 and 2010 as BMP upgrades were in progress to estimate reductions achieved by road upgrading (Table 1). Re-measurements were made on this schedule unless the land was sold, or the company did no BMP upgrades or new watercourse crossings.

An additional 22 watersheds were inventoried and modeled using WARSEM over the time period 2002–2010 after BMP upgrades had been completed (Table 1, Figure 1). The assessments were completed in watersheds with populations of native trout, highly erodible soils, or in areas that supported state water-quality planning. These additional assessments serve as an expanded sample to compare road sediment delivery estimates to the 10 repeated-inventory watersheds. Combined, the 10 repeated-inventory watersheds and the 22 additional watersheds encompass 14% of PCTC ownership in the study area (Table1).

The WARSEM methodology allows for sampling of the road network. However, in nine of the 10 repeated watersheds in this study (and all 22 post-BMP watersheds), all stream crossings and stream-adjacent roads were assessed. The one exception is Belmont Creek, where the road network was stratified and sampled in the baseline data collection year of 1994. In Belmont, the strata of moderate-traffic roads was 100% sampled, and strata of light-use roads was 10% sampled. In aggregate, 25% of the road network was sampled in the baseline year. In reassessments of Belmont Creek, a 100% inventory was conducted.

Only road sediment delivery points that were connected to downstream waters were included in the sediment budget for watersheds. For example, sediment delivery to an intermittent stream was not included in the watershed sediment budget if the channel entirely disappeared downslope and no sediment routing to downstream waters was deemed possible. This lack of stream connection is not uncommon in the semi-arid, post-glaciated landscape of western Montana.

Quality assurance and control of field data was managed in several ways. In addition to the author, three hydrologists with forest road BMP experience performed all surveys. If a hydrologist had no prior training in the WARSEM field data collection protocol, field training was provided by the author, who is trained in the methodology by WFPB. Unless the author was also present, hydrologists worked individually to inventory watersheds. All assessments were reviewed and field-checked. For consistency, repeated watershed surveys were performed by the same hydrologist, and the prior inventory data was reviewed to see what specific conditions had changed at each delivery location.

Throughout the entire study area, the BMP condition of all roads, based on PCTC forester field inspections, was tracked in a geographic information system (GIS). The GIS road information was updated annually, based on additional inspections and road upgrading that was accomplished. This landscape-scale tracking provided a basis for evaluating confidence in extrapolating results from sample watersheds to the larger study area.

Background sediment yields for watersheds in or near the study area were obtained from all available sources that could be located, both in the published literature and other available federal agency monitoring data. This search was restricted to less disturbed forested watersheds draining less than 100 km^2 to be most comparable to our study watersheds.

Results

Across PCTC ownership in this landscape, 44% of the road network in 1998 was compliant with BMPs (Figure 2). Between 1998 and 2005, approximately 6% of company roads were upgraded annually, after which time the pace slowed to about 1% annually, until the NFHCP BMP upgrade commitment was fulfilled at the close of 2015. During the period 2001–2015, 330 km of PCTC

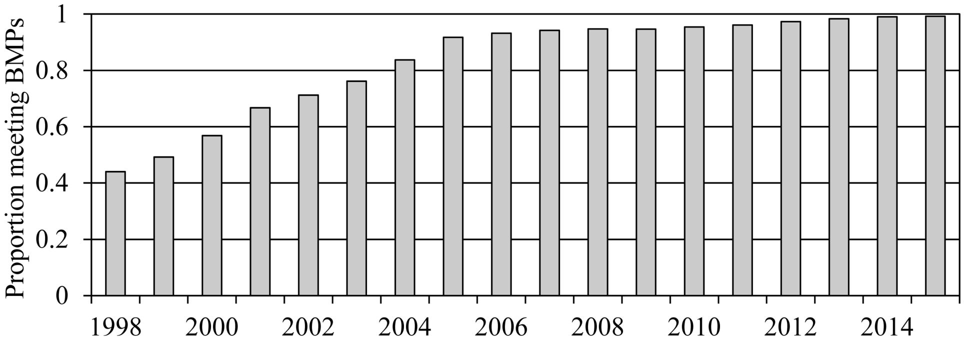

Figure 2. The proportion of Plum Creek Timber Company (PCTC) roads in the western Montana and northern Idaho study area meeting road best management practices (BMPs) by year, based on PCTC forester inventories as tracked in GIS.

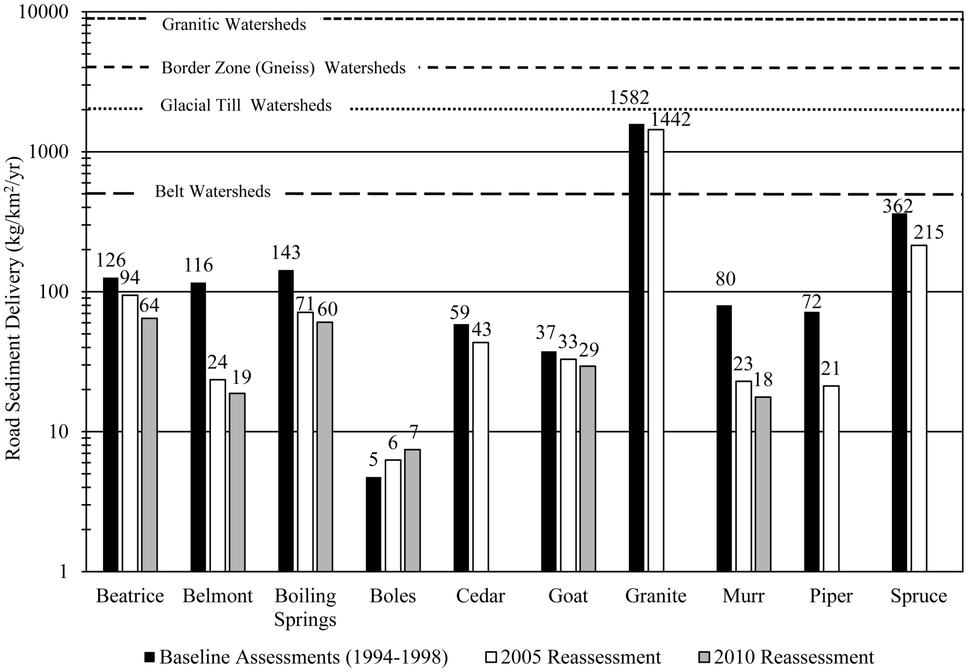

Figure 3. Estimated sediment delivery to streams from surface erosion (kg/km²/yr) for 10 repeated-inventory study watersheds in western Montana and Northern Idaho by survey year. Horizontal bands are lower-range estimates of background watershed sediment loading from less disturbed forest watersheds draining less than 100 km².

roads were decommissioned across the study area, and 940 km were constructed.

Weighted by length of PCTC roads, the mean estimated reduction in sediment delivery from road surface erosion in the 10 repeated-inventory watersheds was –46% (Figure 3). The observed range was –84% (Belmont Creek) to +57% (Boles Creek). Median road sediment delivery per unit watershed area was 36 kg/km²/yr. A higher mean rate of 192 kg/km²/yr (Standard Deviation = 443 kg/km²/yr, Standard Error = 140 kg/km²/yr) was driven by the high erosion rate in Granite Creek, which is in the southwestern corner of the study area and in the 2% of the study area containing granitic soils. Nine of 10 watersheds had reduced delivery compared to the baseline. Explanation of watershed-specific results is provided in the Discussion section.

For 22 post-BMP watersheds inventoried between 2002 and 2010, the median watershed sediment delivery was 48 kg/km²/yr, and the mean was 54 kg/km²/yr (Standard Deviation = 37 kg/km²/yr, Standard Error = 8 kg/km²/yr). A box plot comparing the BMP upgraded condition in the 10 repeated-inventory watersheds with the 22 post-BMP watersheds suggests similar estimated delivery rates (Figure 4).

In the 10 repeated watershed baseline inventories, 6.4% (Range: 1.4–17.8%) of the total road length was found to contribute directly or indirectly to streams (i.e., was “hydrologically connected”). After upgrading, the mean connectivity decreased to 4.1% (Range: 1.2–11.2%) (Table 1). For the 22 post-BMP watersheds, the mean connectivity was 3.0% (Range: 0.6–8.9%).

A majority of estimated sediment delivery occurred at a minority of road stream crossings inventoried. From the baseline inventories in the 10 watersheds (2005 inventory for Belmont), 25% of inventoried crossings contributed 50–75% of total watershed sediment delivery (Figure 5).

Discussion

Watershed-Specific Results

Watershed-specific reduction in road sediment delivery was variable (Figure 3). The greatest estimated reduction in sediment

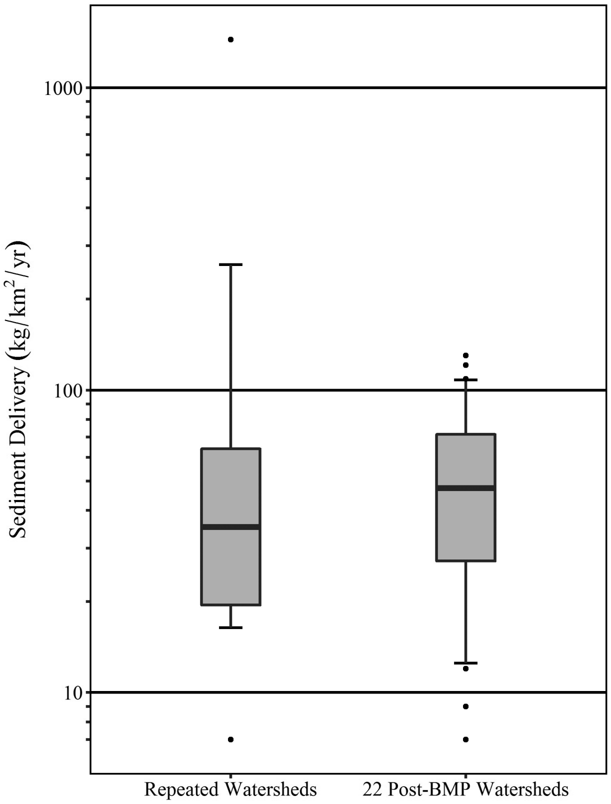

Figure 4. Estimated annual sediment delivery to streams in 10 repeated-inventory watersheds (post-upgrades) and in 22 other post-BMP upgrade watersheds inventoried between 2002 and 2010. Solid horizontal line in middle of box indicates the median. Box ends indicate the 25th and 75th percentiles. Whiskers indicate the 10th and 90th percentiles. Outliers shown as black dots.

delivery was in Belmont Creek (–84%). This watershed had the oldest baseline inventory (1994), and few road segments met BMPs at that time (Sugden 1994). Additionally, PCTC managed almost all of the road network in the Belmont Creek watershed, providing the most opportunity for BMP upgrades to positively affect delivery rates.

Boles Creek was the only watershed to experience an increase in estimated sediment delivery, but it had the lowest absolute loading rate of the 10 repeated-inventory watersheds, at 7 kg/km^2/yr (Figure 3). In the baseline year of 1998, road BMPs were generally applied across the Boles Creek watershed, limiting the sediment reduction benefit of additional upgrades. For the 18 original crossings inventoried in Boles in 1998, sediment delivery was reduced 18% by 2010. However, 13 km of new road was built in this basin with current BMPs (after the baseline inventory), which added seven new sediment delivery locations (five crossings and two stream-adjacent segments). Despite being constructed with current BMPs, these new roads and their active use increased total sediment delivery at a watershed level.

Granite Creek had the highest estimated delivery at 1442 kg/km^2/yr. Roads in this watershed are constructed in granitic soils, which are substantially more erodible than the other soils in the study area. For this inventory, we relied on the WARSEM default base erosion rate for established roads in granitic soils (67 Mg/ha/yr), which was based on research conducted in the Idaho Batholith of central Idaho (WFPB 1993). It could be that actual base erosion rates in Granite Creek differ from the Idaho Batholith research, but we had no location-specific data to support modification of the WARSEM rates such as we had for glacial tills and Belt Supergroup materials. Granite Creek had only a 9% decrease in estimated delivery reduction. The primary reason for this relatively small reduction is that many higher-delivery locations were on roads for which PCTC did not have management responsibility.

Spruce Creek in Idaho had a near-average reduction in estimated delivery (–41%), but the post-upgrading absolute rate was second highest, at 215 kg/km^2/yr. Spruce Creek has one of the highest precipitation rates of study watersheds at 1178 mm/yr. While the calculated stream density based on NHD is only 0.9 km/km^2 (Table 1), the on-the-ground stream density is much higher in this watershed. Because of this, the number of delivery locations per unit road length is the highest of any study watershed.

BMP Evaluation

Exploration of the 10-watershed dataset found that most of the decrease in estimated sediment delivery was explained by reducing the length of road delivering to streams, which decreased by 36%. This was typically done by installing drivable drain dips in the road surface so that runoff distances generally did not exceed 75 to 125 m. Near streams, drivable drain dips were located as close to the stream crossing as possible while still ensuring effective filtration below the dip outlet. The remaining reduction in sediment delivery was achieved through other BMPs. One included improved management of public use through seasonal or annual road use restriction via gates or barricades. Road use restriction reduced the frequency of road grading and increased vegetative cover on roads, the combined effect being substantially lower road erosion rates (Luce and Black 2001, Sugden and Woods 2007, Al-Chokhachy et al. 2016). Improvements to filtration near stream crossings, both on the fill above road culverts, and below drainage feature outfalls near streams, also contributed to reduction in road sediment delivery. Filtration improvements included widespread use of grass seeding, straw mulch, and slash filter windrows, which have all been shown to be highly effective at reducing erosion and sediment delivery (Cook and King 1983, Burroughs and King 1989, NCASI 2009, Wade et al. 2012). Twelve kilometers of road was decommissioned during the study in the replicated watersheds, but this had little overall effect on watershed sediment loading rates since these roads were not in priority delivery areas.

Hydrologic Connectivity

Watersheds with higher hydrologic connectivity (Table 1) tended to have more stream-adjacent roads where delivery could not be fully mitigated, more roads for which PCTC had no management control, or areas with greater annual precipitation and higher associated stream density (i.e., Spruce, Granite, and Brush Creeks). Watersheds with lower hydrologic connectivity were often in glaciated terrain where the majority of roads were in areas with low stream densities and fewer crossings (e.g., Goat Creek, Lazy-Swift Creek). Hydrologic connectivity cannot reach zero, as there will always be some remaining road segment that cannot be fully disconnected at stream crossings. However, additional BMPs can be employed to reduce the fraction of road surface erosion being delivered to streams at these locations. Examples of these BMPs include slash filter windrows, silt fences, and infiltration basins.

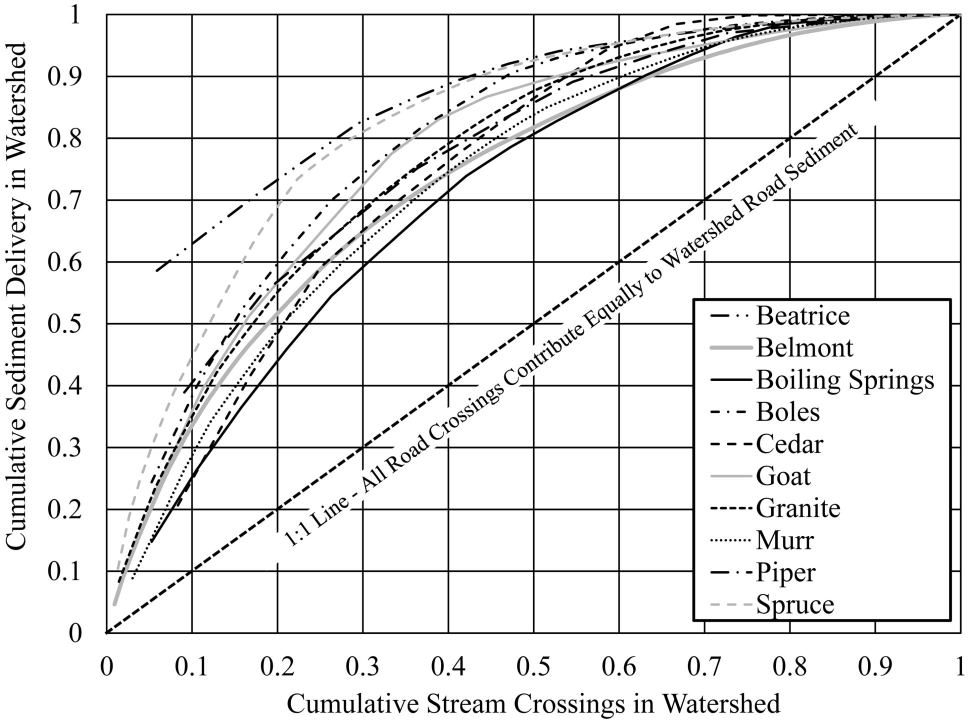

Figure 5. Cumulative sediment delivery from stream crossings in each study watershed as a function of cumulative stream crossings.

Another investigation of road hydrologic connectivity in the study area was completed by the US Forest Service in 2012–2013, and two of their study watersheds included significant land recently acquired from PCTC (Cissel et al. 2014, Al-Chokhachy et al. 2016). They reported mean road hydrologic connectivity in these areas of 4%, which is consistent with these results.

In Washington, legacy forest roads are being addressed through Road Maintenance and Abandonment Plans (RMAP). In eastern Washington, which has precipitation patterns and stream densities similar to this study area, Dubé et al. (2010) reported 6% mean (4% median) hydrologic connectivity for roads after most RMAP BMP upgrades had been completed. This level of hydrologic connectivity is similar to our study, and substantially lower than the wetter climate and higher associated stream densities in western Washington (Bilby et al. 1989, Dubé et al. 2010).

Patterns in Estimated Delivery

The finding that a small percentage of road crossings both generate and deliver the majority of sediment to streams (Figure 5) has important implications for managing stream sediment loading across managed forest landscapes. A simple analysis of watershed road density or a GIS intersection of roads with streams may identify places to prioritize field investigation, but erosion and delivery can only be assessed by on-the-ground inspection. Knowledge of site-specific conditions is essential to determining locations where BMP upgrades would achieve the highest impact for the lowest cost. Such conditions include the presence of direct-delivery ditches or road surface runoff, road ruts, actively eroding road cutslopes, vegetative cover, presence of gravel surfacing, and sediment filtration BMPs such as slash filter windrows. This observation has been reported by others who have conducted similar road inventories (McGreer et al. 1998, Al-Chokhachy et al. 2016).

Interestingly, even after upgrading, it was found that the dimensionless cumulative delivery curves shown in Figure 5 retained a non-linear shape. While watershed sediment delivery may sharply decline following BMP upgrades, there are still locations that inherently contribute more sediment at a watershed scale. This is the result of most watersheds having a mix of more and less heavily trafficked roads, difficult situations to fully mitigate, and many well-vegetated roads that contribute very little to watershed sediment delivery.

Background Erosion Rates

While a 46% decrease in road sediment delivery is substantial, it is helpful to place loading rates into context with total watershed suspended sediment yields. Background yields in the northern Rockies have been found to vary by orders of magnitude based on the time scale examined, with shorter (more recent) periods usually having substantially lower measured yields than longer periods due to the disproportionately large effect of infrequent events such as floods following wildfire (Kirchner et al. 2001). A range of published and unpublished estimates of sediment yields from small forest watersheds in this region by geologic type indicates that estimates of background sediment loading for these watersheds have levels of confidence that range from low (suspended sediment grab samples) to moderate/high (research watershed data—installed flumes, automated sampling). Data found for the study region are summarized in Table 2.

Based on the studies in Table 2, the range in yields for different geologic materials are: Belt Supergroup (500–2000 kg/km^2/yr); glacial tills (2000–6000 kg/km^2/yr); northern Idaho gneiss/Belt Supergroup (4000–7000 kg/km^2/yr); and Idaho Batholith granitics (~9000 kg/km^2/yr). Using the lower range from the range of background erosion rates for the different geologic groupings (horizontal lines in Figure 3) indicates that the sediment contribution by

Table 2. Annual background watershed sediment yields in various geologies from the region of this study. Yields footnoted with an asterisk include some bedload fraction.

Location	Predominant surficial geology	Length of record	Total suspended sediment yield	Data source	Level of confidence
		years	*kg/km²/yr*		
Johnson Gulch, MT	Belts	5	500	Anderson and Potts (1987) and subsequent unpublished data	Moderate/High
NF Blackfoot River, MT	Belts, Till	18	2800	Lolo National Forest unpublished data (from Cissel et al. 2014)	Low
Lion Creek, MT	Till, Belt	9	2800	Flathead NF Forest Plan monitoring data, unpublished	Low
Elk Creek, MT	Till, Belt	9	6000	Flathead NF Forest Plan monitoring data, unpublished	Low
Goat Creek, MT	Till, Belt	7	2200	Flathead NF Forest Plan monitoring data, unpublished	Low
Mica Creek, ID Watershed 1	Gneiss / Quartzite	6	5500	Karwan et al. 2007	Moderate/High
Mica Creek, ID Watershed 2	Gneiss / Quartzite	6	6000	Karwan et al. 2007	Moderate/High
Mica Creek, ID Watershed 3	Gneiss / Quartzite	6	4400	Karwan et al. 2007	Moderate/High
Horse Creek, ID East Fork	Gneiss / Belts	13	4500*	Larson and Sidle 1980	Moderate/High
Horse Creek, ID West Fork	Gneiss / Belts	13	7500*	Larson and Sidle 1980	Moderate/High
Silver Creek, ID WS-3 (Control)	Granitic	28	8900*	Kirchner et al. 2001	Moderate/High

roads after BMP upgrades in this area typically fall between 1 and 5% of background watershed sediment yield. Beatrice Creek roads were higher, at 13% of the lower-range background estimate and 3% of higher-end range, due to a higher fraction of stream-adjacent road contribution that could not be fully mitigated without road removal. Roads in Granite Creek are estimated to deliver about 16% of background sediment yield, but additional BMP upgrade opportunities still exist in that watershed. While background erosion estimates based on suspended sediment measurement can be subject to significant errors (Bunte and MacDonald 1999), this comparison does suggest that roads in this region, if managed properly, can contribute a relatively small fraction of total watershed sediment yields.

Applicability of Results

These findings compare favorably with those of Cissel et al. (2014), who evaluated former PCTC land in the study area. They used the Geomorphic Road Assessment Inventory Procedure (GRAIP) model (Black et al. 2012), which is also based on field-obtained data. For their three study areas, Cissel et al. reported road surface erosion contributions of 100, 190, and 210 kg/km²/yr. These values are slightly higher than rates we observed at most of the repeated-inventory and post-BMP watersheds in this study (Figure 5). Cissel et al. estimated that their road sediment delivery rates represented 1–2% of background rates.

Estimated road sediment delivery per unit watershed area is very low in this western Montana and northern Idaho study area. Factors that contribute to this include: 1) low amounts of summer rainfall and thus low annual rainfall erosivity; 2) a relatively low stream drainage density; 3) the low erodibility of coarse soils (Packer 1967, Sugden and Woods 2007); and 4) some streams are discontinuous, lacking a surface flow connection to downstream waters.

PCTC only had direct, or shared, management responsibility for about 85% of the roads in these watersheds (Table 1). The pace of BMP upgrades on roads managed by other owners was slower than that on PCTC lands, so full upgrading of all roads did not occur in many of these watersheds. If baseline data for all study watersheds been collected in the late 1980s prior to any road upgrades, it is likely that the documented reductions would have been even greater. It is possible that moving from a no-BMP road network to a full-BMP road network could have reduced loading on the order of 80–90%, which is consistent with results for Belmont Creek, and other estimates of BMP effectiveness (NCASI 2009, Reiter et al. 2009, Ice and Schilling 2012, Nolan et al. 2015, Cristan et al. 2016).

Legacy road BMP upgrading is occurring in Montana across all ownership categories. Between 2000 and 2010, state BMP implementation monitoring revealed that two-thirds of audit sites in Montana had legacy road BMP improvements that were judged by audit teams to have reduced overall sediment loading in the watershed (Sugden et al. 2012). This clearly demonstrates that active management provides opportunities for landowners to make significant improvement to reducing sediment delivery by upgrading legacy roads to modern state BMPs.

Sources of Uncertainty

The assigned base erosion rates and determination of indirect delivery are the factors with greatest uncertainty in the estimation of sediment delivery to streams using the model we employed. This uncertainty was reduced by the application of locally derived base erosion rates (Sugden and Woods 2007) and local information on downslope sediment movement below drivable drain dips (Parker 2005, Woods et al. 2006). However, there are additional sources of variability that are not accounted for in the regression model developed by Sugden and Woods (2007). Hydrologic measurements of road runoff likely could have helped improve our prediction of onsite road erosion in the WARSEM model (Surfleet et al. 2011). Cissel et al. (2014) conducted an independent analysis of road sediment loading in several watersheds in the study area that included former PCTC lands and roads. They collected their own empirical data on road erosion, used a different model (GRAIP), and reported results comparable to those in this paper (see also Al-Chokhachy et al. 2016).

Study watersheds were not randomly sampled. Rather, they were selected over time to represent the diversity of the soil types and terrain across the study area, and address other management questions. Sites ended up being well distributed across PCTC ownership (Figure 1); and combined, they represent 14% of the total ownership. Tracking condition of all roads in the PCTC GIS shows that BMP upgrades were applied across the landscape, and that results from sample watersheds should be broadly applicable.

Field measurements and determinations of sediment delivery percentages were made by four trained hydrologists, and the same hydrologist conducted repeated inventories. Spot-checks of field inventory data found that data were properly and consistently collected. Most inventories were made during dry-season conditions of late spring and summer (June, July, and August). However, evidence of sediment flowpaths in these silty soils generally remain visible during the dry season. Hydrologists were instructed to be conservative in determinations of indirect delivery percentages, and local data on sediment movement below drivable drips suggests this was the case (Parker 2005, Woods et al. 2006). Nonetheless, this is a source of uncertainty.

This study did not explore other potential road-related watershed sediment sources, such as landslides, gullies, or culvert failure, which may be locally significant (Al-Chokhachy et al. 2016). BMP upgrades over time are increasing the size of culverts, which is undoubtedly reducing failure risk, but is unquantified. Landslide risk in this study area is generally low relative to other parts of the Pacific Northwest (McGreer et al. 1998), but when landslides occur and deliver sediment to streams, it can represent a significant part of the watershed sediment budget.

Conclusion

This study found that as a large legacy road network on industrial forestland in the northern Rocky Mountains was systematically upgraded to current BMPs over a 10–15-year span, a 46% reduction in surface erosion sediment delivery to streams was estimated by a road surface erosion model. In the Belt Supergroup and glacial till soil types in this study area, road surface erosion where BMPs are fully applied is estimated to contribute less than 5% of background sediment loading rates.

Road surface erosion modeling based on comprehensive field surveys indicates that sediment delivery in these watersheds is dependent on the site-specific BMP conditions, and that a majority of watershed sediment delivery occurs at a minority of crossing locations. Field inspection by BMP-trained personnel can identify and prioritize BMP improvements or maintenance.

The road network assessed had a high level of forest management activity during the study period, which allowed for efficient BMP upgrades. While BMP upgrades were completed by the end of 2015 under a Native Fish Habitat Conservation Plan, most upgrades would have occurred anyway under state BMPs and corporate commitments under the SFI forest management standard. State monitoring of BMP implementation on private and public lands in Montana indicates that legacy road BMP improvements are being made across all ownership categories.

Endnote

1. In 2016, Plum Creek Timber Company (PCTC) merged with Weyerhaeuser. About half of the original land base described in this study is currently owned by Weyerhaeuser, with most of the remaining acreage now in federal or state ownership.

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The use of shaded fuelbreaks in landscape fire management

James K. Agee[a,*], Berni Bahro[b], Mark A. Finney[c], Philip N. Omi[d], David B. Sapsis[e], Carl N. Skinner[f], Jan W. van Wagtendonk[g], C. Phillip Weatherspoon[h]

[a]*College of Forest Resources Box 352100, University of Washington, Seattle, WA 98195, USA*
[b]*Placerville Ranger District, El Dorado National Forest, Camino, CA 95667, USA*
[c]*Systems for Environmental Management, Missoula MT 59802, USA*
[d]*Western Forest Fire Research Center (WESTFIRE), Department of Forest Sciences, Colorado State University, Ft. Collins, CO 80523, USA*
[e]*University of California in Davis, Davis, CA 95814, USA*
[f]*USDA Forest Service, Pacific Southwest Research Station, Redding, CA 96001, USA*
[g]*US Geological Survey, Biological Resources Division, Yosemite Field Station, El Portal, CA 95318, USA*
[h]*USDA Forest Service, Pacific Southwest Research Station, Redding, CA 96001, USA*

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Abstract

Shaded fuelbreaks and larger landscape fuel treatments, such as prescribed fire, are receiving renewed interest as forest protection strategies in the western United States. The effectiveness of fuelbreaks remains a subject of debate because of differing fuelbreak objectives, prescriptions for creation and maintenance, and their placement in landscapes with differing fire regimes. A well-designed fuelbreak will alter the behavior of wildland fire entering the fuel-altered zone. Both surface and crown fire behavior may be reduced. Shaded fuelbreaks must be created in the context of the landscape within which they are placed. No absolute standards for fuelbreak width or fuel reduction are possible, although recent proposals for forested fuelbreaks suggest 400 m wide bands where surface fuels are reduced and crown fuels are thinned. Landscape-level treatments such as prescribed fire can use shaded fuelbreaks as anchor points, and extend the zone of altered fire behavior to larger proportions of the landscape. Coupling fuelbreaks with area-wide fuel treatments can reduce the size, intensity, and effects of wildland fires. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Prescribed fire; Thinning; Forest fire; Western United States

1. Introduction

Fuelbreaks have a long history in the western United States, and interest in them has waxed and waned over past decades. Currently, there is renewed interest in the role of shaded fuelbreaks (where some forest canopy remains) in forest landscape management. The recent interest in fuelbreaks and similar concepts has even spawned new names, such as defensible fuel profile zones and community protection zones (Omi, 1996; Weatherspoon and Skinner, 1996). The term 'fuelbreak' is used here to describe areas manipulated for the common purpose of reducing fuels to reduce the spread of wildland fires, and in forested

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[*] Corresponding author. Tel.: +1-206-543-2688; fax: +1-206-543-3254.
E-mail address: jagee@u.washington.edu (J.K. Agee).

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areas the term is synonymous with 'shaded fuelbreak' as forest canopy is retained on site. We attempt here to describe the various key components that characterize fuelbreaks, evaluate their use, and discuss alternatives to traditional fuelbreak approaches.

A fuelbreak is 'a strategically located wide block, or strip, on which a cover of dense, heavy, or flammable vegetation has been permanently changed to one of lower fuel volume or reduced flammability' (Green, 1977). Green's definition of fuelbreak does not specifically define exactly how wide a fuelbreak may be, or exactly what kind of changes in fuel volume or reduced flammability are created. It differs from a fireline, defined by Green (1977) as 'a narrow line, 2–10 ft wide, from which all vegetation is removed down to mineral soil…' or a firebreak, 'specifically, a fireline wider than 10 ft, frequently 20–30 feet wide…'.

The effectiveness of fuelbreaks remains a subject of debate within and outside of the fire management community. There are many reasons for this broad range of opinion, among them that objectives can vary widely, fuelbreak prescriptions (width, amount of fuel reduction, maintenance standards) may also vary, they can be placed in many different fuel conditions, and may be approached by wildland fires under a variety of normal to extreme weather conditions. Furthermore, fuelbreaks are never designed to stop fires but to allow suppression forces a higher probability of successfully attacking a wildland fire. The amount of technology directed at the fire, and the requirement for firefighter safety, both affect the efficacy of fuelbreaks in the suppression effort. A major criterion of effectiveness may be economic, in balancing creation and maintenance costs against changes in wildland fire suppression expenditures and values (habitat, homes, etc.) protected from loss. Experimental treatments where fires would be ignited against fuelbreaks of varying prescriptions have not historically been possible to conduct (Davis, 1965), and estimating reductions in wildland fire losses is difficult. Recent developments in fire simulation technology (Finney, 1998) are opening up new ways to evaluate fuel treatments in the context of spatially explicit fuel mosaics and varying suppression levels.

The shaded fuelbreak concept in forested areas is the type of fuelbreak discussed here, along with area treatment such as prescribed fire. A shaded fuelbreak is created by altering surface fuels, increasing the height to the base of the live crown, and opening the canopy by removing trees. This type of fuelbreak spans a wide range of understory and overstory prescriptions and methods of creation through manual, mechanical, and prescribed fire means. The timing of the action will also be important: is it created at once, staged, or mixed with other treatments that may be occurring over time and over the landscape? Other issues associated with the residual overstory are problems with senescent or diseased trees, or economic issues of retaining harvestable overstory trees.

2. Fire behavior theory and fuelbreaks

The primary reason for fuelbreaks, as well as any other type of fuel treatment, is to change the behavior of a fire entering the fuel-altered zone. Fuelbreaks may also be used as points of anchor for indirect attack on wildland fires, as well as for prescribed fires. We can define the ways that forest fire behavior is altered by modification of fuels, and these principles apply to all forests where fuel treatments are applied and maintained.

2.1. Surface fire behavior

Surface fuel management can limit fireline intensity (Byram, 1959) and lower potential fire severity (Ryan and Noste, 1985). Operations conducted for 'forest health' can unfortunately increase fireline intensity or increase fire severity, if fuels are not appropriately managed and forest structure is altered without regard to fire resistance of the residual stand (Weatherspoon, 1996; Agee, 1997). The management of surface fuels so that potential fireline intensity remains below some critical level can be accomplished through several strategies and techniques. Among the common strategies are fuel removal by prescribed fire, adjusting fuel arrangement to produce a less flammable fuelbed (e.g., crushing), or 'introducing' live understory vegetation to raise average moisture content of surface fuels (Agee, 1996). Wildland fire behavior has been observed to decrease with fuel treatment (Helms, 1979; Buckley, 1992), and simulations conducted by van Wagtendonk (1996) found both pile burning and prescribed fire, which reduced fuel loads, to decrease subsequent fire behavior. These treatments usually result in efficient fireline construction rates, so that control potential (reducing 'resistance to control') can increase dramatically after fuel treatment.

The various surface fuel categories interact with one another to influence fireline intensity. Although more litter and fine branch fuel on the forest floor usually results in higher intensities, that is not always the case. If additional fuels are packed tightly (low fuelbed porosity), they may result in lower intensities. Although larger fuels (>3 in.) are not included in fire spread models as they do not usually affect the spread of the fire (unless decomposed (Rothermel, 1991)), they may result in higher energy releases over longer periods of time when a fire occurs, having significant effects on fire severity, and they reduce rates of fireline construction.

The effect of herb and shrub fuels on fireline intensity is not simply predicted. First of all, more herb and shrub fuels usually imply more open conditions. These should be associated with lower relative humidities and higher surface windspeeds. Dead fuels may be drier – and the rate of spread may be higher – because of the altered microclimate compared to more closed canopy forest with less understory. Live fuels with higher foliar moisture, while green will have a dampening effect on fire behavior. However, if the grasses and forbs cure, the fine dead fuel can increase fireline intensity and localized spotting. Post-fire analyses of fire damage to plantation trees after the 1987 fires in the Hayfork District of the Shasta-Trinity National Forest (Weatherspoon and Skinner, 1995) showed a positive relationship between grass cover and damage and a negative relationship between forb cover and damage, most likely because grasses were cured and forbs were not.

2.2. Conditions that initiate crown fire

A fire moving through a stand of trees may move as a surface fire, an independent crown fire, or as a combination of intermediate types of fire (Van Wagner, 1977). The initiation of crown fire behavior is a function of surface fireline intensity and of the forest canopy: its height above ground and moisture content (Van Wagner, 1977). The critical surface fire intensity needed to initiate crown fire behavior can be calculated for a range of crown base heights and foliar moisture contents, and represents the minimum level of fireline intensity necessary to initiate crown fire (Table 1; Alexander, 1988; Agee, 1996). Fireline intensity or flame length below this critical level may result in fires that do not crown but may still be of stand replacement severity. For the limited range of crown base heights and foliar moistures shown in Table 1, the critical levels of flame length appear more sensitive to height to crown base than to foliar moisture (Alexander, 1988).

Table 1
Flame lengths associated with critical levels of fireline intensity that are associated with initiating crown fire, using Byram's (1959) equation.

Foliar moisture content (%)	Height of crown base (m)			
	2	6	12	20
70	1.1	2.3	3.7	5.3
80	1.2	2.5	4.0	5.7
90	1.3	2.7	4.3	6.1
100	1.3	2.8	4.6	6.5
120	1.5	3.2	5.1	7.3

If the structural dimensions of a stand and information about foliar moisture are known, then critical levels of fireline intensity that will be associated with crown fire for that stand can be calculated. Fireline intensity can be predicted for a range of stand fuel conditions, topographic situations such as slope and aspect, and anticipated weather conditions, making it possible to link on-the-ground conditions with the initiating potential for crown fires. In order to avoid crown fire initiation, fireline intensity must be kept below the critical level. This can be accomplished by managing surface fuels such that fireline intensity is kept well below the critical level, or by raising crown base heights such that the critical fireline intensity is difficult to reach. In the field, the variability in fuels, topography and microclimate will result in varying levels of potential fireline intensity, critical fireline intensity, and therefore varying crown fire potential.

2.3. Conditions that allow crown fire to spread

The crown of a forest is similar to any other porous fuel medium in its ability to burn and the conditions under which crown fire will or will not spread. The heat from a spreading crown fire into unburned crown ahead is a function of the crown rate of spread, the crown bulk density, and the crown foliage ignition energy. The crown fire rate of spread is not the same as the surface fire rate of spread, and often includes effects of short-range spotting. The crown bulk density is the mass of crown fuel, including needles, fine twigs, lichens, etc., per unit of crown volume (analogous to soil bulk density). Crown foliage ignition energy is the energy required to ignite fuel, and varies primarily by foliar moisture content, and differs from heat of combustion, that may vary by species (van Wagtendonk et al., 1998). Crown fires will stop spreading, but not necessarily stop torching, if either the crown fire rate of spread or crown bulk density falls below some minimum value.

If surface fireline intensity rises above the critical surface intensity needed to initiate crown fire behavior, the crown is likely to become involved in combustion. Three phases of crown fire behavior can be described by critical levels of surface fireline intensity and crown fire rates of spread (Van Wagner, 1977, 1993): (1) a passive crown fire, where the crown fire rate of spread is equal to the surface fire rate of spread, and crown fire activity is limited to individual tree torching; (2) an active crown fire, where the crown fire rate of spread is above some minimum spread rate; and (3) an independent crown fire, where crown fire rate of spread is largely independent of heat from the surface fire intensity. Scott and Reinhardt, in prep., have defined an additional class, (4) conditional surface fire, where the active crowning spread rate exceeds a critical level, but the critical level for surface fire intensity is not met. A crown fire will not initiate from a surface fire in this stand, but an active crown fire may spread through the stand if it initiates in an adjacent stand. A ‘crown-fire-safe’ landscape would have characteristics such that, at most, only limited tree torching would result under severe fire weather.

Critical conditions can be defined below which active or independent crown fire spread is unlikely. To derive these conditions, visualize a crown fire as a mass of fuel being carried on a ‘conveyor belt’ through a stationary flaming front (Fig. 1). The amount of fine fuel passing through the front per unit time (the mass flow rate) depends on the speed of the conveyor belt (crown fire rate of spread) and the density of the forest crown fuel (crown bulk density). If the mass flow rate falls below some minimum level (Van Wagner, 1977) crown fires will not spread. Individual crown torching, and/or crown scorch of varying degrees, may still occur.

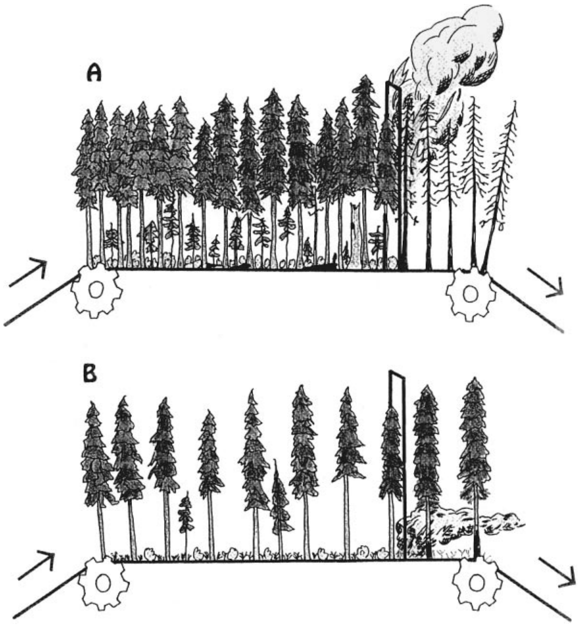

Fig. 1. Critical conditions for mass flow rate can be visualized by passing a forest along a ‘conveyor belt’ through a stationary flaming front. (A) Under severe fire weather and high rate of spread, crown mass passes through the flaming front rapidly and exceeds a critical mass flow rate, and crown fire occurs. (B) Where crown bulk density is lower under the same rate of spread, critical levels of mass flow rate cannot be obtained and the fire remains a surface fire. Lower crown fire rate of spread (i.e., lower windspeed), might also result in loss of crown fire activity.

Defining a set of critical conditions that may be influenced by management activities is difficult. At least two alternative methods can define conditions such that crown fire spread would be unlikely (i.e. mass flow rate is too low). One is to calculate critical windspeeds for given levels of crown bulk density (Scott and Reinhardt, in prep.), and the other is to define empirically derived thresholds of crown fire rate of spread so that critical levels of crown bulk density can be defined (Agee, 1996). Crown bulk densities of 0.2 kg m^{-3} are common in boreal forests that burn with crown fire (Johnson, 1992), and in mixed conifer forest, Agee (1996) estimated that at levels below 0.10 kg m^{-3} crown fire spread was unlikely, but no definitive single 'threshold' is likely to exist.

Therefore, reducing surface fuels, increasing the height to the live crown base, and opening canopies should result in (a) lower fire intensity, (b) less probability of torching, and (c) lower probability of independent crown fire. There are two caveats to these conclusions. The first is that a grassy cover is often preferred as the fuelbreak ground cover, and while fireline intensity may decrease in the fuelbreak, rate of spread may increase. van Wagtendonk (1996) simulated fire behavior in untreated mixed conifer forests and fuelbreaks with a grassy understory, and found fireline intensity decreased in the fuelbreak (flame length decline from 0.83 to 0.63 m (2.7 to 2.1 ft)) but rate of spread in the grassy cover increased by a factor of 4 (0.81 to 3.35 m/min (2.7-11.05 ft/min)). This flashy fuel is an advantage for backfiring large areas in the fuelbreak as a wildland fire is approaching (Green, 1977), as well as for other purposes described later, but if a fireline is not established in the fuelbreak, the fine fuels will allow the fire to pass through the fuelbreak quickly. The second caveat is that more open canopies will result in an altered microclimate near the ground surface, with somewhat lower fuel moisture and higher windspeeds in the open understory (van Wagtendonk, 1996).

3. Fuelbreak prescriptions

3.1. Creation

Fuelbreaks must be created in the context of the landscape within which they are placed. Some of the early fuelbreaks, such as the Ponderosa Way in California, were intended to separate the foothill-woodland vegetation type from the higher elevation ponderosa pine forest. Others have been designed as networks of primary and secondary fuelbreaks, with the primary ones being wider (Davis, 1965; Omi, 1977). A major implication of past linear fuel modifications, as the sole fuel treatment on the landscape, is that areas between the linear strips were 'sacrificed', in that control efforts were focused in the fuelbreaks, and significant value loss might occur in the interior of an untreated block surrounded by a fuelbreak. Hence, the relationship between potential ignition sources and fuelbreak locations becomes critical. Fuelbreaks can be created as initial fuel treatments, with the intent to follow up with more extensive landscape fuel treatments, gradually reducing potential fire damage within interior untreated areas as more of the landscape becomes treated.

No absolute standards for width or fuel manipulation are available. Fuelbreak widths have always been quite variable, in both recommendations and construction. Based on radiant heat loads from high intensity chaparral fires, Green and Schimke (1971) recommended that widths at least 65 m (200 ft) were necessary for safety considerations. A minimum of 90 m (300 ft) was typically specified for primary fuelbreaks (Green, 1977). As early as the 1960s, fuelbreaks as wide as 300 m (1000 ft) were included in gaming simulations of fuelbreak effectiveness (Davis, 1965), and the recent proposal for northern California national forests by the Quincy Library Group (see web site http://www.qlg.org for details) approved by the Federal Government includes fuelbreaks 400 m (0.25 mi) wide. Fuelbreak simulations for the Sierra Nevada Ecosystem Project (SNEP) adopted similar wide fuelbreaks (van Wagtendonk, 1996; Sessions et al., 1996).

Fuel manipulations can be achieved using a variety of techniques (Green, 1977) with the intent of removing surface fuels, increasing the height to the live crown of residual trees, and spacing the crowns to prevent independent crown fire activity. In the Sierra Nevada, van Wagtendonk (1996) prescribed the following fuel alterations from untreated forest levels to fuelbreaks: 1 h timelag fuels, 6.6–2.2 t/ha (3 to 1 t/ac); 10 h timelag fuels, 4.5–1.1 t/ha (2 to 0.5 t/ac); 100 h timelag fuels, 4.5–1.1 t/ha (2–0.5 t/ac); live load, 4.5–0 t/ha (2–0 t/ac); depth, 0.3–0.15 m (1–0.5 ft), resulting in a total fuel reduction from 20.2 to 4.5 t/ha (9–2 t/ac). In the Sierra Nevada simulations, pruning of residual trees to 3 m (10 ft) height was assumed, with canopy cover at 1–20% (van Wagtendonk, 1996). Canopy cover less than 40% has been proposed for the Lassen National Forest in northern California, USA (Olson, 1997). Clearly, prescriptions for creation must not only specify what is to be removed, but must describe the residual structure in terms of standard or custom fuel models so that potential fire behavior can be analyzed.

Most fuelbreaks are located where indirect attack tactics would be employed, such as along ridges, or roads along valley bottoms (Davis, 1965; Green, 1977), and upper south and west slopes (Weatherspoon and Skinner, 1996). Fuelbreaks around developed areas have been recognized as an effective strategy (Green, 1977; Omi, 1996). Networks of fuelbreaks have been designed to confine fires to less than 400 ha (1000 acres) (Green, 1977), or to break the landscape into units less than 4000 ha (10 000 acres) in size (the Quincy Library Group proposal for some northern California national forests), but Weatherspoon and Skinner (1996) suggest the appropriate extent will vary by topography and many other factors, such as 'values at risk'.

3.2. Maintenance

Sustained alteration of fire behavior requires effective and frequent maintenance, so that the effectiveness of any fuel treatment, including fuelbreaks, will be not only a function of the initial prescription for creation, but also standards for maintenance that are applied. The efficacy of many past fuelbreaks has been largely lost because of inadequate or no maintenance. If a fuelbreak is to remain effective, permanent cover type change must occur. Obviously, if maintenance is not done, woody vegetation will encroach, fuel loads will increase, and the effectiveness of the fuelbreak will be decreased. There are few data to evaluate effectiveness of maintenance techniques. Seeding perennial grass cover reduced brush and conifer invasion for at least 5 years in a mixed-conifer fuelbreak in California (Schimke et al., 1970), while unseeded areas were rapidly invaded by pine and brush seedlings. Restricted availability of herbicides on public lands will result in alternative techniques being more commonly used to control woody plant invasion. Manual treatment is very expensive, and mechanical treatment is only feasible on gentle terrain. Prescribed fire can be effective (Schimke and Green, 1970) but there is potential for fire escape along the edges. Late winter burns, when the previous year's production is cured, the perennials have not yet greened up, and the adjacent forest is not very flammable, may be a possible cost-effective treatment to avoid risk of escape from maintenance burns and achieve effective maintenance at low cost.

4. Fuelbreak effectiveness

The effectiveness of fuelbreaks continues to be questioned because they have been constructed to varying standards, 'tested' under a wide variety of wildland fire conditions, and measured by different standards of effectiveness. Green (1977) describes a number of situations where traditional fuelbreaks were successful in stopping wildland fires, and some where fuelbreaks were not effective due to excessive spotting of wildland fires approaching the fuelbreaks. One successful account from Green (1977) is from the 1971 Romero fire near Santa Barbara, CA:

> If there was one successful feature in this fire it was the East Camino Cielo fuelbreak which served as final control line for approximately 12 miles. Without this fuelbreak, which enabled men, equipment, and air tankers to control that part of the fireline, it is certain that a large portion of the valuable Santa Ynez River Watershed…would have been destroyed.

An illustration of the variables important to fuelbreak effectiveness is the gaming scenario that Davis (1965) tested on experienced California Division of Forestry (CDF, now Department of Forestry and Fire Protection) personnel (Table 2). The CDF employees were asked to rate the probability of stopping wildland fires in fuelbreaks of differing width, given different levels of equipment and firefighters, and different fire behavior in adjacent fuels. Increasing the width of fuelbreaks was most effective when firefighting effort was increased (by 1963 standards when the survey was conducted) and oncoming fire behavior was not extreme.

Fuelbreak construction standards, the behavior of the approaching wildland fire, and the level of suppression each contribute to the effectiveness of a fuelbreak. Wider fuelbreaks appear more effective than narrow ones. Fuel treatment outside the fuelbreak may also contribute to their effectiveness (van Wagtendonk, 1996). Area treatment such as prescribed fire beyond the fuelbreak may be used to lower fireline intensity and reduce spotting as a wildland fire approaches a fuelbreak, thereby increasing its effectiveness. Suppression forces must be willing and able to apply appropriate suppression tactics in the fuelbreak. They must also know that the fuelbreaks exist, a common problem in the past. The effectiveness of

Table 2
Estimated probability of stopping a wildfire at a fuelbreak under differing levels of adjacent fire behavior and suppression level. Fuelbreaks are 100 and 300 m wide. L = 0–20% probability, or little chance of stopping the fire; M = 21–50% probability, or moderate chance; H = 51–100% probability, or good chance (Davis, 1965). All levels based on averages of expert opinions of 10 California Division of Forestry personnel

Fire behavior level[a]	Suppression level: current			Suppression level: augmented		
	Fuelbreak width					
	0 (none)	100 m	300 m	0 (none)	100 m	300 m
Spot 0.8 km, front 0.8 km	L	L	L	L	L	M
Spot 0.8 km front 0.16 km	L	L	M	L	M	H
Spot 0.4 km, front 0.8 km	L	L	L	L	H	H
Spot 0.4 km, front 0.16 km[b]	L	M	H	M	H	H

[a] Spotting distance of fire and front width of fire approaching the fuelbreak.
[b] Davis' Table 14 has a typo, showing front as 0.8 km when it should be 0.16 km.

suppression forces depends on level of funding for people, equipment, and aerial application of retardant, which can more easily reach surface fuels in a fuelbreak. Effectiveness is also dependent on the psychology of firefighters regarding their safety. Narrow or unmaintained fuelbreaks are less likely to be entered than wider, well-maintained ones.

Economic studies of fuelbreaks are difficult, because they must balance costs of creating and maintaining fuelbreaks against acres and dollars 'saved' because of assumed declines in burned area or reduced damage. The general approach used by Davis (1965) was to evaluate 'saved' area by superimposing past wildland fires on varying densities of planned fuelbreak systems and first defining the area which might be affected by the presence of a fuelbreak (Class 3 area, see Fig. 2). Then a proportion of that area would be estimated as 'saved', based on the average probability of control from expert opinion, depending on the level of suppression, the width of fire front, and the width of the fuelbreak. For example, if 300 ha are identified as Class 1, 700 ha as Class 2, and 500 ha identified as Class 3 for a sample wildfire and the suppression probability at the fuelbreak is 70%, then the expected area saved is 350 ha (70% of the Class 3 area). The percent reduction, or area saved, is the reduced total area of Class 1–3 divided by the original Class 1–3 area, or $(1-(1150/1500)\times 100 = 23\%)$. Davis did not consider reduction of size or damage in Class 4 areas (the area of the fuelbreak), which could be significant when the fuelbreak becomes very wide (as is a typical prescription in defensible fuel profile zones). He found effectiveness was greater in timber types than brushland or grassland types, but concluded that the marginal cost of area 'saved' exceeded the benefits, at least in 1965 values, particularly for high density fuelbreaks. He cautioned that his analysis did not result in a conclusion that 'no fuelbreaks are worthwhile', and

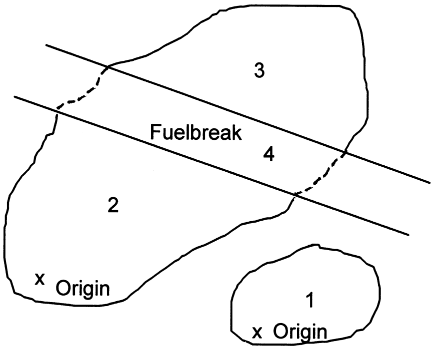

Fig. 2. An analysis of the effect of fuelbreaks on wildfire area burned and fire damage includes four types of areas: (1) those fires that never approach a fuelbreak, (2) those portions of fires that burn before the fuelbreak is encountered, (3) those portions of fires where the fuelbreak might reduce area burned if the fire is stopped before it arrives there, and (4) areas inside the fuelbreak where fire size and damage may be reduced because of the fuel treatment. Fuelbreaks can have an effect on fire size only on the Class (3 and 4) area, and will have an effect on reducing damage within areas burned in the Class (4) area. A transition to landscape treatment would expand the Class 4 area across more of the landscape, usually with more attention to surface fuel reduction and increasing the base to live crown, and less canopy alteration than applied to the fuelbreak.

in fact at low levels of fuelbreak density, investments in fuelbreaks derived more benefits than investments in suppression forces.

The site-specific nature of any economic analysis of fuelbreaks is apparent from Davis' study, a primary reason that he cautioned against extrapolating his results beyond the CDF district studied in the central Sierra Nevada. Where timber types are proposed for fuelbreaks, the value of timber will offset some to all of the construction cost. As Green (1977) noted, Davis' study did not include evaluation of effectiveness under less than extreme fire behavior conditions, or the usefulness of fuelbreaks in flanking orientations to the main fire front. Also not addressed was the degree of damage within areas burned. Burn severity and level of resource damage to areas that burn outside of the fuelbreaks generally will be unaffected by the presence of the fuelbreak. In contrast, fire damage should be reduced within the fuelbreaks (and this can be a significant area for wide fuelbreaks) as in any other areas receiving effective fuel treatment (Figs. 3 and 4).

In southern California, Omi (1977) concluded that 'primary' fuelbreaks had been fairly successful in aiding fire control, but that secondary breaks had been much less successful. He noted that if age-class management were to be employed to manage chaparral fuels, with younger age classes created with prescribed fire being less flammable, the secondary fuelbreaks would be useful as places to start or control prescribed burn operations.

The question of linking fuelbreaks together into a network system is also a tough one. As individual fires are most likely to encounter one segment of fuelbreak (and hopefully be stopped there), an appropriate design for fuelbreak placement must factor in ignition potential and values at risk. Otherwise, if ignition were random and values were either regular or uniformly distributed, a fishnet approach to placement would always be preferable. A fuelbreak network in a watershed might consist of surrounding subdivisions with traditional wide fuelbreaks, while more remote areas might have much narrower fuelbreaks, perhaps not all connected to one another. These narrower fuelbreaks, with less-altered conditions, might be designed primarily as anchor points for prescribed fires. There is no a priori rule that each segment must be connected to all other segments for a fuelbreak strategy to be effective (Finney et al., in press).

5. Landscape-level fuel treatments

In the drier forest zones of the West, including much of the mixed-conifer forest with Douglas-fir and

Fig. 3. Fuelbreak construction along the eastern boundary of Rocky Mountain National Park, Colorado. The treatment involved thinning of the original stand, with stem removal and hand piling prior to burning. Photo by P.N. Omi.

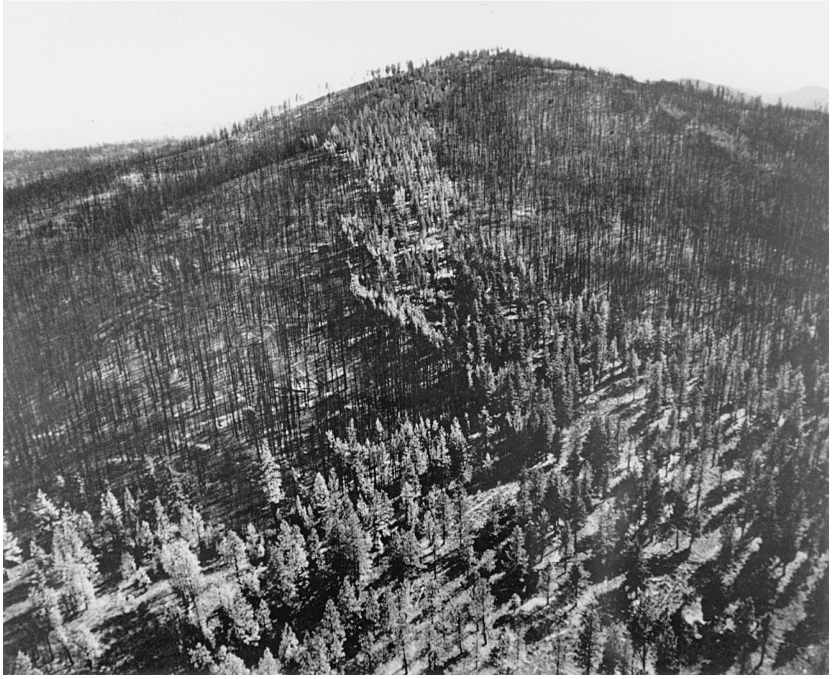

Fig. 4. Fire behavior was changed from crown to surface fire as a severe wildland fire passed through this fuelbreak on the Wenatchee National Forest, Washington. The fire then re-emerged as a crown fire on the far side. Area treatment of fuels beyond this narrow fuelbreak would have altered fire behavior over a wider area. USDA Forest Service photo.

ponderosa pine, as well as much of the pure ponderosa pine type, historical fires were primarily of low severity. Substantial changes have occurred in these forests with the exclusion of fire, as well as from harvest activity (Biswell et al., 1973; Agee, 1993). A landscape-level approach to fuels looks at the large areas as a whole (Weatherspoon and Skinner, 1996), in an attempt to fragment the existing continuous, heavy fuel in high risk areas. Fuelbreaks may be a part of that strategy but are not considered a stand-alone strategy. If utilized, the fuelbreak component of a broad fuel management strategy might best be viewed as a set of initial (perhaps 10–20 years), strategically located entries into the landscape – places from which to build out in treating other appropriate parts of the landscape – not as an end in itself. Fuelbreaks may provide a measure of protection against large fires (assuming suppression forces are present) while longer-term, area-wide treatments are being implemented. Compartmentalization of fires by fuelbreaks, which may or may not be laid out in a connected network, can help to reduce fire size but generally will not reduce damage per unit areas burned outside of the fuelbreaks themselves. Other configurations of treated areas – e.g., larger blocks that may or may not be connected (Finney et al., in press) – have been proposed for initial landscape-level treatments. Comparing the efficacy of such alternative configurations with that of fuelbreaks for reducing size and severity of large wildland fires, using newly available modeling tools (Finney, 1998; Johnson et al., 1998) would be a valuable contribution.

The word ‘fragmentation’ has had a notorious context since the publication of (Harris (1984) The Fragmented Forest, in which the harvesting of old-growth Douglas-fir forest in the Pacific Northwest was associated with loss of biodiversity. While high levels of continuous canopy may have been characteristic of northern Oregon and Washington Douglas-fir forests, west of the Cascades, high levels of structural diversity (fragmentation) were associated with historic Douglas-fir forest in the Siskiyou mountains of Oregon and California (Taylor and Skinner, 1998), and most drier forests had little fragmentation of fuel but uniformly very low fuel loads because of frequent fire (Agee, 1998). A trend towards more fuel fragmentation or lower fuel loads in these drier forests (essentially a diversity in fuel loading) is a trend away from severe fire and its attendant large patches and high severity. Fuel fragmentation does not have to be associated with structural fragmentation or overstory removal, but must be associated with declines in at least one of the factors affecting fire behavior discussed earlier: reduction of surface fuels and increases in height to live crown as a first priority, and decreases in crown closure as a second priority. On most landscapes these treatments should be prioritized in that order, but economic issues tend to reverse the order and focus on thinning only that directly affects crown closure. Thinning must be linked with surface fuel reduction and increases in height to live crown to be an effective fuel treatment.

Evidence for fuel treatment effects on fire behavior in the natural landscape is evident in many forest types. In the red fir forests of Yosemite, natural fires over the past 25 years have created a jigsaw puzzle of fire boundaries, with more recent fires naturally extinguishing at the edge of past fires (van Wagtendonk, 1995). In Baja California, frequent uncontrolled chaparral fires have created a fuel-buffered ecosystem where fire size is limited, in contrast to US chaparral north of the border, where fire suppression has resulted in larger expanses of continuous fuel and larger fires, even though the overall fire return intervals are similar (Minnich and Chou, 1997). Reconstructions of historic fires in eastern Washington pine forests have shown fires going out at the edges of fires that had burned 1–2 years previously (Wright, 1996). Might these effects on fire behavior and resultant size apply if area treatments were applied to today's mixed conifer forests?

A spatial simulation of fire suppression scenarios using the fire growth model FARSITE (Finney et al., in press) showed for the central California Sierra Nevada that area-wide fuel treatments (prescribed fire and thinning) similar to those of van Wagtendonk (1996) had an effect on decreasing fire size and cost, even if applied to limited areas of the landscape. Isolated, treated blocks of landscape in strategic locations slowed fire spread and decreased the potential for major fire runs, essentially allowing fire suppression forces to catch the wildland fire at smaller size and with less damage within the fireline. Lower fire size and severity may combine to lessen losses considerably, and need to be considered in economic analyses of landscape-level treatments. In the study by Finney et al. (in press), adding damage as another economic variable made the fuel treatment even more cost-effective. The major economic problem is that investment in fuel treatments must be made upfront to achieve the savings when a wildland fire occurs. Funds have not been usually available for such investments until recently, when Federal policy began to allow such upfront expenditures. However, air quality constraints associated with prescribed fire may limit the area that can be treated by fire.

Area treatments, rather than being an alternative to fuelbreaks, are an expansion of the fuelbreak concept to wider areas of the landscape. Fuelbreaks are often good points to tie in control lines for prescribed fire operations. Ridgetop fuelbreaks, if tied into area treatments, could be located in areas of the landscape where the historic fire regime would likely have created more open conditions. When combined with other treatments in the landscape, they might well be created with a more light-on-the-land approach. This would recognize that some portions of landscapes (ridgetops, upper thirds of slopes, south and west aspects) would have historically experienced more frequent fires and, as a result, had more open conditions than the rest of the landscape. Fuelbreak width or canopy alteration, for example, may depend on what treatments are applied to adjacent lands to reduce excessive fuels, and need not be totally cleared areas, manually or mechanically created, straight lines, or crisscrossed grids across the landscape (Agee, 1995). 'Feathering' the canopy away from the center of the fuelbreak may be one way to create a less visually obtrusive fuelbreak. However, in terms of construction standards, a general rule of thumb will be that the less 'obvious' manipulations will usually be less effective per unit area, so that they will have to be applied over wider areas of the landscape. For example, if canopy cover was maintained above 40%, surface fuel reduction and understory vegetation clearing would need to be more intensive over wider expanses. Higher levels of overstory cover, although associated with potential for independent crown fire, might also restrict the recovery of the manipulated understory and allow lengthened maintenance intervals. Maintenance is essential for area treatments as much as for traditional fuelbreaks, although the degree of manipulation and the maintenance schedule may vary.

6. Conclusions

There is a clear theoretical basis for concluding that fuelbreaks will alter fire behavior in ways amenable to limiting both the sizes of wildland fires and reducing the severity of damage from them. It is also clear that physical effectiveness of fuelbreaks depends not only on their construction specifications but on the behavior of wildland fires approaching them, and the presence and level of fire control forces. Combining fuelbreaks with area-wide fuel treatments in adjacent areas can reduce the size and intensity of wildland fires. These conclusions offer little guidance, however, in the specific design of a fuelbreak system. What criteria for construction (width, fuel treatment) should be used, where should they be placed, and how should one fuelbreak segment be linked with others? Creation of a fuelbreak network in a given area will be a site-specific decision, and will often be part of a wider scale landscape treatment of fuels. The conclusions of Omi (1996) are especially relevant:

> There will always be a role for well-designed fuelbreak systems which provide options for managing entire landscapes, including wildfire buffers, anchor points for prescribed natural fire and management-ignited fire, and protection of special features (such as urban interface developments, seed orchards, or plantations). In this context, fuelbreaks and prescribed burns should be viewed as complements to one another, rather than substitutes.

Landscape-level treatments including fuelbreaks have been proposed as a fuel management strategy that can aid wildfire control and help to achieve more broad-based ecosystem management goals (Agee and Edmonds, 1992; Weatherspoon, 1996; Weatherspoon and Skinner, 1996), particularly in areas that have historically low- to moderate-severity fire regimes (Agee, 1993). The presence of fuelbreaks in those areas may ease the application of prescribed fire treatments and allow fire control forces to conduct backfiring operations even with the bulk of forces deployed elsewhere. Fuelbreaks will not typically be stand-alone treatments, to the exclusion of either prescribed fire or the level of fire suppression capability. An appropriate combination of treatments will help to reduce unwanted wildland fire effects and the attendant ecosystem effects such fires often cause.

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