Fire Effects on Soils and Restoration Strategies

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Rehabilitation Strategies after Fire: The California, USA Experience

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Abstract

Emergency rehabilitation to mitigate the effects of flooding, accelerated erosion, and sedimentation that inevitably follows wildfire has been practiced in California, USA for nearly a century. However, California is a physically and culturally diverse area, and rehabilitation measures that work in one part of the state may not be appropriate in other regions. Rehabilitation philosophy can vary with different land management or hazard protection agencies, and may often reflect socio-political considerations as much as the resources or values at risk. Initial rehabilitation efforts in California focused on seeding burned hillsides and building engineering structures in the stream channels or at the mouths of canyons. Measures were refined, new techniques were developed, and the process was formalized in the 1960s and 1970s, with many agencies adopting Burned Area Emergency Response (BAER) programs. Current rehabilitation approaches still include treatments both on the hillslopes and in the stream channels, but also address the problems associated with wildland roads. Many lessons have been learned over the years, but many challenges remain, not the least of which is communicating the vast body of knowledge and experience both to the general public and to political decision-makers in order to make educated post-fire rehabilitation choices.

INTRODUCTION

During a two-week period of October 2003, nearly a dozen wildfires were burning simultaneously in southern California. Fanned by hot, dry *foehn*-type winds, known locally as Santa Ana's, this Fire Siege eventually consumed the

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vegetation on over 290,000 hectares, making it the largest fire event in Californian history. The fires occurred in a variety of plant communities, including some forested lands, but primarily burned in chaparral shrublands and coastal sage scrub ecosystems. Fire suppression costs were in the tens of millions of dollars (US).

Even before the fires were out, interdisciplinary teams of resource specialists deployed to inventory the damage, assess the likely impacts of the coming winter storms, identify the values at risk from the inevitable flooding and accelerated erosion that would ensue, and recommend cost-effective mitigation treatments. These emergency rehabilitation measures are designed to protect human lives, public and private property, infrastructure (roads, bridges, pipelines, utility lines, communication sites, reservoirs, etc.), water quality, heritage and archaeology resources, and the habitat for threatened and endangered species of animals and plants. Every fire in the 2003 southern California Fire Siege was different in its location, topography, proximity to urban areas, and threats to values at risk, hence the recommended treatments varied accordingly. Cumulative treatment costs eventually exceeded US$7 million.

The foregoing example illustrates the problem of wildfire across California. Wildfire is commonplace – with the state experiencing numerous fires every year – and extremely large fires or complexes of many fires are not rare occurrences. Consequently, rehabilitation after fires is a highly-evolved management practice in California. However, California is a large and diverse area containing many different vegetation communities and resources in need of protection. Moreover, rehabilitation techniques have developed over time and continue to be refined. This chapter begins with a discussion of California as a diverse landscape, and then traces the historical development of burned area emergency rehabilitation practices throughout California, including the lessons learned and the future directions.

CALIFORNIA AS A DIVERSE LANDSCAPE

California covers a huge area – some 41,000 km^2 – larger than many countries (Fig. 1). Moreover, California is extremely heterogeneous, exhibiting much diversity in both physical and social characteristics. Consequently, post-fire rehabilitation strategies depend on the geography, the agency jurisdiction, and the resources or values at risk associated with a specific wildfire.

Physical Landscape

California covers 10 degrees of latitude that encompasses coastal environments, mountains, valleys and lowlands, and deserts (Fig. 1). California contains both the tallest mountain (Mt. Whitney – 4418 m) and the lowest elevation (Death Valley – 86 m below sea level) in the co-terminus

Fig. 1 Location map of California, USA with topography (courtesy of geology.com).

United States (excluding Alaska and Hawaii) (Oakeshott 1978). Although the state is incredibly diverse, there are some recognizable regional similarities across California. The northern portion of the state is more mountainous, receives more rainfall, and has more forest stands than its southern counterpart, which is generally less mountainous, drier, and dominated by brushfields and desert scrub vegetation. The contrast between the coastal strip and the inland section of California is even more pronounced, with greater rainfall and moderate temperatures along the coast promoting more mesic conditions that support luxurious vegetation growth and some unique environmental niches (Durrenberger and Johnson 1976).

The topography of California is dominated by coastal mountain ranges, a large central valley, and a large mountain mass in most of the eastern parts of the state (Fig. 1). The structural grain of this topography trends along a northwest-southeast axis. The lofty heights coupled with the large relative relief in the uplands reflect the ongoing tectonic activity at the junction of the Pacific and North America crustal plates (Hornbeck et al. 1983). The overall climate of California is classified as Mediterranean; characterized as having cool, moist winters and hot, dry summers. Temperatures approach 40°C in the summer but seldom drop below –10°C in the winter, except in the high mountains. Annual precipitation varies from 40 to 60 cm along the coast to 10 to 25 cm inland, with mountain ranges receiving 70 to 100 cm along orographic gradients. A section of the northwest coast can receive as much as 250 cm of rainfall annually (Hornbeck et al. 1983). While there are rivers and perennial streams throughout California (especially in the north), many of the canyons and valleys only support ephemeral watercourses for much of the year (primarily in the south).

Vegetation patterns in California mirror the trends in temperature and precipitation. Forests of pine (*Pinus*), fir (*Abies*), and oak (*Quercus*) with minor other hardwoods dominate the uplands, especially in the northern section of the state. Foothills and the lee side of many lower mountain chains are covered with chaparral brushfields. Grasslands were once prevalent in the valley bottoms and lowlands, but most of these areas have been converted to agriculture or urban centers. Sparse scrub – including cacti – and sagebrush covers most of the deserts and arid rangelands, especially in the southern part of the state (Hornbeck et al. 1983).

Erosion and sedimentation in California reflect both gravitational processes associated with steep topography and hydrologic processes resulting from seasonal winter rains. Dry ravel is the dry gravitational flow of soil material, and can be a major process by which sediment is delivered from the hillslopes to the stream channels (Rice 1974). Ravel is a ubiquitous erosion process in southern California, but also occurs on steep slopes in the north. Fire greatly accentuates the efficacy of dry ravel (Rice 1974).

Rainsplash and overland flow are the two hydrologic erosion processes that operate on hillside slopes. Raindrops can dislodge loose soil material and preferentially transport it downhill. Overland flow may concentrate into micro-channels that can entrain and transport sediment, creating rills or gullies, especially on steep slopes (DeBano et al. 1998). Both rainsplash and overland flow are negligible on unburned landscapes with a sufficient vegetation canopy. Fire consumes the protective vegetation and may alter the surface soil structure. This is typical of fire behavior in chaparral brushfields, but is also experienced in forested ecosystems, especially if there is a brush understory. The bare soil becomes very susceptible to erosion by hydrologic processes. Moreover, chemical changes in the soil following fire can produce a non-wettable or water repellent condition that restricts infiltration and

promotes overland flow (DeBano 1981). This extra water flows from the hillsides to the adjacent stream channels, where it can mobilize sediment stored in dry ravel deposits. The slurry that is created can propagate down the stream channel as a debris flow with tremendous erosive power (Wells 1987).

Management Landscape

Although there are significant tracts of private property, most of the uplands of California are administered as public lands. Lands managed by the federal government include 7 National Parks, 9 National Monuments or National Recreation Areas, 18 National Forests, 6 military reservations, and scattered areas under the jurisdiction of the Bureau of Land Management. There are also many square kilometers of land administered by local Native American tribes. Lands managed by the State of California include 10 State Parks and several State Forests. Numerous county and municipal parks also cover upland areas.

Across the various federal, state, county, and municipal agencies that administer these lands, there is no uniform policy for post-fire rehabilitation. In keeping with their conservation preserve mandate, national and state parks tend to avoid ground-disturbing mitigation practices, unless there are high-value resources at risk, such as critical habitat for endangered species. They also avoid the use of non-native seeds or mulches that may introduce exotic weeds into pristine stands of native vegetation. Several federal agencies – the U.S. Department of Agriculture, Forest Service and the U.S. Department of Interior, Bureau of Land Management – have long-established programs of emergency response that include standing teams of resource specialists who consider all techniques when making their rehabilitation recommendations.

A major difference in agency philosophy is the contrast between land management and hazard protection. Land management agencies, at whatever governmental level, have long-range plans that direct recreation development, commodity extraction, and resource protection on the lands within their jurisdiction. Hence, post-fire rehabilitation would proceed only within the context of the existing land management planning. Hazard protection agencies, such as the California Department of Forestry and Fire Protection, which oversees fire suppression and post-fire rehabilitation on non-federal public and private lands, react to immediate emergencies and respond to specific events with mitigation as their sole focus. Thus conflicts can arise in recommending and implementing post-fire rehabilitation projects for fire incidents that cover multiple landowners.

Socio-political Landscape

Specific post-fire rehabilitation measures are usually dictated by on-site or downstream resources or values at risk from the flooding and accelerated erosion that typically follow wildfires. While resource specialists strive to

make cost-effective treatment recommendations based on the best available science, often decisions reflect socio-political considerations.

Protection of human life is paramount when recommending emergency rehabilitation treatments. Measures to prevent threats to human communities are implemented first, often with redundant techniques. Early warning systems may be established to sound the alarm if rainfall in the burn area exceeds some critical threshold or if the creeks rise to some specified flood stage. Evacuation orders may also be issued if the area is deemed too dangerous for human occupation. Following the 2003 Old Fire in southern California, a storm cell stalled over the burned area. After several days of rain, a high-intensity burst occurred on Christmas Day, producing debris flows in the stream channels within the burned area. Tragically, 16 fatalities occurred in these flow events because people were unaware or ignored the repeated evacuation orders (Hubbert 2005).

Threats to private property and technological infrastructure are usually the main targets of rehabilitation measures. Homeowners and business proprietors downstream from a burned area may erect sandbag barriers or deflection structures to protect their property, but the most effective treatments try to control runoff and erosion at the source; in the burned area itself. Roads and bridges are critical values at risk, as they often provide the only access to isolated communities or remote communication sites. Pipelines, whether they carry water or petroleum products, also receive special consideration for rehabilitation treatment protection because of the potential for environmental disaster if flooding or erosion should damage the conduit. Similarly, utility lines warrant special protection. Flood control reservoirs and debris basins were built specifically to handle the floods generated from burned areas, but the hillsides and stream channels contributing to water supply reservoirs are usually treated to prevent siltation and the loss of storage capacity.

Loss of soil productivity is always an issue for maintaining ecosystem integrity, but it is of special concern in forest stands used for commercial timber production. Although burning liberates nutrients from the standing biomass and the forest floor, accelerated erosion and leaching can remove these chemical compounds before they can benefit stand regeneration. Rehabilitation treatments on hillside slopes attempt to retain valuable topsoil and prevent site degradation through unacceptable losses of critical nutrients, such as nitrogen and phosphorus (DeBano et al. 1998).

The soil and nutrients stripped off the burned hillsides are usually deposited in the stream channels at the bottom of the slopes. If these channels support surface runoff, the character of the water will be tremendously altered. Increased turbidity from the sediments and elevated solute concentrations of compounds from the ash can be lethal to aquatic organisms, especially fish populations important for food production and recreation. Post-fire sedimentation will also preferentially fill stream pools, further degrading fish habitat. Rehabilitation efforts strive to keep sediment from initially entering

the stream channels, and then subsequently remove the entrained load, usually by a series of barrier structures.

The California floristic province is considered a hotspot of biodiversity (Myers et al. 2000) because of the large number of rare species and the ongoing habitat loss that affects them. As a result, consideration of rare species is now a part of most post-fire rehabilitation decisions within the state. For National Forest lands, rehabilitation treatments may be applied to prevent permanent impairment of critical habitat for threatened and endangered species (Forest Service Manual 2523.2), including measures such as planting of streamside willows for waterway shading, so long as the treatment(s) will be effective within two years. Areas known to harbor populations of rare plants may be excluded from seeding or mulch treatment prescriptions in order to prevent competition or other adverse effects. For example, after the Cedar Fire of 2003 in San Diego County, locations of suitable habitat for rare endemic annual plants were excluded from an aerial hydromulch application.

In extreme cases, where post-fire flooding or debris flows are expected to greatly alter habitat, populations of rare species may be collected and moved or retained in a zoo for later reintroduction. After the Old Fire in 2003, for example, mountain yellow-legged frogs were captured from a creek on the San Bernardino National Forest and taken to the Los Angeles zoo, where they thrived. Winter storms scoured out the stream channel where they had occurred. Amazingly, however, some frogs were found in the creek a year later, possibly washed down from tributary streams unaffected by the fire. Other treatments for rare species may include seeding grasses along stream banks to help reduce sediment movement into streams, as was done after the 2000 Manter Fire to protect populations of California golden trout.

Heritage or archeological resources often need protection following fires. The removal of plant cover is the primary concern due to increased accessibility and visibility of the cultural sites. The sites then become more susceptible to vandalism and artifact looting. However, managers can also perform surveys to identify new, undiscovered sites before vegetation recovery. Treatments in California usually consist of patrols, fencing, and road closures to discourage the above activities. Monitoring of the sites continues until vegetative groundcover recovers to the extent that visibility of the sites is obscured.

Wildfire can create ideal conditions for the growth and spread of invasive species. The bare mineral soil, lack of overstory shading, and readily available nutrients deposited in the ash layer after a fire provides an ideal seedbed for many non-native plants (Brooks and D'Antonio 2001). The role of fire in the spread of invasive plants has been receiving increased attention in recent years (e.g., Galley and Wilson 2001, Brooks et al. 2004). Fire disturbance has aided the spread of weed infestations that were already present before the fire, either in the seedbank or in proximity to the burn. In most cases, weed species that are found were likely present prior to the burning, but were released from

competition following the fire. Over the years, pre-fire seed banks of invasive weed species have increased in quantity and area covered. Most of the invasive weeds are prolific seed producers and can remain viable for long periods of time. In California, fires that occur too frequently can also facilitate the conversion of native shrub and herbaceous vegetation into non-native grasslands (Keeley 2001).

Preventing the spread of invasive species into burned areas has become an important part of post-fire rehabilitation strategies in California. Measures taken can range from surveys to identify and remove new infestations to seeding native or short-lived non-native grasses in an attempt to out-compete invasive plants. However, it is still unknown whether this seeding can prevent the establishment of noxious weeds. Increased weed infestations are commonly observed in areas of fire suppression activities. Most of the incursions are associated with roadsides, bulldozer lines constructed to create fuel breaks, and drainages near human habitation (BAER Guidance Paper: Noxious and Invasive Weed Treatment, March 2004, unpublished data).

INITIAL REHABILITATION EFFORTS

The association between wildfire and subsequent flooding, accelerated erosion, and massive sedimentation has long been recognized throughout California, especially in the mountains along the southern coast. Observations of the phenomenon were reported in newspaper articles as far back as the late 1800s, and erosion control treatments following fires were suggested in the early part of the last century (Munns 1919). The event that galvanized public awareness and focused attention on the need for post-fire rehabilitation projects was the 1934 New Year's Day flood in La Crescenta, located in the foothills near Los Angeles. A high-intensity storm produced heavy rainfall on a freshly burned landscape and produced debris flows that scoured side tributaries to depths of up to 5 m and moved boulders the size of automobiles several kilometers from the mountain front (Kraebel 1934). The community experienced massive property damage and several people were killed. Initial rehabilitation efforts in the first half of the 20th century consisted of seeding the burned hillsides to produce a rapidly growing ground cover, and building engineering structures in the stream channels and at the mouths of the canyons to trap and remove sediment.

Foresters in southern California tried seeding burned-over hillside slopes with native shrubs as early as the 1920s to try to reduce post-fire erosion (Department of Forester and Fire Warden 1985). When they realized that shrub seeds germinated no earlier than natural regeneration, faster-growing non-native herbaceous species, such as Mediterranean mustards (*Brassica* L. spp.) were used (e.g., Gleason 1947). However, mustard seeds would subsequently be spread to downstream agricultural areas, where the plants were considered nuisance weeds by the local farmers. By the 1950s annual

ryegrass (*Lolium multiflorum* Lam., native to Europe and Asia) had come to be regarded as the most effective and economical choice for charred California wildlands (Barro and Conard 1987). Ryegrass was relatively inexpensive, readily available, and could easily be applied from the air over wide areas.

One benefit of heavily seeding chaparral burns with ryegrass was that it tended to inhibit shrub seedling regeneration, which could be used to increase pasturage by type-converting dense shrub stands to annual grasses with occasional shrubs (see Schultz et al. 1955). Type-conversion of brushlands was also a goal of some prescribed fire programs on both private and public lands during this period, especially in the coast ranges and the foothills of the Sierra Nevada (Keeley 2001).

As in other areas, seeding forestlands after fire for soil retention and range improvement used species of predominantly non-native pasture grasses and forbs (see Chapter 11). Seed mixes generally contained annual grasses to provide quick cover, perennial grasses to establish long-term protection, and often legumes to add nitrogen to the soil (Ratliff and McDonald 1987).

Engineering solutions for post-fire rehabilitation and erosion control took the form of building barrier structures to trap and retain the transported debris once it had reached the stream channels. Channel checks are low dams (<2 m high) constructed in a series, spaced approximately 50 to 60 m apart. Although they could be made of any materials, often they were fabricated using wire cages filled with local rock material ranging in size from large cobbles to small boulders (Eaton 1932). These check dams could only trap and store modest amounts of sediment material, but they also served as drop structures to dissipate the energy of the flow, as well as grade control features to prevent channel incision and potential destabilization of the lateral banks and adjacent colluvial toeslopes (Eaton and Gillelen 1931). However, these check dams are time-consuming to plan and complete. As it is unrealistic to build a series of check dams on many creeks in the short period between the fire and flood-producing rains, they must be constructed in advance on streams within fire-prone areas.

Debris basins are large earthen or concrete settling reservoirs built at the mouth of major canyons where the streams flow onto the adjacent flatlands. As sediment-laden floods and/or debris flows enter the basin, the coarse load drops out in the low energy environment and becomes trapped. Relatively clear water then escapes over a spillway. After the event, the basin is cleaned out with heavy equipment so that storage capacity is sufficient for the next storm. This becomes problematic when a series of storms strikes over the course of several days. Moreover, these debris basins are very expensive and require considerable time to build. As with check dams, debris basins must be constructed in advance at the base of canyons within fire-prone areas. Many dozens of debris basins were built by local flood control districts throughout California between 1925 and 1960.

DEVELOPMENT OF THE REHABILITATION PROCESS

Nationally, the 1960s and early 1970s saw the preparation of the first official written reports on emergency postfire watershed rehabilitation. Funding for postfire rehabilitation treatments came from fire suppression accounts, emergency flood control programs, or funds appropriated for watershed restoration. After a Congressional inquiry on fiscal accountability, formal authority was provided for Burned Area Emergency Rehabilitation, now called Burn Area Emergency Response (BAER) programs in the federal interior and related agencies appropriation in 1974 (Robichaud et al. 2000). This authority integrated the evaluation of burn severity, funding request procedures, and treatment options. In the U.S. Department of Agriculture, Forest Service, a standardized Burned Area Report form was developed and used for this purpose. Interdisciplinary teams were assembled after major fires to assess the burned area, identify threats, and recommend treatments.

This was also a period of active investigation into the effectiveness of established and new post-fire rehabilitation treatments in California. Broadcast seeding of entire burned areas, usually with annual ryegrass, was commonplace (Barro and Conard 1987), and controversy over its use ensued, particularly in southern California chaparral (Gautier 1983). Engineering solutions to runoff and erosion threats were also employed. The contribution of roads to sediment movement and water channelization was recognized, and road treatments to reduce these effects were increasingly prescribed (Burroughs and King 1989).

Hillslope Treatments

After the 1960 Johnstone Peak fire on the San Dimas Experimental Forest in southern California, Forest Service researchers set up an extensive experiment testing different hillslope rehabilitation treatments in burned-over chaparral watersheds. Several seeding treatments, hillslope terracing, and various combinations were applied to small catchments, in which sediment deposition and runoff were measured. When the first winter after the fire proved to be one of the driest on record, with negligible grass establishment, the treatments were reapplied, and the next year the highest rate annual grass-seeded catchments recorded a 16 percent reduction in sediment production. Seeded grass cover was about 8 percent (Krammes and Hill 1963). The researchers noted that the seeded catchments had lower cover of native plants than the unseeded controls (Corbett and Green 1965). In contrast, the watersheds with the terrace treatment reduced sediment production by 60 percent compared to un-terraced catchments (Rice et al. 1965).

Contour trenches were also installed operationally after fires where flood control was a major concern. In the Sierra Nevada, their effectiveness was found to depend on the soils and geology of the affected area (DeByle 1970). However, terraces and trenches are radical ground disturbing practices, and

remnants of these treatments that were applied in the 1960s in some cases can still be seen on the landscape today.

The effectiveness of annual ryegrass seeding for erosion control in chaparral ecosystems was questioned in the late 1970s and early 1980s. After fire in a chaparral, annual plants and shrub seedlings take advantage of the abundant light, space and soil nutrients suddenly available and fairly quickly occupy burned sites (Sampson 1944, Sweeney 1956, Keeley 1991). Seeded ryegrass was shown to displace those species, often without increasing ground cover or reducing erosion (Keeley et al. 1981, Gautier 1983, Taskey et al. 1989). The debate fueled research that extended into the 1990s (see next section).

Seeded annual ryegrass could also have negative effects on pine seedling establishment (Griffin 1982), as had been shown for other pasture grass species commonly used for post-fire seeding (Baron 1962). Massive wildfires in the Sierra Nevada, northern California, and southern Oregon in 1987 resulted in millions of dollars being spent on emergency rehabilitation treatments and brought greater scrutiny to the methods employed. A number of investigations of treatment effectiveness were reported at a symposium in 1988 (Berg 1989). Grass seeding was found to be highly variable in efficacy. Two papers attested to the effectiveness of straw mulch for erosion control (Gross et al. 1989, Miles et al. 1989), and others pointed out that post-fire logging, or 'salvage logging', could have beneficial effects on burned watersheds, especially when residual material, or 'slash', was left on the ground for soil protection (Barker 1989, Poff 1989). The symposium concluded with encouragement to develop better information to help managers make the best choices (MacDonald 1989).

Channel Treatments

Post-fire rehabilitation measures in stream channels continued to be dominated by engineering structures. More check dams were built in fire-prone watersheds, especially in the steep mountains of southern California (Ruby 1973). Besides these semi-permanent channel traps, land managers and protection agencies also began experimenting with temporary low dam structures made of logs or straw bales (Miles et al. 1989). Log dams, used in the forested northern part of the state, were fabricated from fire-killed trees taken directly off the burn site. Trees were felled, stacked to the desired height, secured with cables or bailing wire, and braced on the downstream face. It was of little consequence that these dams were semi-permeable, as long as they retained the coarser debris load. Straw bales – brought to the work site by trucks, helicopters, and/or hand crews – were used as large building blocks secured with fence posts and bailing wire to construct custom dams throughout California. Over time, both the logs and the straw would biodegrade, and the wedges of trapped sediment would slowly be released

back into the channel system, and the longitudinal profile of the stream would return to a natural gradient (Miles et al. 1989).

Channel clearing was a popular rehabilitation treatment throughout California in the 1970s and 1980s (Barro et al. 1989). Clearing was done to prevent freshly toppled fire-killed trees (and any pre-fire downed material) from organizing into impromptu dams that would temporarily restrain the rising waters. The fear was that these makeshift dams would eventually burst, creating a large flood that would be dangerous to any downstream resources or values at risk. However, this desire to quickly and efficiently convey flood waters away from the burned area had to be balanced by the what often became the wholesale removal of the entire riparian ecosystem (Barro et al. 1989). Ironically, in northern California, post-fire measures in stream channels began to include intentionally placing pieces of large woody debris into the drainages to create stability points in order to preserve or create new fish habitat (O'Connor and Ziemer 1989).

Debris basins continued to be built at the canyon mouths of fire-prone watersheds to protect downstream communities from floods and/or debris flows. Over 100 of these structures now exist in Los Angeles County alone. Besides these carefully engineered structures, agencies also began to use temporary earthen catchment basins on smaller stream tributaries to protect high-value features, such as remote developments or critical habitat (USDA Forest Service 1992). Usually these earthen structures would not be maintained, and they would eventually be breached and revert back to a natural landscape after the post-fire emergency was over. Another new development to protect downstream human communities were deflection walls that, rather than creating a holding barrier, attempted to divert the sediment-laden flows away from property and infrastructure and back to the natural channels (Robichaud et al. 2000).

CURRENT REHABILITATION APPROACHES

From 1990 to the present, there has been a shift in the combinations of land, channel, road/trail, and protection/safety treatments that are selected by the BAER assessment teams. There has been a trend towards prescribing less hillslope treatments. Seeding has decreased in northern California, and is rarely prescribed in southern California. In southern California, aerial straw mulch and straw wattles have replaced seeding treatments. Straw mulching is also popular in northern California because of slower re-establishment of ground cover in the forested regions compared to the rapid recovery of southern California chaparral systems. Contour-felled logs, also known as log erosion barriers (LEBs), are used in northern California as a replacement for seeding where trees are available. Channel treatments are still being prescribed, although there is no clear consensus of their success or failure. More channel treatments are used in northern than in southern California

because of fishery issues. BAER teams are not only treating to prevent excess sediment, but are also attempting to reestablish fish habitat as well. More recently, there has been greater emphasis on road and trail treatments, off-highway vehicle containment, protection of cultural resources, and noxious weed treatments. Additionally, the importance of monitoring the success or failure of these treatments has been recognized, and studies have been implemented to assess or quantitatively evaluate their performance.

Hillslope Treatments

The source of much of the sediment of concern to land managers and protection agencies in the post-fire environment originates on the hillside slopes. The following rehabilitation techniques attempt to retain the soil material on the hillslopes and delay its delivery to the adjacent stream channels.

Seeding

Routine broadcast use of annual ryegrass for post-fire stabilization seeding has decreased tremendously since 1990. Research studies that pointed out its lack of effectiveness for erosion control and detrimental impacts on native plants, especially annual fire-followers, contributed to this trend (Conard et al. 1995, Wohlgemuth et al. 1998, Beyers 2004). The U.S. Department of Agriculture, Forest Service rarely seeds at all in southern California, where unpredictable rains and generally good natural vegetation recovery do not make seeding cost-effective. Other agencies have tried native seed mixes, with generally low success (Keeley et al. 1995). Land managers recognize the dilemma posed by seeding in forested areas of northern California, where loss of site productivity due to erosion is a major concern but successful grass growth may suppress natural tree seedling establishment (Griffith 1998, Van der Water 1998). The U.S. Department of Agriculture, Forest Service now uses non-reproducing cereal grains for most post-fire seeding, both to reduce erosion and to reduce establishment by invasive non-native plants. Seeding is done only in carefully-targeted areas, such as above roads or streams critical to the survival of rare fish. However, even cereals may displace native plant species and suppress tree seedlings in the short term (Keeley 2004). For more discussion of post-fire grass seeding, see Chapter 11.

Contour-felled log erosion barriers

Contour-felled logs erosion barriers are more apt to be used in northern California because of the predominance of forested ecosystems. In southern California, most of the area consumed by fire is in chaparral shrublands where logs are scarce. The 2003 southern California wildfires burned through over 290,000 ha of diverse plant communities dominated by chaparral, but coniferous forests comprised only 5 percent of the total area burned (Keeley et

al. 2004). In northern California, contour-felled logs have been minimally used and are not usually prescribed. Miles et al. (1989) monitored the effectiveness of the contour-felled logs on the Shasta-Trinity National Forest and found that the logs retained 3.6 to 15.1 Mg ha^{-1} of soil on site. They considered the sediment trapping efficiency low and costs of the treatment high (Robichaud et al. 2000). See Chapter 12 for further discussion.

Aerial straw mulch, hand-placed straw, and wood mulch

Due to its relatively low cost and history of success in reducing hillslope erosion, aerial straw mulching is one of the more popular hillslope erosion control treatment used in California. On the Grand Prix/Old Fire, the average cost including helicopter, personnel, straw, trucking, salary and per diem was US$1850 per hectare (Hubbert 2005, 2006). Miles et al. (1989) reported 13.5 to 22.5 Mg ha^{-1} reduction in soil erosion on the Shasta-Trinity National Forest when wheat straw was applied at 4.5 Mg ha^{-1}.

The use of certified weed-free rice straw has replaced the use of other non-certified straws such as wheat on most lands in California. The change to rice straw reflected the threat of invasive weed species that were being introduced in the applied straw. Rice straw is certified to be weed free, but monitoring by botanists after application have suggested otherwise. After the 2001 Darby Fire on the Stanislaus National Forest, 28 ha were aerial straw mulched with weed free rice straw and 25 ha of yellow starthistle (*Centaurea solstitalis*) were mapped the following year (Clines 2005). Yellow starthistle is of special concern as it is considered one of California's worst noxious weeds; infesting rangelands, pastures, hay fields, and orchards. In horses it can cause the fatal nervous disorder equine nigropallidal incephalomalacia, or 'chewing disease.'

Following the Grand Prix/Old Fire of 2003, land managers monitored both aerial straw mulch and hand-placed straw (Hubbert 2005, 2006). High winds contributed the most to straw mulch failure, either blowing the mulch offsite or piling the straw in deep clumps so that vegetation was suppressed. Poor application of the straw mulch also contributed to the failure of the material to provide cover. For best results, the large 330 kg hay bales were to be dropped from 60 m above the surface. However, because of the unevenness of the terrain, the bales were either dropped too low and did not break up completely resulting in piling or clumping; or were dropped too high resulting in uneven coverage and scattering beyond the projected treatment area. When applied correctly, straw mulch provides ground cover that reduces erosion and increases soil infiltration. Janicki and Grant (2002) noted that 330 kg bales did not break up as well as lighter 250 kg bales. Straw suppliers stated that bailing pressure, moisture content, and how fine the straw is chopped are factors determining how well the straw breaks up and spreads (Janicki and Grant 2002). Additionally, on steep slopes, mulch may increase downstream peak flows by artificially decreasing storage capacity (lowering evaporation

and allowing greater infiltration), resulting in larger subsurface preferential flow. This may be an important factor in steep watersheds where soils are shallow and have developed on hard, unweathered bedrock.

Hand-placement of straw is more labor intensive than aerially applied straw, but usually results in better ground coverage. Good ground cover only holds true in areas that do not experience high winds. Most of the hand-applied straw was blown off-site in the wind-prone areas of the Grand Prix/Old Fire (Hubbert 2005, 2006). In areas where the straw was blown off-site, high impacts of foot traffic during straw application disturbed the soil surface increasing the soil erosion hazard. Ground cover approached 70 percent in areas that did not experience strong winds.

Recent unpublished experimentation with wood mulches has shown it to be an effective treatment. If a tool is developed that helps apply the mulch in a cost effective way, it will gain in popularity, especially with the concerns of noxious plants in straw.

Aerial hydromulching and road hydromulch

Hydromulching combines a wood and paper fiber matrix with a non water-soluble binder, mixes the ingredients into a slurry, and applies the mixture by high-pressure nozzles or by a helicopter. The intent of the mulch treatment is to bind the loose surface soil together, reducing detachment and transport by rainsplash and overland flow, while still allowing infiltration across the landscape. Aerial hydromulching is a relatively new treatment in California and because of its expense (~US$4000 per ha) has been used sparingly. A total of US$320,000 was spent for aerial hydromulch on the Curve Fire that occurred on the Angeles National Forest in 2002. After the 2003 Cedar Fire, aerial hydromulch was applied to watersheds located above a residential community to help reduce flood peaks and sediment yield downstream. A total of 444 ha were treated at a total cost of US$1,650,000.

The use of road hydromulch (hydromulch applied through hoses from tanker trucks) has remained stable. Due to its expense and limited coverage range, it is mainly used to protect specific structures of high value. For example, following the Curve Fire, US$930,000 was spent protecting a state highway that provided access to the local mountains (Andressen 2002).

Straw wattles (fiber rolls)

The use of straw wattles has increased slightly in recent years. Straw wattles provide an alternative hillslope treatment when there are no trees available for contour-felling and seeding is undesirable. Implementation of the treatment is very labor intensive, and can be expensive if no volunteers are available. Although they weigh only 14 kg, they can be awkward and often take two people to transport them. With placement of the wattles, foot traffic is increased causing added disturbance to the soil surface.

Straw wattles were used following the 2003 Cedar Fire. Many of the fiber rolls were placed incorrectly across natural drainage positions. During the first year winter storm events, most of these failed (Hubbert 2005, 2006). Problems continued when the fiber rolls were repaired by backfilling the undercut portions with fresh hillslope material adjacent to the rolls. The next storm events removed this material as well, resulting in additional material being transported off-site (Hubbert 2005, 2006). Placement of the fiber rolls with their ends turned downslope also caused problems. Rills formed at the edge of many of the down-turned rolls, contributing to increased erosion the first year. This site experienced low rainfall, and therefore it was difficult to determine if the treatment was successful or not. Even after some intense rain events, there was little sediment accumulating behind the wattles (Hubbert 2005, 2006).

Channel Treatments

Sediment can be stored in stream channels for many years awaiting a significant flushing event, especially in ephemeral watercourses. In the post-fire environment, the extra water delivered from the burned hillsides swells the streams and can entrain and transport the stored sediment, threatening downstream infrastructure and habitat. The following treatments attempt to reduce the energy of the flowing water and retain some of the coarsest sediments behind barrier structures.

Straw bale check dams

Straw bale check dams have been used frequently in northern California, but much less so in southern California. Results have been mixed in evaluating the success or failure of the treatment. In a report by Miles et al. (1989), 1300 5-bale check dams were installed with only 13 percent failing the first year due to piping or undercutting. They considered straw bale check dams easy to install and highly effective (Robichaud et al. 2000). Collins and Johnston (1995) reported a 63 percent failure of 440 straw bale check dams 4 months following the 1991 Oakland Fire. After the Old Topanga Fire of 1993, Booker and Dietrich (1998) monitored straw check dams in 3 fire areas and reported that initially the dams had less than a 50 percent success ratio, with total failure by the 2nd year. They suggested that temporary structures should not be used in catchments with drainage areas greater than 1 ha. The straw bale dams failed because of piping, dam faces being undermined by flow over the structure, and destabilization of channel banks due to localized flow.

More recently in southern California monitoring of straw bale check dams was conducted following the Grand Prix/Old Fire (Hubbert 2005, 2006). After the Christmas Day storm of 2003, sediment completely filled to storage capacity all of the check dams. Once the check dams were filled with sediment, water was free to flow over the dams with no loss of energy. This

resulted in severe downcutting and gully formation below the dams. Following the second winter of above average precipitation, all the straw bale check dams failed. In many cases, no signs of the straw bales could be found. Under these circumstances, the treatment was considered a failure.

Log check dams

Log check dams have not been used extensively in California as a treatment. Miles et al. (1989) reported a 15 to 30 yr life expectancy for the dams, but that they were expensive and labor intensive to install. After the 2003 Piru Fire, it was recommended by the BAER implementation team to construct log check dams in the lower and upper portions of a creek that drained into a water supply reservoir. The lower drainage section of log check dams immediately filled with sediment following the 2003 Christmas Day storm. The log check dams began to fail during rain events in February 2004. The check dams that failed at the sides resulted in further cutting of the bank resulting in bank erosion and more sediment contributed to the channel (Hubbert 2005, 2006). All of the check dams failed during the record-breaking rain events of the 2005 winter.

Engineering Techniques: Road, Stream Crossing, and Trail Treatments

Due to the rapidly expanding urban interface and greater encroachment into wildlands, post-fire road and stream crossing treatments have continued to increase in both quantity and costs in California. On the 2001 Star Fire (El Dorado National Forest), costs for road and trail treatments were US$112,000 out of a total BAER expenditure of US$190,100. Where road access was critical on the Piru Fire, costs for road treatments were US$2,136,500 out of a total of US$2,324,000. In southern California, a large portion of treatment money was spent on road debris removal (dry ravel accumulation on roads), debris basin cleanouts, and culvert cleanouts.

The use of storm patrols has also increased over the last five years. On the 2004 Fred's Fire (El Dorado National Forest), US$69,900 out of a total of US$116,000 was spent on storm patrols. Storm patrols were considered effective as pro-active maintenance operation to keep drainage structures free of sediment and debris. During the large storm events in the winter of 2004-2005, storm patrols were less successful in preventing drainage structure failures on the Piru Fire. This was mainly due to numerous landslides that blocked road access during the storms.

After the Piru Fire, concrete construction barriers were placed at low water crossings to add structural integrity and stability to the road surface. In some cases, low water crossings were considered more desirable than a culvert pipe because of its ability to pass a large amount of debris without 'plugging'. However, low water crossing can become flooded and cause delays, so are

often used only on low traffic roads. By placing the barriers at a lower position below the road, it was believed that the vertical curve of the road could be lowered thus preventing flooding and failure. The barriers were originally placed too high with no spillway or low point. At first, water worked itself around the barriers. Subsequent storm events resulted in further erosion around the newly placed barriers, introducing up to a meter of new sediment. This was repaired by lowering and moving barriers nearer the bank, and creating a spillway toward the center. During the record setting rain events in the winter of the 2004-2005, all the barriers failed with some broken up and transported down stream for kilometers (Hubbert 2005, 2006).

Upgrading of culverts has continued to increase and has been considered a successful treatment. Trash rack installation has also increased and has been determined to be an effective treatment (Robichaud et al. 2000). Regrading rolling dips and repairing and replacing overside drains has continued to be an important and ongoing treatment. Rolling dips and overside drains are relatively inexpensive and fail often, but are considered to be effective in maintaining road access by removing water from the road. Of the road treatments prescribed on the Cedar Fire, more than 80 percent involved overside drains (Hubbert 2005, 2006).

The use of closure gates, removable pipe barriers, and fences that prevent public access has increased in recent years. Some closure gates are considered critical in protecting the public from rock fall, washouts, hazard trees, and flash flood events. Another important purpose of the gates is to limit public access of unauthorized off-highway vehicles (OHVs). The OHVs have become a major resource problem. On the Angeles and San Bernardino National Forests in southern California, thousands of hectares have been degraded from past OHV use because of the close proximity of 20 million people and 130 km of urban interface. After the Grand Prix/Old Fire, a total of 15 gates were installed. More than 5 km of fencing was installed bordering roads on the Cedar Fire (Hubbert 2005, 2006).

Trail repair and maintenance has seen an increase in BAER prescriptions since 1990. Due to increased use of the wildlands by a rapidly growing population base, keeping hiking trails open and accessible to the public has gained in importance. In addition, some high profile trails generate a large public response to their needs for repair.

No Treatment Alternative

Over the last decade, it has become apparent that the capability of wildlands to recover without treatments needs to be documented. In the majority of cases, wildfires do not devastate forest or rangeland ecosystems and eliminate sources of seed for desired tree and plant species. Wildfires do not sterilize soils. They do not delay or even preclude the reestablishment of plant cover, and they do not adversely impact the sustainability of ecosystems and the well-being of adjacent ecological communities. Moreover, only by monitoring

no treatment areas can the effectiveness of treatments be evaluated. Future BAER assessment teams unfamiliar with local recovery periods would also benefit from this monitoring information that documents the natural recovery. Monitoring burned but untreated hillslopes provides data for future determinations of potential erosion risk that may be useful for future post-fire treatment decisions. This could be critical as both erosion and sediment potential define the emergency, based on the values at risk (Napper 2005).

LESSONS LEARNED AND FUTURE DIRECTIONS

After nearly a century of post-fire emergency rehabilitation in California, the practice has become fairly well-developed and there have been many lessons learned along the way. It was once standard operating procedure to seed every burned hectare and erect heroic engineering works on every stream channel to protect all onsite and downstream values at risk. Today this is seen as both unnecessary and unrealistic. We now understand that fire is an integral part of nearly all ecosystems, and that the consequences of wildfire are not necessarily devastating to the environment. There are still critical natural resources and human development that need extra protection in the aftermath of fire, but these need to be clearly identified and specifically targeted with environmentally sensitive measures. If there are no resources or values at risk, no treatments are needed. After the 2003 southern California Fire Siege, only about 2 percent of the over 290,000 ha burned were treated with some form of emergency rehabilitation measures (Hubbert 2005).

While human life and infrastructure are of paramount importance, emergency rehabilitation techniques must also be sensitive to environmental concerns. Grass seeding has been all but abandoned in California, as research has shown that rapidly growing non-native grasses do little to reduce erosion, provide no extra ground cover, and can be harmful to native species (Wohlgemuth et al. 1998). Radical ground disturbing measures whose impacts on the landscape can last much longer than the anticipated emergency are now discouraged. Engineering solutions can be prohibitively expensive and their protection results can not be guaranteed if the worst case scenario is realized and the design criteria are exceeded. Perhaps the most realistic protection measures from the consequences of post-fire flooding would be to redirect human development away from the canyon mouths and steeplands at the wildland/urban interface.

Although post-fire rehabilitation and restoration have been practiced for many decades, land management and hazard protection agencies have not always done a thorough job of monitoring the success and effectiveness of rehabilitation practices (GAO 2003). Both the U.S. Department of Agriculture, Forest Service (Robichaud et al. 2000) and the U.S. Department of Interior (Pyke and McArthur 2002) produced reports recommending that more research on and systematic monitoring and analysis of post-fire stabilization

methods be conducted. Results of some of that monitoring have been described in this chapter and other chapters, and many other projects are being documented, often in internal agency reports. In the future these assessments need to consider not only the effectiveness of these practices but also their cost-effectiveness.

The practice of post-fire logging or 'salvage logging', often considered part of post-fire rehabilitation or restoration, has come under greater scrutiny as well (McIver and Starr 2000, Donato et al. 2006). The U.S. Department of Agriculture, Forest Service and the U.S. Department of Interior Joint Fire Science research program has recently (2006) awarded several grants dealing with the impacts of current and past post-fire logging, including projects in Sierra Nevada and northern California (see http://jfsp.nifc.gov for a list of past and current projects).

Perhaps the greatest challenge in the future to post-fire rehabilitation specialists lies in the realm of education. Vast knowledge and experience has accrued over the past century, but the communication of this information has lagged. The general public needs to be aware that the emergency is not over when the flames are doused, understand that – even seemingly removed from the burned area – there can be serious consequences of flooding and sedimentation in the post-fire environment, and appreciate the possibilities and costs of emergency rehabilitation. More importantly, land managers and political decision-makers need to receive objective information from the rehabilitation specialists in order to make educated post-fire restoration choices.

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