Impacts of Fire-Suppression Activities on Natural Communities

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Abstract: *The ecological impacts of wildland fire-suppression activities can be significant and may surpass the impacts of the fire itself. A recent paradigm shift from fire control to fire management has resulted in increased attention to minimizing the negative effects of suppression. While the philosophy behind minimum-impact suppression tactics has provided a good first step in this direction, increased attention to the ecological effects of suppression is needed, especially in the management of public lands. We reviewed the potential impacts of suppression on land, air, and water resources and the impacts of using fire to help control fire. Effects on land resources include erosion, which is exacerbated by the construction of fire lines, temporary roads, and helicopter pads, and some postfire rehabilitation activities. Although the fire itself is the most obvious source of air pollution, the vehicles used in suppression activities contribute to this problem and to noise pollution. Water resources, including aquatic flora and fauna, may be seriously affected by suppression activities that can increase erosion, sedimentation, turbidity, and chemical contamination. Finally, the use of backburns and burnout operations contributes to the risk of soil and water contamination, increases the total area burned, and promotes more intense fires or more homogeneous burned areas. Although no fire-management strategy should be applied uniformly, some general techniques such as use of natural clearings, natural barriers, and appropriately sized fire lines, "leave no-trace" camping, and careful application of fuels and retardants can be employed to minimize the impacts of suppression.*

Key Words: disturbance, erosion, fire suppression, minimum-impact suppression tactics, pollution

Impactos de Actividades de Supresión de Fuego sobre Comunidades Naturales

Resumen: *Los impactos ecológicos de actividades de supresión de incendios pueden ser significativos y pueden rebasar los impactos del fuego mismo. Un reciente cambio de paradigma de control de fuego a manejo de fuego ha resultado en mayor interés para minimizar los efectos negativos de la supresión. Mientras que la filosofía subyacente en las tácticas de supresión con mínimo impacto ha proporcionado un buen primer paso en esa dirección, se requiere mayor atención a los efectos negativos de la supresión, especialmente en la gestión de tierras públicas. Revisamos los impactos potenciales de la supresión sobre recursos terrestres, aéreos y acuáticos y los impactos de la utilización de fuego para ayudar a controlar fuego. Los impactos sobre recursos terrestres incluyen erosión, que se agrava por la construcción de guardarrayas, caminos temporales y plataformas para helicópteros, y algunas actividades de rehabilitación post-incendio. Aunque el fuego mismo es la fuente más obvia de contaminación del aire, los vehículos utilizados en actividades de supresión contribuyen a este problema y a la contaminación acústica. Los recursos acuáticos, incluyendo la flora y fauna, pueden ser afectados seriamente por actividades de supresión que pueden incrementar la erosión, sedimentación, turbidez y contaminación química. Finalmente, la utilización de retroquemas y operaciones para apagar incendios contribuye al riesgo de contaminación de suelo y agua, incrementa el área quemada y promueve incendios más intensos o áreas quemadas más homogéneas. Aunque no debe aplicarse uniformemente ninguna estrategia de manejo de incendios, para minimizar los impactos de la supresión se pueden emplear algunas sugerencias*

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generales como el uso de claros naturales, barreras naturales y guardarrayas de tamaño apropiado, campismo "sin dejar rastro" y aplicación cuidadosa de combustibles y retardantes.

Palabras Clave: erosión, perturbación, contaminación, supresión de fuego, tácticas de supresión con mínimo impacto

Introduction

Natural resource managers and the public they represent generally accept the idea that some lightning-ignited fires should not be suppressed. On the other hand, various socioeconomic, political, and ecological factors mandate suppression of most fires. A growing literature indicates that the cost of suppressing a fire nearly always includes damage to ecosystems. In a system of fire management that attempts to weigh the costs of fire suppression against potential losses due to fire, the ecological cost is often not acknowledged, despite the fact that adverse effects from suppression activities may be substantial and persistent and, in some instances, may exceed impacts attributable to the fires themselves (Pyne 1984; Mohr 1989). In some cases, it may also be difficult or impossible to differentiate the effects of fires from those of suppression activities.

The process of developing a fire-management strategy involves assessment of land-management objectives, economics, and resource values (and potential reduction of these values) such as soil retention, presence of rare species, and water quality (Mohr 1989). During the past two decades, some fire managers have incorporated environmentally sensitive suppression tactics that were historically considered only in wilderness areas. For example, "light-hand-on-the-land" tactics were incorporated into fire suppression by many managers in the mid-1980s in an attempt to avoid unnecessary adverse impacts on natural resources. These techniques evolved into minimum-impact suppression tactics (MIST), which are intended to reduce impacts to natural resources, including visual impacts, while ensuring timely and effective fire-suppression actions (Jolly 1993). The MIST guidelines are described in fire-management plans and environmental assessments for most land-management agencies. The MIST guidelines are not intended to represent a separate classification of tactics but rather a philosophy of wildfire suppression that aims to minimize the long-term effects of suppression activities (USFS 2001*a*). The U.S. Department of Agriculture Forest Service (USFS) and U.S. Bureau of Land Management (BLM) use MIST guidelines in wilderness, proposed wilderness, or areas with similar land-management objectives, and the National Park Service (NPS) uses them when it is safe to do so. Nonetheless, more area is not covered by MIST guidelines than is covered by the guidelines. As a result, the majority of public land is susceptible to degradation of biological resources as a result of heavy-handed suppression tactics.

Although numerous impacts associated with fire-suppression activities have been described, there has been no review, synthesis, or quantification of these impacts. Our objective is to organize and synthesize information about the effects of fire suppression on ecosystems, including postfire rehabilitation. No management is devoid of impacts. Even a broad "let-burn" approach has significant consequences for natural communities. Similarly, no fire-management strategy should be applied uniformly; instead it should take advantage of system-specific knowledge about ecosystems and sociopolitical elements. As a result, recommendations and considerations for avoiding unnecessary and excessive impacts can only be discussed in general terms.

We arranged our review according to the four elements of ancient Greek science and philosophy: earth, air, water, and fire (Table 1). As with any organizational structure, there is some redundancy between these sections (e.g., fire lines affect earth via compaction and water via erosion-induced sedimentation).

We intended to represent a pragmatic, intuitive "next step" toward an understanding of and approach to fire management. We accept and support the idea that a highly structured, organized approach to suppressing wildfires, with its obvious analogy to war, does not grant us the right to overlook our responsibility as land stewards (Mohr 1992–1993). Rather, a change in fire policy from control to management has resulted in a paradigm shift toward the identification and implementation of appropriate strategies that achieve suppression and management objectives without unnecessary environmental impact (Nelson 1979; Mohr 1989). Contemporary fire-management policy directs fire managers to minimize suppression costs and damage consistent with land and resource objectives and to consider the effects and consequences of both the fire itself and the fire-suppression activities (Husari & McKelvey 1996). This approach is an important extension of wilderness fire-suppression priorities into nonwilderness areas. These priorities encourage the use of tactics and equipment that cause minimal impact to wilderness values, including alterations of the landscape, disturbance to visitor solitude, air and visual pollution, and reduction of visibility (Lunsford 1988).

The first priority of any firefighting effort is to protect human lives, as codified in the 10 Standard Firefighting Orders and the 18 "Situations That Shout Watch Out" listed in the Fireline Handbook (National Wildfire Coordinating Group 1998). We are criticizing neither historical approaches to fire management nor individual firefighters.

Table 1. Impacts associated with fire-suppression activities.

Element affected	*Impact*	*Potential sources*
Earth	soil compaction	fire camps
		fire lines
		helibases
		incident command posts
		road construction
	erosion	fire lines
		road construction
	non-native species	fire camps
		fire lines
		helibases
		incident command posts
		rehabilitation activities (seed mixes, straw-bale check dams)
	litter and waste	fire camps
		fire lines
		extinguished fuses, line explosives, and aerial ignition devices
		rehabilitation activities
	reduction of habitat	contour-felled logs (rehabilitation activities)
		snag removal (mop-up activities)
	soil contamination	fuel spillage
Air	air pollution	fossil fuel emissions-aircraft, vehicles, machinery
	noise pollution	aerial support
	visual pollution	increase of air traffic
Water	sedimentation	contour-felled logs and channelization
		fire camps
		fire lines
		road construction
	disturbance	amphibious aircraft
		removal of water for suppression activities (heli-buckets, pumping)
	fish mortality	fire retardant
	eutrophication	fertilizer use with rehabilitation activities
		fire retardant
	pollution	fire camps
		fire retardant
		fuel spillage
		rehabilitation activities (introduction of synthetic materials)

Rather, we hope to promote a constructive dialog that enhances environmental protection along with protection of lives and property.

Earth

Suppression efforts generally result in disturbances that engender long-term consequences for natural resources (Benson & Kurth 1995). Erosion can be initiated or exacerbated by both fires and fire-management activities, including the construction of fire lines, temporary roads, and helicopter pads, as well as postfire rehabilitation activities (Robichaud et al. 2000). Whenever possible, the use of natural barriers for line construction and natural openings for helicopter landings and fire camps is recommended to minimize the impact of suppression activities (U.S. Fish and Wildlife Service 2002).

Fire lines are used during initial attack to stop advancing fire fronts or as anchor points for starting backfires; these may be constructed with hand tools, heavy equipment, or fire-line explosives. The USFS's Missoula Technology and Development Center, which has researched, developed, and tested fire-line equipment since the 1930s, has shown that various approaches and equipment used in fire-line construction result in degrees of effectiveness and a range of impacts (Abell 1937; Hanson 1941; Storey 1969; Ramberg 1974; Phillips & Barney 1984).

Depending on the fuels and terrain, equipment such as trenchers, blowers, plows, and bulldozers have been used to construct fire lines. The use of bulldozers in fire suppression has been curtailed in some ecosystems, although they can be valuable where heavy vegetation must be removed (Phillips & Barney 1984). Tractors, bulldozers, and wheeled skidders produce soil compaction, the extent of which depends on soil type, soil moisture content, and the number of times an area is traversed (McNabb 1983; Cullen et al. 1991; Froehlich & Reisinger et al. 1992). Soils typically recover from compaction, although recovery times may be as long as 45 years (Froehlich & McNabb 1983; Reisinger et al. 1992). Environmental impacts also vary with the type of device used to plow the line; wider vehicles require more clearing (Arno & Arno 1996).

Although manual construction of fire lines provides a useful mechanism to control the width of the line, it requires a well-trained hand-line crew, which is often not available. Alternative means of constructing fire lines include the use of linear explosives (pentaerythritol tetranitrate and diammonium phosphate) and water-gel explosives (ammonium nitrate with a sensitizer). Explosives represent a low-cost alternative to construction of fire lines with machines or hand tools. The environmental impacts of linear explosives may be less than those associated with conventional fires lines (Lott 1975), and they may revegetate more rapidly than fire lines constructed with hand tools (Barney 1984). Although fire-line explosives are relatively ineffective when fuel moisture is high (Lott 1974, 1975), this is rarely a problem when fires are being suppressed. The potential toxicity to soil organisms from fire-line explosives is unknown. Regardless of the methods and equipment used to construct fire lines, extensive rehabilitation efforts may be required (Lott 1975), MIST guidelines notwithstanding.

Some ecosystems, especially those in notably wet, dry, or cold regions, are particularly vulnerable to the effects of fire-suppression tactics. Marshes, for example, have been known to experience substantial, persistent effects (Taylor & Gibbons 1985). In one case, plow lines were still visible 30 years after a fire in the Everglades National Park (Taylor 1981). In the Mojave Desert, tracks are evident decades after they are formed (Belnap & Warren 2002). The mechanisms behind these effects are not well understood, although one possibility is that damage to mycorrhizae limits the potential for soil rehabilitation (Meador 1976). In addition, construction of fire lines in areas underlain by permafrost may remove the entire insulating vegetative layer, exposing mineral soil to sunlight that rapidly melts the permafrost (DeLeonardis 1971; Sykes 1971; Viereck 1982). In interior Alaska, Viereck (1982) noted higher soil temperatures and greater duration and depth of high temperatures beneath fire lines than in burned and unburned areas for several years following a fire.

Increased erosion is a common result of fire-suppression efforts. Bulldozer-constructed fire lines may produce severe erosion (Bolstad 1971), even to the point that the fire line produces more erosion than the fire itself (DeLeonardis 1971; Lotspeich & Mueller 1971). Fire lines and the associated berms cause artificial channeling, thus further accelerating erosion. The resulting transport of sediment may cause long-term damage to aquatic ecosystems (Lotspeich et al. 1970). Stream turbidity and suspended sediments (discussed in the section on water) can also be exacerbated by fire lines, particularly those constructed with bulldozers (Landsberg & Tiedemann 2000).

The disturbances created by wildfire suppression foster a strong potential for the introduction and spread of invasive species (Crawley 1987). Fire camps, helibases, incident command posts, and fire lines are predisposed to invasion by non-native plants because personnel, vehicles, and equipment act as vectors for propagules. For example, bulldozed plots in Glacier National Park had a greater composition and cover of non-native species than either the undisturbed or burned plots (Benson & Kurth 1995). The Standards for Fire and Aviation Operations Wildland Fire Resource Policy addresses noxious weed prevention, suggesting that "to reduce the transportation, introduction, and establishment of noxious weeds or other biological contaminants on the landscape due to fire suppression activities, fire suppression and support vehicles should be cleaned at a pre-designated area prior to leaving the incident" (U.S. Bureau of Land Management 2003:81). According to the USFS, weed species are among the greatest threats to burned areas. Thus, early detection and eradication was the USFS's highest priority in the wake of the 2000 fire season. Nearly 460,000 acres (186,155 ha) of state and national forests and grasslands were vulnerable to postfire invasion in the 2000 fire season alone (USFS 2001*b*). Preliminary results from Bitterroot National Forest following the 2000 fire season showed higher densities of spotted knapweed (*Centaurea maculosa* Lam.) on bulldozer-constructed fire line and exponentially decreasing knapweed density with distance from the fire line (S. Sutherland, USFS, Missoula, Montana, personal communication).

With the focus on the fire (and recently on fire lines), fire camps have received little attention with regard to environmental impacts. The numerous intensive activities and large numbers of people in wildland areas can have long-lasting effects. Wildfires often require fire camps in remote areas, and they necessitate clearing of vegetation before the arrival of fire crews and equipment. Potential impacts on the environment from fire camps include soil compaction, litter, and contamination from improper waste disposal. Some fire camps have initiated recycling programs (Van Buren 1995), encouraged "leave-no-trace" camping, and implemented MIST guidelines to reduce the amount of impact and need for excessive rehabilitation (Mohr & Curtiss 1998). These have been successfully implemented on large fires, where resource advisors assigned to the incident team are expected to develop and implement policies that protect and restore camps and helispots to prefire conditions (Mohr 1992–1993).

Rehabilitation activities and expenditures fall within the domain of fire suppression and are therefore addressed here. The Burned Area Emergency Rehabilitation (BAER) and Emergency Stabilization and Rehabilitation (ESR) programs are interagency programs that gather information on fire-induced watershed conditions in the wake of large wildfires for use in determining the existence of significant threats to life, property, or natural resources (USFS 1995). They also provide policy, standards, and procedures for implementing emergency stabilization treatments and rehabilitation of damage from fire-suppression activities (U.S. National Park Service 1999). Special rehabilitation as a result of environmental and resource impacts is often necessary for fire camps, fire lines, helispots, and incident command posts (Mohr 1992–1993; U.S. Department of Agriculture Forest Service 1999; U.S. National Park Service 1999).

Robichaud et al. (2000) reviewed publications and monitoring reports and conducted interviews to evaluate the effectiveness of rehabilitation treatments at reducing postfire erosion and runoff, mitigating downstream effects, and assessing natural processes of ecosystem recovery. Broadcast seeding of grasses is the most common method for establishing vegetation to reduce hillslope erosion and promote infiltration. For many decades, these efforts relied primarily on fast-growing, non-native annual grasses such as ryegrass (*Lolium multiflorum* Lam.) because they are available in large quantities at low cost, can be applied by air, and have fibrous root systems that apparently stabilize the soil (Barro & Conard 1987). The use of ryegrass for postfire erosion reduction has had mixed results (Barro & Conard 1987; Taskey et al. 1989; Conard et al. 1991; Beyers et al. 1998; Wohlgemuth et al. 1998). For example, ryegrass and other non-native plants tend to suppress the establishment and growth of native vegetation, potentially retarding the long-term recovery of the ecosystem (Nadkarni & Odion 1986; Taskey et al. 1989; Conard et al. 1991; Beyers et al. 1998; Loftin et al. 1998). The BAER and similar programs suggest using nonreproducing annual plants or sterile hybrids, and they advocate the use of native species for postfire revegetation whenever practical (U.S. National Park Service 1999; Robichaud et al. 2000).

Other rehabilitation treatments that can introduce or promote the spread of non-native plants include tilling or ripping the soil (Leuschen & Frederick 1999), postfire logging (Greenberg et al. 1994*b*; Sexton 1998; McIver & Starr 2000), and the application of straw mulch contaminated with weeds (Robichaud et al. 2000; U.S. Department of Agriculture Forest Service 2002*a*). Use of heavy equipment for contour trenching, terracing, and postfire logging activities (also including road building and skid-pad construction) may produce substantial soil disturbance (McIver & Starr 2000; Robichaud et al. 2000; U.S. Fish and Wildlife Service 2002), with implications for compaction, erosion, sedimentation (Helvey 1980; Helvey et al. 1985; Klock et al. 1985), and spread of non-native plants. The effectiveness of contour-felled log barriers, commonly recommended under BAER, is questionable in reducing storm runoff, erosion, and sediment movement, and they are costly (Miles et al. 1989). Felling trees and snags for erosion control or salvage logging removes or changes potential wildlife refugia (Lindenmayer & Possingham 1995; McIver & Starr 2000; Robichaud et al. 2000), causes further disturbance, and may damage resprouting plants (McIver & Starr 2000). A further potential effect of postfire logging on the community is reduction of insect populations that provide food for various wildlife species (Blake 1982; Saab & Dudley 1998).

Finally, chemicals in fire retardants and suppressants (discussed further in the section on water) may have negative effects on soils and vegetation. Because surfactant suppressant foams partially dissolve plant epicuticular wax, they tend to make plants more susceptible to other threats (Tamura et al. 2001). Plant species richness declined immediately after application of suppressant foam on shrub steppe vegetation in northern Nevada, but returned to a level comparable to that of control plots by the end of one growing season (Larson et al. 2000). This suggests that fire has a much greater influence on plant species richness than do suppressant foams. Firesorb, an acrylic-based polymer used as a fire retardant, decreased nitrogen mineralization but otherwise did not have a measurable effect on chemical properties or on soil microbial communities in a laboratory setting (Basanta et al. 2002).

More recent fire-management plans incorporate site-specific recommendations to avoid excessive impacts of fire-suppression activities. To determine which tactics are appropriate, an incident fire manager must assess a broad suite of variables that include natural and cultural resources in addition to social, economic, and political elements. The MIST guidelines include selecting natural openings for helispots, using natural barriers for fire lines, minimizing the number of felled trees, and using appropriate fire-line width and depth. Several case studies assessing suppression activities and evaluating the effectiveness of postfire rehabilitation are provided by Robichaud et al. (2000).

Air

The vehicles used in fire-suppression activities, including both trucks and aircraft, indirectly release retardant particulates into the atmosphere, contribute to noise pollution on and off the site, and expend large amounts of fossil fuels and associated emissions. Although it is difficult to quantify the contribution of fire-suppression vehicles to air pollution, it is worth noting that fossil-fuel burning has contributed about three-quarters of the anthropogenic emissions of CO_2 over the past 20 years and has also been identified as a major contributor of methane (CH_4) emissions. The potential effects of these and other greenhouse gases are well documented (IPPC 2001).

Air-support suppression activities are the most visible symbol of fire-suppression efforts and the most expensive for large fires (Mangan 2001). Due to recent increases in air traffic associated with large fires, airspace coordination is an essential part of wildland fire aviation, and temporary flight restrictions are often implemented (Stewart 1999). For example, helicopter operations may disturb nesting Bald Eagles (*Haliaeetus leucocephalus*) and are therefore restricted from flying directly over inactive nests or within one-half mile (0.8 km) of known active nests (U.S. Department of Agriculture Forest Service 2002*b*). Attempts to minimize the environmental effects of fire-suppression operations should account for potential impacts on noise-sensitive species, especially those listed under the U.S. Endangered Species Act.

Water

The potential effects of fire on water resources include increased erosion, sedimentation, turbidity, contamination of surface and ground water, and other impacts that affect the suitability of water for drinking and other purposes. Most of these are directly associated with the fire itself, but some fire-management activities also reduce water quality (Landsberg & Tiedemann 2000). Use and disposal of water at fire camps has been addressed in MIST guidelines, including the use of biodegradable soap, bathing away from streams and lakes, and proper disposal of human waste and gray water (U.S. Department of Agriculture Forest Service 1999).

During suppression, local water sources are tapped either by pumps or helibuckets. Water extraction from lakes, ponds, and reservoirs can use helibuckets that range in size from 100 to 2000 gallons (378.5–7570.8 L; U.S. Department of Agriculture Forest Service 2001*c*). This disturbance, along with that of amphibious fire-suppression planes, can increase suspended sediment, contribute to turbidity, and affect aquatic fauna and habitat. Helicopters are permitted in wilderness areas if excessive erosion from bucket work is avoided (U.S. Department of Agriculture Forest Service 1999).

Fire lines near streams are potential sources of suspended sediment and turbidity. They provide direct channels for sediment and are slow to revegetate because much of the nutrient-rich topsoil is moved aside (Landsberg & Tiedemann 2000). When the overlying vegetation mat of a taiga ecosystem is removed by heavy equipment for fire lines, the permafrost melts to greater depths, thereby releasing silt through melting (rather than true erosion) and increasing sedimentation in streams (Lotspeich & Mueller 1971).

Rehabilitation of watershed conditions, notably water quality, is the primary focus of BAER teams. Ironically, various types of rehabilitation activities that have been used to mitigate fire effects have the potential to reduce water quality. Straw-bale check dams are commonly used in channels to prevent flooding and debris (e.g., sediment, slash). Straw bales, even those certified as "weed-free" straw, may be contaminated with invasive non-native grass seed and therefore may provide a vector for the introduction of non-native species into extensive stream systems (Robichaud et al. 2000). Contamination of straw bales with cheatgrass (*Bromus tectorum* L.) and seed mixes contaminated with wild oats (*Avena fatua* L.) were documented recently in Colorado (Chong et al. 2002). This analysis also suggested negative impacts to species of concern by erosion-control materials—straw mulch, hydromulch, and seeds—that could collect in riparian and wetland areas following storms, especially if the erosion-control materials contain invasive non-native seeds (Kotliar et al. 2002). Synthetic materials used in channel treatments, such as metal posts, synthetic fabric, and fencing, may remain in the environment long after the fire (Winchester 1999). Ineffectively placed contour-felled logs can intensify erosion and sedimentation. Reconstruction of channel morphology with heavy equipment may threaten natural resources by diverting substantial flow (D.M.B., personal observation).

Another major fire-suppression activity is the aerial or manual application of fire-suppressing and -retarding chemicals. These efforts involve the application of millions of liters of fire-control chemicals in the United States each year (Buhl & Hamilton 1998). The chemicals used in fire control fall into two classes: fire-suppressant foams, which are primarily detergent-based, and fire-retardant chemicals, which are usually based on nitrogen or phosphorus. Most documentation of the effects and potential effects of these chemicals focuses on threats to aquatic habitats and species.

Suppressant foams extend the longevity and effectiveness of water by inhibiting evaporation and dissolving the waxy coating on live vegetation (Schlobohm & Rochna 1988). Their primary advantage lies in reducing the amount of water needed to control fire. "Twelve dollars [of foaming agent] can make 500 gallons (1892.7 L) of water into 5000 gallons (18927.1 L) of effective water as foam" (Schlobohm & Rochna 1988:19). Some kinds of suppressant foam have negative impacts on humans and the natural environment. For example, aqueous film-forming foams used to extinguish many hydrocarbon fuel fires contain perfluorinated surfactants, which accumulate in the human body and the environment (Moody & Field 2000). Surfactant (detergent-based) foams are used most frequently in wildland fires, although common foams also include foam stabilizers, inhibiting agents, and solvents (Monsanto 1990, cited in Gaikowski et al. 1996*a*). Literature on the environmental impacts of these foams is extremely limited (but see our section on earth). A relatively new kind of fire retardant is an acrylic-based synthetic polymer that increases water viscosity, essentially turning it into a gel. In addition to increasing the fire-fighting effectiveness of water, this polymer may improve soil structure and increase infiltration rates (Basanta et al. 2002).

Fire retardants, which are primarily composed of nitrogen and phosphorus, may affect water quality, vegetation, and animals. Some fire-retardant chemicals contain sodium ferrocyanide, an anticorrosive agent that can release cyanide when exposed to a certain level of UV radiation. A summary of research produced for the USFS found that the presence of sodium ferrocyanide increased the toxicity of fire-retardant chemicals to a variety of aquatic species; in one instance, 100% mortality of fathead minnows (*Pimephales promeleas*) occurred in field stream tests conducted on sunny days (Little & Calfee 2002).

In the past, it has been assumed that the effects of the nitrogen and phosphorous in retardants are minimal because the nutrient pulses are short-term and infrequent (Handleman 1971). However, because phosphorus is usually the limiting factor for productivity in surface waters, and because the quantitative relationship between nutrient concentration and productivity is unclear, nutrient-based fire retardants should be used with care near water resources. The potential for eutrophication of surface waters depends on several factors, including the amount of nutrients added, the prior productivity of the affected waters, the effects of other stressors, and the seasonality and timing of the additions (Freedman 1995). Similarly, postfire use of fertilizer may accelerate eutrophication of lakes and ponds (Landsberg & Tiedemann 2000). Although fertilization may produce higher concentrations of nitrate than the fire itself (Tiedemann 1973; Tiedemann et al. 1978), the impact on water quality will necessarily depend on these numerous site-specific factors.

At some concentrations, nitrogen and phosphorus retardants (e.g., Fire-Trol LCG-R) may be moderately toxic to algae, with similarly great potential to affect the functioning of aquatic systems (McDonald et al. 1996).

Another possible threat from retardants to aquatic habitat is direct toxicity to flora and fauna. Much of the research on retardants and suppressants has addressed acute toxicity in fish, and significant fish kills have been associated with stream contamination from inaccurate application of retardant (Gaikowski et al. 1996*a*). Acute toxicity of various common fire-fighting chemicals has been described for different life stages of several species, including fathead minnows (*Pimephales promelas*), rainbow trout (*Oncorhynchus mykiss*), and Chinook salmon (*Oncorhynchus tshawytscha*) (Gaikowski et al. 1996*a*, 1996*b*; Buhl & Hamilton 1998). Gaikowski et al. (1996*a*, 1996*b*) and Buhl and Hamilton (1998) found that acute toxicity to fish is greater with fire-suppressant foams than with fire retardants. These authors concluded that both chemicals pose a significant threat to fish populations because the application concentrations of both types of chemicals are considerably greater than the observed values for acute toxicity. The timing of chemical application should also account for the life stages of fish, especially when endangered species are present (Gaikowski et al. 1996*a*, 1996*b*). Sublethal effects on aquatic vertebrates should also be considered (Buhl & Hamilton 1998).

Regarding water, MIST guidelines for fire-suppression activities (U.S. Department of Agriculture Forest Service 2001*a*) suggest bathing, cooking, and camping away from lakes and streams, using water blivits and gravity socks to collect water, and using weed-free straw bales for channel treatment. During initial attack, fire managers should compare the impacts of water drops versus the use of foam or retardant. Fire retardant and other suppressants should not be dropped near surface waters, and contamination of water sources should be avoided.

Fire

Several kinds of hydrocarbon fuels and ignition devices are used to light backfires. Diesel and gasoline (liquid or jellied) are the most common fuels; propane is used somewhat less frequently. Ignition devices include aerial ignition devices (AIDs, or ping-pongs), which achieve delayed ignition though a combination of potassium permanganate pellets and liquid ethylene glycol, and ground ignition devices, including drip torches with a diesel and gasoline mixture and magnesium-based fuses (Orion Safety Products 2001). The residue from these fuels and devices is unknown but probably minor, because most potentially hazardous materials are combusted and contribute to the already affected air quality. However, the unquantified risk of fuel spills suggests the potential environmental impacts described below.

Spills of hydrocarbon fuels may be acutely toxic or subtoxic to plants, microorganisms, and animals, and they may contaminate groundwater (Siddiqui et al. 2001). The primary groundwater contaminants associated with gasoline (benzene, toluene, ethylbenzene, and the xylenes) are relatively readily biodegraded; however, oxygenate additives such as methyl tert-butyl ether (MTBE) are more hazardous. Depending on the season of year and source of fuel, MTBE may not be present in gasoline used for fire-suppression equipment (it is used primarily as a winter additive in urban areas). Methyl tert-butyl ether is less biodegradable, more soluble, and more mobile than other contaminants derived from gasoline, and it is carcinogenic to animals (Schirmer et al. 2003). At levels normally encountered, it does not appear to be lethal to freshwater organisms, but because the potential concentration of MTBE following a spill cannot be predicted, it could be toxic to aquatic organisms (Werner et al. 2001). Benzene itself is a known carcinogen (Hartley & Englande 1992). In addition, there are strong associations between gasoline or diesel contamination and plant response, including acute toxicity (Green et al. 1996), inhibited germination (Siddiqui et al. 2001), and stunted or retarded growth (Adam & Duncan 1999). The MIST guidelines (U.S. Department of Agriculture Forest Service 2001*a*) recommend that fuels be stored and dispensed in accordance with the recommendations of the National Fire Protection Association and the Health and Safety Code Handbook. They should be stored downhill and downwind from fire camps and away from ignition. To avoid spills, the use of absorbent pads and containment berms is suggested.

Backfires from containment lines may comprise a significant proportion of the total area burned, substantially increasing a fire's extent. In addition, backfire operations may produce higher-intensity fires than the fire being "contained" by the backfire, thus contributing to high tree mortality and postfire erosion. "Burnout" operations likewise may contribute to increased fire size. By removing unburned "islands" of vegetation, these operations produce a much more homogeneous burned area than occurs within typical fires. Refugia for plants and animals may be removed by these "burnout" operations.

Summary and Recommendations

Many agency fire plans include minimum-impact suppression tactics, and resource advisers are often included on incident command teams. Despite these precautions, some suppression activities have deleterious effects on natural communities. Fire-suppression activities begin to affect natural communities as soon as initial attack forces are deployed to the fire, and direct and indirect impacts on the environment can continue long after fire crews have departed. Trucks, equipment, and clothing laden with propagules of non-native plants arrive at the scene of the fire. Impacts increase substantially as equipment and personnel arrive on site; these vary from obviously intense but localized impacts at heavily disturbed staging areas, helispots, and fire breaks (e.g., soil compaction, erosion, tree felling associated with staging areas and firelines) to the presumably innocuous consequences of drawing water from lakes and ponds and setting up fire camps. Other consequences associated with fire suppression result from the use of hazardous materials and other pollutants (e.g., retardants, fuel residue, extinguished fuses, noise). After the fire is contained and controlled, postfire rehabilitation efforts often include the introduction of organisms and organic materials into natural communities. It is clear that the individual and combined effects of various fire-suppression activities on natural communities merit increased attention from planners, wildland firefighters, and rehabilitation crews.

Appropriately light-handed suppression tactics can be determined only on a case-by-case basis; therefore, we provide very broad recommendations for fire managers to consider. To minimize environmental impacts, use natural barriers when possible; use the minimum fire-line width and depth sufficient to accomplish the task; avoid heavy equipment in riparian areas and meadows; minimize felling of live trees and solid snags; use natural openings for staging areas and camps; employ "leave no-trace" camping; avoid the spread of non-native plants and do not introduce them during postfire rehabilitation; do not drop retardant or other suppressants near surface water; and use folding water tanks to minimize water impacts (U.S. Department of Agriculture Forest Service 1999, 2001*a*).

It is important to note that in most cases the ecological effects of a fire are significantly greater than those of fire-suppression activities. Many of the phenomena we have discussed here, such as sedimentation and increased spread of non-native species, are common and significant products of the fire itself, so that in any particular burned area it may be impossible to separate the two sources of ecological change. Further, deciphering appropriate strategies to minimize the impact of one particular tactic while not exacerbating another is a difficult task for fire managers to face.

The impacts of fire and fire suppression are numerous, and the consideration of all impacts within the framework of a fire-management plan is a significant challenge. Nonetheless, progressive fire managers will attempt to incorporate the effects of actions (including lack of action) into assessments.

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