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10. Shrubland Management Effects on Air Quality[1]

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Abstract: Prescribed burning is a valuable shrubland management tool, but the resulting emissions may have adverse effects on air quality. Visibility impairment is often a most sensitive issue. The most significant hazards to human health are inhalation of carbon monoxide and particles containing benzo[a]pyrene, a carcinogen. Formation of ozone in smoke plumes may add slightly to existing ozone pollution. Carbon dioxide produced by both prescribed and wildfire contributes to the unfavorable accumulation in the global atmosphere, but regulation of prescribed burning would have a negligible influence on this phenomenon. Chemical makeup, size distribution, amount, and moisture content of shrubland fuels largely determine fire intensity and emission rate. Emissions can best be controlled by burning during optimum weather and fuel conditions, and by using suitable ignition procedures. Smoke dispersion models aid in predicting the behavior of plumes. Alternatives to burning need to be considered near sensitive areas including highways, airports, hospitals, and schools.

Prescribed burning is the scientific application of fire as a vegetation management tool (Society of American Foresters 1980a). In shrublands, objectives of prescribed burning may include reduction of wildfire hazard by eliminating accumulated fuel, improvement of wildlife habitat, preparation for conversion to grass or trees, increasing water yield, and increasing accessibility to livestock and recreationists (Green 1981). However, in most situations, the land manager must take steps to minimize the adverse effects of the emissions on other resources and sensitive locations including highways, airports, and inhabited areas with hospitals and schools. Visibility is most often adversely affected. In interpreting the 1977 Clean Air Act amendments that protect visibility, the U.S. Environmental Protection Agency urged that emissions from prescribed fire be reduced where feasible, and that alternatives to burning be considered (U.S. Environmental Protection Agency 1979). Consequently, land managers have suggested smoke management procedures (Society of American Foresters 1980b) and developed improved guidelines for prescribed burn planning (U.S. Dep. Agric., Forest Serv. 1982; Wright and Bailey 1982).

Smoke management involves three main functions: appraisal, specifications and scheduling, and execution (U.S. Dep. Agric., Forest Serv. 1982). In its simplest terms, the task involves selecting a favorable wind direction and conditions for dispersion that will prevent visibility and pollution concentration standards from being exceeded. The fire manager also has to consider many other fixed and variable elements that determine fire intensity which in turn regulates emission rates of pollutants from woody fuels (Table 1). Invariably, the experience and intuition of the fire manager and support staff determine whether the prescribed burn will meet its vegetation management and air quality protection goals. The major decisionmaking tools available include knowledge of fuel conditions, weather, and the burn area, and a choice of ignition patterns (Green 1981). To estimate downwind impact of smoke, several types of atmospheric transport and dispersion models may be considered, but these are usually not suitable for complex terrain where most chaparral burning is done (U.S. Dep. Agric., Forest Serv. 1982; Fox and Fairobent 1981).

This chapter examines the current knowledge of fuel types, the combustion process, types of emissions, transport and dispersion of smoke, and the effects of smoke components on visibility, health, and ecosystem components. Information gaps are filled with knowledge from forest burning. It also summarizes regulations that pertain to prescribed burning and how emissions can be minimized by choice of prescription variables.

FUEL CHARACTERISTICS

The chemical makeup, size, distribution, amount, and moisture content of shrubland fuels are important elements that determine fire intensity and the emission rate. The chemical makeup of fuel varies with species and between live and dead fuels of the same species. Wood is the principal constituent of most fuels, and cellulose makes up about half of the woody framework of plants (Mobley et al. 1976; Sandberg et al. 1979). Lignin comprises 16 to 33 percent with softwoods having higher amounts than hardwoods. Hemicellulose comprises about 15 to 30 percent of wood. Ether extractives from wood range from 5 to 30 percent and include tannins, oils, fats, resins, waxes, and starches. The ether extractive portion of leaves from 18 species of forest and shrub species ranged from 2.3 to 19.1 percent (Montgomery 1976; Rothermel 1976). Extractives have about twice the heat value of cellulose and thus may contribute to flame height and forward propagation of the fire (Philpot 1969). Ash-forming materials comprise from 0.1 to 3 percent of wood (Forest Products Laboratory 1974).

Each fuel component participates to a different degree in preignition (pyrolysis), flaming (gas phase oxidation), and glowing (solid oxidation), the three major phases of combustion (Ryan and McMahon 1976). The many types and sizes of individual fuel elements (leaves, twigs, branches, and main stems) and their random configuration result in variable heat transfer, varying rates of pyrolysis, and combustion. Rapid heating produces highly flammable gases (hydrogen, carbon monoxide, and hydrocarbons); slow heating produces less flammable gases and more water and carbon monoxide. Charcoal production is low under rapid heating and conversely tar production is high. Moisture in both dead and live fuels acts as an energy sink; this contributes to variable states of heat transfer

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Table 1—Fire intensity as influenced by elements of a burn prescription for standing chaparral (Green 1981)

Indicators	Units	Values that produce given fire intensity response: Low	Medium	High
Fixed				
Total biomass	kg x 10^3/hectare	7 to 22	25 to 148	153 to 222
Available fuel	kg x 10^3/hectare	7 to 13	13 to 22	22 or more
Dead fuel	pct of total	20 to 30	31 to 45	46 or more
Live fuel moisture	pct	90 to 76	75 to 60	59 to 45
Continuity of fuel	pct cover	< 40	41 to 70	71 to 90
Slope	pct	0 to 19	20 to 40	41 to 70
Aspect		N, NE	E, SE, NW, W	SW, S
Season		Spring	Winter, early spring	Late summer, fall, early winter
Flammable chemical content		Low	Medium	High
Variable				
Dead fuel moisture when fuel is	pct fuel stick			
20 to 30 percent dead		12 to 9	8 to 6	5 to 3
31 to 45 percent dead		18 to 12	11 to 7	6 to 5
46 to 65 percent dead		20 to 15	14 to 9	8 to 6
66 to 100 percent dead		30 to 19	18 to 11	10 to 8
Relative humidity when fuel is	pct			
20 to 30 percent dead		35 to 26	25 to 18	17 to 15
31 to 45 percent dead		45 to 36	35 to 24	23 to 18
46 to 65 percent dead		60 to 41	40 to 31	30 to 25
66 to 100 percent dead		75 to 41	40 to 36	35 to 20
Windspeed	km/h	0 to 6	8 to 13	15 to 19
Air temperature	°C	7 to 15	16 to 26	27 to 35
Time of day		Early morning	Late morning, late afternoon	Early to midafternoon

in the fuel bed, limits the efficiency of the pyrolysis and flaming phases, and results in greater emissions of some pollutants. The importance of dead and live fuel moisture content in chaparral prescribed burns was thoroughly discussed by Green (1981).

KINDS OF EMISSIONS

Primary

Primary products emitted during combustion of woody fuels are carbon dioxide (CO_2), water (H_2O), carbon monoxide (CO), particulates, hydrocarbons such as methane (CH_4), and nitrogen oxides (N_2O, NO_2, and NO). "The stoichiometric combustion of 1 ton (908 kg) of wood (containing 50 percent carbon, 6 percent hydrogen, and 43 percent oxygen) would yield 3,670 pounds (1,666 kg) of CO_2, and 1,080 pounds (490 kg) of H_2O. Roughly 7 tons (6,356 kg) of air or 175,000 cubic feet (4,956 cubic meters), would be required" (Sandberg et al. 1979). Estimated ranges of emission factors for the major combustion products of dry wood include these (Geomet, Inc. 1978):

Primary Product	Emission Range (kg metric ton^{-1})
CO_2	1001 - 1752
H_2O	250 - 751
CO	10 - 250
Particulates	9 - 34
Hydrocarbons	5 - 20
N_2O and NO	1 - 3

On a global scale, biomass burning contributes substantially to the budgets of CO, hydrogen (H_2), methane (CH_4), nitrous oxide (N_2O), nitric oxide (NO), methyl chloride (CH_3Cl), and carbonyl sulfide (COS) (Crutzen et al. 1979).

Carbon dioxide is not usually classified as an air pollutant; however, unfavorable climatic changes may result from a net CO_2 input to the global atmosphere (Emanuel et al. 1980). Within 60 to 80 years the global CO_2 concentration is expected to double. The greenhouse effect created by higher CO_2 concentration will cause a global temperature rise of 1.5° to 4.5° C--an increase sufficient to raise sea levels, diminish water supplies, and alter rainfall patterns (Carbon Dioxide Assessment Committee, National Research Council 1983). The gross input of carbon dioxide to the atmosphere from burning wood, particularly from forest fires and prescribed fires in boreal, temperate, and tropical regions, is estimated to be 5.7 x 10^{15} g of carbon per year. The net input is estimated at 1.5 x 10^{15} g of carbon per year (Wong 1978). It is not known what proportion of the net input is due to prescribed burning in temperate regions.

A proven hazard to human health, CO results from the inefficient combustion (smoldering) of heavy or damp fuels and may reach 250 kg metric ton^{-1} (Ryan and McMahon 1976). Concentration of CO measured near flames was 200 ppm and less than 10 ppm at 100 feet from the fire (Ryan 1974). The human health hazards of CO are discussed in the section or adverse effects on health.

Particulate pollutants from wildfires and prescribed burns account for 24 percent of all

particulates in the atmosphere (Martin et al. 1977), and may reach 75 kg metric ton^{-1} from wildfires (Ward et al. 1976). Particulates produced by heading fires (those moving with the wind) were three times the quantity from backing fires (those moving against the wind) (Ryan and McMahon 1976). Backing fires produce black, sooty particulates while heading fires produce particulates that are yellowish to dark brown and oily. The benzene soluble fraction from forest fire particulates (which may include carcinogens) ranges from 40 to 75 percent compared with 8 percent in ambient air (Sandberg et al. 1979). Approximately 80 percent of the mass of particulates in smoke have diameters less than 1 μm, as measured in forest fire plumes (Radke et al. 1978). Light scattering and resultant visibility impairment is caused almost entirely by particles in the size range 0.1 to 1.0 μm (Charlson et al. 1978).

Total concentration (ppbC) of nonmethane hydrocarbons measured by instrumented aircraft in the vicinity of a slash burn was 13.5 upwind, 642 in the plume over the burn, and 142 at 5.6 km downwind in the plume (Westberg et al. 1981). Some of these hydrocarbon compounds participate in the photochemical formation of ozone.

Polynuclear aromatic hydrocarbons are also present in forest fire smoke. The most studied of these compounds is benzo[a]pyrene which is classified as strongly carcinogenic. In the laboratory, backing fires in pine needles produced more benzo[a]pyrene (274 mg g^{-1} total suspended particulates - TSP) than did heading fires (3 mg g^{-1} TSP) (McMahon and Tsoukalas 1978). Concentration of benzo[a]pyrene in the air around Caracus, Venezuela, was 2.5 times higher during the 3 driest months of the year when forest fires are frequent (Morales et al. 1979).

Nitric oxide (NO) is formed during combustion of forest and chaparral fuels when air is heated higher than 1540° C (Hall 1972). Such high temperatures are unusual during the flaming phase of combustion. The usual range is from 300 to 1400° C (Sandberg et al. 1979). Nitrogen oxides may be formed in this temperature range from the reaction of hydrogen-free radicals with nitrogen compounds in fuels (Tangren et al. 1976). In a slash fire plume in southeastern Washington, the NO concentration reached 29 ppb, 1.1 km downwind of the burn while NO_2 exceeded 50 ppb, 3.2 km downwind (Westberg et al. 1981). In the same study, upwind NO and NO_2 concentrations did not exceed 5 ppb. Stith et al. (1981) observed 60 ppb of NO and NO_2 at 3 km downwind and 20 ppb at 10 km.

Sulfur dioxide is often an important urban and industrial air pollutant. The sulfur content of woody fuels is too low to produce a significant amount of sulfur dioxide in smoke (Stith et al. 1981).

Secondary Products

Secondary emission products are formed in the atmosphere from primary products. The well-known photochemical mechanism for ozone formation in which reactive hydrocarbons (olefins) and nitrogen dioxide produce a net buildup of ozone in the presence of ultraviolet light is the most prominent example. An ozone concentration of 100 ppb was reported after 45 minutes of irradiation of an air sample from a forest fire plume in Australia (Evans et al. 1974). In the tops of slash fire plumes, ozone concentrations in the range of 40 to 50 ppb above the ambient background (20 to 40 ppb) have been reported (Westberg et al. 1981; Stith et al. 1981; Radke et al. 1978). The maximum concentrations of ozone observed in studies carried out by Westberg et al. (1981) and Stith et al. (1981) (50 to 60 ppb) do not exceed the 1-hour Federal ozone standard of 120 ppb when added to background (20 to 40 ppb). The concentration of 100 ppb reported by Evans et al. (1974) was determined from air samples irradiated in plastic bags while the other studies represent real-time plume samples.

In the rural settings typical of prescribed fires, where plumes usually do not mix back to the surface, the chance is small that ozone concentrations would be high enough or of sufficient duration to injure plant or animal life. In some California airsheds, already polluted by ozone from urban sources of hydrocarbons and nitrogen oxides, the additional ozone formed in smoke plumes could cause the 120 ppb standard to be exceeded. The highest concentrations would result when ozone is transported to higher elevations (1220-2135 m) where the concentrations remain higher for longer periods each day.

Small amounts (~ 2 ppb) of another secondary product peroxyacetyl nitrate (PAN) were observed near Calgary, Alberta, where air trajectories suggested that forest fire smoke may have provided the precursors (NO_2 and hydrocarbons) for PAN synthesis (Peake et al. 1983).

ADVERSE EFFECTS OF SMOKE

Impaired Visibility

In some forested regions, particularly the Pacific Northwest and the Southeast, prescribed burns contribute heavily to visibility impairment (Cooper and Watson 1979; Tangren 1982). Reduction of visibility is most important in Class I areas, i.e., National Parks and wilderness areas because long vistas are a major part of the visitor's experience. A comprehensive review of the visibility issue including statutory requirements, fundamentals of physics and chemistry, and identification of sources and control strategies is available (U.S. Environmental Protection Agency 1979).

Health Risks

Primary concerns with particulate pollutants and their effects on human health are depth of deposition in the respiratory system and resultant clearance times for insoluble particles. Most coarse particles are deposited in the extrathoracic region--the head and throat. They are moved by mucociliary clearance, that is in mucous expelled by cilia, usually in minutes. Both fine and coarse particles are deposited in the tracheo-bronchial region where they can cause constriction of the bronchia, reduced mucociliary clearance, aggravation of chronic respiratory diseases, and possibly cancer. Particles less than 10 μm diameter can be absorbed in the deepest (alveolar) region of the lungs where they may remain for weeks to years. They may aggravate chronic lung disease by disturbing normal ventilation and causing a reflex constriction of blood vessels that supply parts of the lung; inflammation and fibrosis may also result (Hileman 1981). The

particulate emissions from forest fire smoke have a multimodal size distribution with most of the mass contained in the 0.1 to 1 μm diameter range (Radke et al. 1978). The mass of fine particles (< 10 μm) deposited in the alveolar region increases 10 to 20 percent during mouth breathing (Hileman 1981). The heavy exercise associated with fire ignition and control activities should tend to increase the amount of mouth breathing and deep inhalation of particulates. Benzo[a]pyrene, a well-known carcinogen, is associated with particles in the smallest size range (Ryan and McMahon 1976).

The recent upsurge of wood burning as a source of domestic heat has resulted in new community air pollution problems and an increased concern for the possible adverse health effects of smoke. Certain gases, trace elements, and organic compounds in combination with fine particulates may cause significant adverse health effects in relatively low concentrations (Duncan et al. 1980). Organic extracts of fine particles produced during wood combustion contain polyaromatic hydrocarbons (e.g., benzo[a]pyrene) quinones, phenols, and acids of polycyclic aromatics. The biological activity of these compounds is tested with the Salmonella typhimurium plate incorporation assay (Ames et al. 1975) for the ability to cause mutagenic effects in the Salmonella tester strains. The implication of the mutagenic effect in Salmonella is that the test compounds may be carcinogenic in humans. One of the latest findings is that NO_2 alone and NO_2 plus O_3 increase the mutagenicity of dilute wood soot. The gaseous pollutants were injected into smoke filled chambers from which smoke samples were later collected on filters, extracted, then used in the Ames test. Mutagenicity increased as a function of the length of time that the wood smoke, ozone, and NO_2 were allowed to react. More mutagenicity was observed from the combination of O_3 and NO_2 with wood smoke than from NO_2 alone (Kamens et al. 1983).

The adverse effects of CO on human health are well-known and exposure standards have been established (Committee on Med. and Biol. Effects of Environ. Pollutants 1977). The EPA standard for CO is 9 ppm maximum for an 8-hour average exposure or 35 ppm maximum for 1-hr average exposure. Uptake rate increases with exercise. The adverse reactions to be expected include decreases in vigilance and reaction time.

Prolonged work under conditions of poor ventilation near a smoldering fire conceivably could cause decreases in oxygen-carrying molecules in the blood. Adequate ventilation or limitation of exposure time is essential to prevent adverse exposure to carbon monoxide.

Neither O_3 nor NO_2 should cause adverse health effects in the near vicinity of a prescribed burn, but these pollutants may add to an existing photochemical smog problem in some California air basins.

Effects on Plants and Microorganisms

Neither SO_2 or NO_2 is present in smoke from prescribed burns at concentrations sufficient to cause plant injury. Ethylene and various other hydrocarbons (Ryan and McMahon 1976) are emitted during combustion of woody material, but there is no evidence that concentrations and durations of exposure would be sufficient to cause plant injury.

Ozone formation in smoke plumes resulted in concentrations 40 to 50 ppb above the ambient background (Westberg et al. 1981; Stith et al. 1981; Radke et al. 1978). The resultant concentration of 70 to 100 ppb could injure sensitive herbaceous species if sunny, stagnant conditions persisted for 48 to 72 hours. Some wildlands are already exposed to ozone transported from urban areas in California. In this case the ozone synthesized in smoke plumes may temporarily exacerbate a chronic regional problem but without any visible increase of plant injury. Favorable atmospheric dispersion conditions selected for prescribed burning probably would prevent ozone accumulation near ground level.

The work of Parmeter and Urenholt (1975a; 1975b) may be the only test of the effect of smoke (pine needles and grass) on forest micro-organisms. Spore germination and growth of several fungal pathogens were reduced and germination of one fungus was enhanced. The smoke component responsible for these effects was not identified.

When fires are not hot enough to produce a plume and/or during the smoldering phase of intense fires, the smoke may interact with the remaining plant canopy above and at the margins of the burn. Under these conditions, the leaf and stem surfaces create turbulence and reduce windspeed, larger smoke particulates settle by gravitational force and smaller particles impact on surfaces. Some scavenging of gases (CO_2, NO_2) by leaves is expected. Gas and particle removal by surfaces is called dry deposition (Sehmel 1980; Hosker and Lindberg 1982). Extreme variability is encountered, for example, deposition velocities of gases range over four orders of magnitude and deposition rates of particles range over three orders of magnitude. The characteristics of micrometeorology variables, surface variables, and properties of particles and gases combine in many ways to influence deposition rates (Sehmel 1980).

Although plant canopies remove particles and gases from the atmosphere, the probability is small that the dose of pollutants in smoke from prescribed fires is sufficient to cause plant injury.

REGULATION OF PRESCRIBED BURNING

The Clean Air Act and its 1977 Amendments provide standards for the control of several gaseous pollutants and total suspended particulates. Protection from visibility impairment in Class I Federal areas is the most recent requirement of the Act (U.S. Environmental Protection Agency 1979). Prescribed burning is a temporary pollution source and is not regulated under the provisions of the Act designed to prevent significant deterioration of air quality in Class I areas.

The California Air Resources Board (CARB), in 1971, established its own rules to regulate agricultural and forestry burning under Title 17 of the California Administrative Code. These rules include meteorological criteria for determining "permissive-burn days," i.e., days on which existing and expected meteorological conditions will adequately

disperse and transport the emissions from agricultural burning. In 1983, the Board decided to implement in the Sacramento Valley Air Basin only the permissive-burn/no-burn system in conjunction with a variable burn acreage control strategy (Crowe and Kinney 1983).

Ambient air quality standards for California specify concentrations of individual pollutants which cannot be equaled or exceeded during specified averaging times ranging from 1 to 24 h (California Air Resources Board 1982). Emissions from prescribed burns in California must not exceed these specified values (Table 2). For visibility, the standard states that during one observation the prevailing visibility cannot be reduced to less than 16 km at 70 percent relative humidity. Standards for the size range of particulates that reduce visibility, and total suspended particulates, are more likely to be exceeded than are those for gases because stable atmospheric conditions required for gas accumulation are usually not coincident with fires. Also, visibility-reducing particulates scatter light effectively at relatively low concentrations.

The USDA Forest Service, California Department of Forestry, and certain other fire protection agencies are authorized by CARB to issue burn permits jointly with the local Air Quality Management District (AQMD). A desired burn date is requested 7 days in advance. The AQMD provides 48-hour permissive-burn/no-burn meteorological forecasts each day until a permissive burn notice can be issued up to 48 hours before the scheduled date. The final determination of whether the following day will meet burn requirements is announced before 1500 h or it can be as late as 0745 h on the proposed burn day. The CARB can cancel any burn permit issued more than 24 h in advance; the local AQMD also has this authority.

Certain exceptions should be acknowledged. Prescribed burning permits are not required for elevations above 1830 m except in the Lake Tahoe Basin. Burns may be conducted under permit on a no-burn day between January 1 and May 31 provided that more than 50 percent of the fuel has been modified by crushing, felling, or spraying. Local AQMDs may enforce rules more stringent than the CARB rules. For example, San Diego County requires a minimum number of drying days for various types of fuels.

Table 2—Air quality standards in California (California Air Resources Board 1982)

Pollutant	Averaging time	Concentration	
	hours	$\mu g\ m^{-3}$	ppm
Oxidant	1	200	0.10
Carbon monoxide	8	10,000	9.0
	1	23,000	20.0
Nitrogen dioxide	1	470	0.25
Sulfur dioxide	24	131	0.05
	1	1,310	0.50
Total suspended particulates	24	100	--

MINIMIZING EMISSIONS

By carefully choosing the fuel and meteorological variables that influence fire intensity (Table 1) (Green 1981), the fire manager can minimize emissions from a prescribed burn. Fire intensity is defined by the rate of energy release per unit of time and length of fire front (Rothermel 1972). High fire intensities promote plume rise and improve smoke dispersion. High intensities are characteristic of heading fires. Heading fires can produce up to three times as much particulate material as do backing fires (Ryan and McMahon 1976; Tangren et al. 1976). The plume rise advantage of the heading fire may be offset because the main combustion zone moves ahead rapidly leaving a large zone of partially consumed, smoldering fuel. In backing fires, more fuel is consumed in the flaming zone and smoldering time is reduced (Ryan and McMahon 1976). It is harder to propagate backing fires because a continuous distribution of fine fuels is needed.

The ignition pattern can be varied to achieve the type of combustion desired. Perimeter firing is frequently used on steep chaparral slopes. A back fire is established at the ridgeline followed by ignition along the sides and finally at the bottom. A heading fire develops at the bottom and rushes to meet the flanking and backing fires (Green 1981). Delaying the setting of the heading fire may help to reduce emissions. Center-perimeter firing may be used to increase plume rise when surface winds are low. The fire is started in the center of the burn area first and then in concentric rings around the center until the perimeter is reached. Flames rushing toward the center reinforce the convection column, but large areas of smoldering fuel may be left behind. The behavior of other ignition patterns including strip head firing, flank firing, and area ignition have been discussed (Green 1981; Wright and Bailey 1982).

Emissions of carbon monoxide, hydrocarbons, and particulates are lower from dry fuel than from moist fuels (Darley et al. 1966). A lower proportion of green fuel will also reduce emissions. The ether-extractable components of chaparral shrubs are highest during the autumn months when they increase the hydrocarbon emissions during combustion (Philpot 1969). For example, the extractive content of chamise (Adenostoma fasciculatum) was 8.5 percent in spring and 12 percent in fall.

Burning is best done from midday to midafternoon when fuels are the driest, and air temperatures and winds are relatively high. These conditions reduce the smoldering phase of the fire so emissions will be minimal during the stable, nighttime atmospheric conditions.

In addition emissions will be lowest from backing fires conducted during midday to late afternoon with moderate winds in dry fuels with a low proportion of green fuel and during winter months when the levels of ether-extractable components are the lowest.

DISPERSION MODELING

Because meteorological factors influence fire behavior and smoke dispersion (see reviews by Sandberg et al. 1979; Wright and Bailey 1982),

smoke dispersion modeling is part of the prescribed burn planning and evaluation process (U.S. Dep. Agric., Forest Serv. 1982). The discussion of model application will be limited here to an outline of current practices.

Modeling begins with the vertical rise of the smoke plume. Plume rise is influenced by heat release to the atmosphere, temperature of the surrounding atmosphere, its stability, and the wind profile (U.S. Dep. Agric., Forest Serv. 1982). The plume rise model of Briggs (1969) has been adapted to open burning. Not all fires are hot enough to contribute to plume rise, or after the most intensive period of the fire, smoke is no longer entrained in a convective column. The height of the plume is the effective height at which dispersion begins.

The uses and limitations of particular air quality models have been evaluated by the National Commission on Air Quality (Fox and Fairobent 1981). Three types of models have been adapted to smoke dispersion: the Box model, Grid model, and Gaussian model. The Gaussian model is most often used to predict smoke dispersion from fires on flat or rolling terrain, but it (and all other models) has serious limitations in mountainous situations. The Air Resource Allocation Model (ARAM) tested in the Los Padres National Forest (Fosberg and Record 1980) is based on a Gaussian dispersion model; interactions of terrain and dispersion are evaluated to determine the increments of additional pollution permissible in individual airsheds. A day/night Box model has been developed to determine the statistical effect of prescribed fire on air quality (total suspended particulates) in the Willamette Valley in Oregon where terrain variability is not a serious problem (Lavadas 1982). A summary of the availability and input requirements of dispersion models is available (U.S. Dep. Agric., Forest Serv. 1982). Models alone should not be used as a basis for deciding when to burn. There is no substitute for the experience and good judgment of the fire manager, particularly because personnel safety and prevention of fire spread beyond the burn area are so important.

RESEARCH NEEDS

General categories of current research requirements include (a) quantitative smoke management systems, (b) smoke chemistry and physics, (c) atmospheric transport and removal, (d) receptor response, and (e) inherent trade-offs (Sandberg et al. 1979). Improved capability to model smoke dispersion in complex terrain continues to be a high priority need (Society of American Foresters 1980b). Recent findings that ozone and nitrogen dioxide reactions with dilute wood smoke may increase the mutagenicity of smoke particles suggest a need for a better understanding of the health effects of smoke (Kamens et al. 1983). The issue of the effects of continued CO_2 buildup in the global atmosphere and the contribution of prescribed burning requires careful consideration. Are there feasible alternatives to burning that will accomplish the same vegetation management goals?

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