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FIRE AND PESTICIDES: A REVIEW OF AIR QUALITY CONSIDERATIONS

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ABSTRACT

The classes of primary chemical products naturally produced by the combustion of forest fuels are: carbon dioxide, water, carbon monoxide, particulate matter, methane and non-methane hydrocarbons, polynuclear aromatic hydrocarbons, nitrogen and sulfur oxides, aldehydes, free radicals, and inorganic elements. Secondary chemical products produced by reactions in smoke plumes or volatilized exotic chemicals include ozone and pesticides. With the extensive use of herbicides for site preparation and release in some forest ecosystems and insecticides for insect control in others, public concern has increased about the fate of pesticides in fires. Studies conducted on herbicides and insecticides indicate that hot fires (>500°C) thermally degrade most pesticides. Smoldering fires (<500°C) have the potential to volatilize significant amounts of some pesticides. Exposure analyses indicate that, even under conditions of smoldering fires, no significant human health risks occur from pesticides incorporated into or on forest fuels.

keywords: air quality, herbicides, insecticides, pesticides, prescribed burn.

Citation: Bush, P.B., D.G. Neary, and C.K. McMahon. 2000. Fire and pesticides: a review of air quality considerations. Pages 132–136 *in* W. Keith Moser and Cynthia F. Moser (eds.). Fire and forest ecology: innovative silviculture and vegetation management. Tall Timbers Fire Ecology Conference Proceedings, No. 21. Tall Timbers Research Station, Tallahassee, FL.

INTRODUCTION

Fire continues to be a management tool used by public and private land managers in the southeastern United States to sustain production of natural resources, preserve and maintain wildlife habitat, and improve grazing conditions. The combustion process produces flames and smoke, the universal signal of a fire. The exothermic reactions of combustion produce hundreds of primary and secondary chemical compounds that are either oxidized further or released into the atmosphere (DeBano et al. 1998). The primary chemical products naturally produced by the combustion of forest fuels are: carbon dioxide, water, carbon monoxide, particulate matter, methane and non-methane hydrocarbons, polynuclear aromatic hydrocarbons, nitrogen and sulfur oxides, aldehydes, free radicals, and inorganic elements. Secondary chemical products include those that result from photochemical transformation of primary emissions (e.g., ozone) and exotic chemicals driven off from fuels during the pre-ignition phase of combustion. Pesticides are an example of the latter type of secondary fire-produced chemical. Smoke is produced when chemical products of combustion condense into soot, tar, and water droplets in cooling air columns above a fire.

The use of fire in vegetation management, and the resulting smoke, has raised environmental concerns, such as:

1. particulate matter emissions or inorganic and organic gaseous emissions presenting a threat to public health, along with nuisance concerns;
2. visibility impairment in areas of high humidity; and
3. decrease in recreational aesthetic appeal.

While smoke management considers all three of these concerns, the focus of this paper is on the issue of a secondary chemical product, pesticides, in smoke where these chemicals are used in forest management.

Based on recent health studies, the U.S. Environmental Protection Agency (EPA) proposed revised air quality standards of particulate matter and ground-level ozone in July 1997. A federal court ruling in May 1999 has temporarily placed implementation of the 1997 air quality standards in abeyance. Nevertheless, land managers should endeavor to minimize the adverse impact of smoke on public health and the environment. In addition, they should reevaluate alternatives such as mechanical site preparation, whole-tree harvesting, and yarding of unmerchantable material in situations where smoke might create an air quality problem from a public health, visibility, or public re-

lations viewpoint. Mechanical site preparation in regions with disturbance-sensitive soils, such as the Piedmont, however, often leads to accentuated erosion and soil compaction. Use of herbicides in combination with other site preparation techniques minimizes soil disturbance. In the absence of fire, however, herbicides may result in accumulation of dead vegetation, as well as insect and disease vectors. A movement away from burning as part of site preparation has the additional disadvantage of on-site slash/fuel accumulation and increased potential for intense wildfire.

Pesticide use patterns in forest management are governed by such factors as economics, sensitivity of the ecosystem, and potential liability for off-site impacts. Insecticides and fungicides are extensively used in seed orchards and nurseries, where small land areas are treated to protect highly valued seed sources and seedlings for out-planting. The use of insecticides over extensive forested areas, however, is generally restricted to cases where trees with high commercial or aesthetic value are threatened or where epidemic pest outbreaks occur (e.g., gypsy moth, tussock moth, spruce budworm, and pine bark beetle). In such cases, entire watersheds may be treated. In young pine stands, herbicides are used extensively to assist in site preparation, while insecticides may be applied for insect control. Thus the incidents when timber stands treated with pesticides might be subject to a prescribed fire are limited to times of site regeneration and cleanup of epidemic pest outbreaks.

Prescribed burns routinely used in forest management include: (1) slash burns in harvested stands, (2) "brown and burn" for site preparation, (3) understory burns for wildlife habitat improvement and weed/brush control, and (4) grassland burns. Site preparation slash burns and "brown and burn" burns are used once in a regeneration cycle (20–80 years) to facilitate planting and early regeneration management practices. The "brown and burn" site preparation removes unwanted competing vegetation by burning 30–180 days following herbicide application. The browning of hardwood foliage and herbaceous plants increases the fuel source, making late-summer burns effective for further reduction of smaller residual hardwoods that may have been missed by application or were resistant to the herbicide. In addition, burning the area greatly facilitates planting operations by removing logging debris. Understory burns and grassland burns can be used every 1–7 years to control weed competition and improve wildlife habitat, but usually do not consume fuels treated with pesticides and/or herbicides.

The "brown and burn treatment" management practice has raised concern by forest workers and the public about possible exposure to herbicide residues in smoke from the fire or from burning herbicide-treated hardwoods in fireplaces or stoves. The roots of this concern can be traced back to the warning statement found on herbicide labels, as well as material data safety sheets. These statements referring to fire hazards and toxic decomposition products urge the user to "wear a mask" or, "If herbicide is burned, stay out of the smoke." While these cautions are appropriate in connection with fires near herbicide concentrates and containers found at mixing and storage sites, they were not intended to apply to the diluted forms following an application to forested sites. In these cases, on a given hectare, only a few milligrams or kilograms of herbicide are spread over many metric tons of ground litter and vegetation. The latter material constitutes the predominant fuel in the prescribed fire and the principal smoke risk factor to the worker or the public.

FIELD STUDIES

General Background

The most extensive analyses of the chemical emissions from forest fires, and public and forest worker health risks posed by the chemical and particulate components produced in wildland fire smoke, have been conducted in the United States (Smith 1990, Dost 1991, Reinhardt 1991, and Reinhardt et al. 1994). Vegetation combustion produces hundreds of chemical compounds that are either oxidized further or released into the atmosphere (DeBano et al. 1998). Among the major classes of primary chemical emission products from fire is the polynuclear aromatic hydrocarbon group, consisting of polymers of benzene (ring structure), joined in various patterns, that form in the reducing zone of burning fuels with an optimum range of 700°–850°C (McMahon and Tsoukalas 1978). Polynuclear aromatic hydrocarbons form more frequently, but still at relatively low rates, in backing and smoldering fires. Some of the polynuclear aromatic hydrocarbons, benzo(a)pyrene, chrysene/benz(a)anthracene, and benzofluoranthene, are known carcinogens.

Secondary chemical emissions from fires include ozone and introduced chemicals, such as pesticides. Analyses by Dost (1991) and Sandberg and Dost (1990) determined that pesticide exposure in smoke from prescribed fires or wildfires would not approach levels sufficient to produce human health effects. Sandberg and Dost (1990) cited an unpublished report (G.E. Lande, A Study of Air Quality Sampling during Prescribed Burning for Forest Sites Treated with Desiccants and Pesticides, paper presented at the NCASI West Coast Regional Meeting, 11 November 1987, Portland, OR, 1987) on monitoring of air adjacent to prescribed fires on herbicide-treated stands in the Pacific Northwest. No herbicide residues were detected in any smoke. McMahon and Bush (1992) reported the same results in the South. Even under unrealistic assumptions that produce complete volatilization of pesticide compounds found within or on the surfaces of vegetation, human exposures in dense smoke would be trivial compared to natural combustion emissions (Sandberg and Dost 1990, DeBano et al. 1998). Dost (1991) cited another unpublished report (F.N. Dost, Combustion of Herbicides, Report to the Bonneville Power Administration, Vancouver, BC, 1982) that considered the potential human health impacts of herbicides, or their terminal combustion products, volatilized by forest and brush fires. The conclusion was that herbicide residues most likely would be undetectable

Table 1. Parent pesticide (%) and particulate emissions (%) recovered from burning herbicide-treated and insecticide-treated wood under slow- and rapid-burning conditions (adapted from McMahon et al. 1985).

	Smoldering Fire		Flaming Fire			
	Ambient to 500°C[a]		500°C		600°C	
Pesticide	Pesticide recovered %	Particulate emissions % dry fuel	Pesticide recovered %	Particulate emissions % dry fuel	Pesticide recovered %	Particulate emissions % dry fuel
Herbicides						
2,4-D	92	11.2	2	1.3	—[d]	—[d]
picloram	0[b]	11.2	0[b]	1.3	—[d]	—[d]
hexazinone	11	9.2	0	<1.0	—[d]	—[d]
dicamba	92	10.8	32	3.4	—[d]	—[d]
dichloroprop	>100[c]	10.8	6	3.4	—[d]	—[d]
Insecticides						
lindane	43	10.8	41	10.4	0	<1.0
chlorpyrifos	28	10.8	4	10.4	0	<1.0

[a] Fuel samples heated at 20°C per minute from ambient to 500°C.
[b] 98% and 64%, respectively, was recovered as picloram decomposition product 2, 3, 5 trichloro-4-amino-pyridine.
[c] High recovery reflects an enhanced instrument response in the presence of smoke condensate.
[d] Not tested at this temperature.

in large volumes of smoke, and that the additional combustion products from herbicide molecules would be trivial in relation to the enormous amounts produced by burning vegetation.

The degree of potential herbicide volatilization in treated fuels is a function of the type of combustion (e.g., flaming, smoldering, glowing), the rate of temperature increase, combustion efficiency, and the maximum temperature reached during combustion. Flaming combustion is the most dominant combustion in the type of vegetative material containing pesticides (leaves, needles, twigs, branches, and bark). Smoldering and glowing predominate in ground and soil fires, and in slash piles. Flaming combustion is the most efficient at reducing fuel to elemental components (e.g., carbon dioxide, carbon monoxide, oxygen, water, and nitrogen oxides) (Pyne et al. 1996, DeBano et al. 1998). Flaming combustion typically produces initial temperatures in the 300°–500°C range that can rise to 800°–1,000°C, and can sometimes reach 1,400°C (Pyne et al. 1996, DeBano et al. 1998). Smoldering and glowing combustion fires are usually cooler (300°–600°C), but are of longer duration.

Pesticide Fate in Smoke

The most extensive studies of pesticide fate during the combustion of wildland fuels have been conducted by Bush et al. (1986, 1987*a*, 1987*b*), McMahon and Bush (1986,1992), and McMahon et al. (1985). Although these studies mainly deal with herbicides, they do include insecticides. Prescribed fires and wildfires do occur in stands recently treated to control insect outbreaks.

In a forest fuel combustion laboratory study (McMahon et al. 1985), wood treated with 5 herbicides and 2 common insecticides was burned under controlled combustion conditions (Table 1). Except for dicamba (herbicide) and lindane (insecticide), >94% decomposition occurred when wood was burned under conditions of rapid (flaming) combustion at 500°C. Raising the temperature to 600°C completely decomposed lindane since it was not detected in smoke at that temperature. Dicamba would behave similarly at the higher temperature.

More variable amounts of pesticide residues (0 to >100%) were recovered from the smoke stream in the case of smoldering combustion. Relatively stable compounds such as lindane and dicamba, as well as compounds with significant vapor pressures, can be expected to be released under smoldering or slow-heating conditions. For example, lindane and dicamba and the herbicide 2,4-D were extensively recovered intact in the smoke stream (43%, 92%, and 92%, respectively), while the insecticide chlorpyrifos and the herbicides hexazinone and picloram were extensively decomposed (<28% residue recovery).

The data produced by the laboratory study are overestimates of what would be encountered in smoke from actual fires. The smoke emanating from the laboratory fuels was not mixed with smoke from fuels that were clear of pesticides. In a real fire situation, dilution by smoke that did not contain pesticide residues would probably reduce air concentrations below detectable levels.

This hypothesis was tested in a follow-up study (McMahon and Bush 1992). Fourteen prescribed burning operations ("brown and burn") were monitored to determine possible worker exposure. Field worker breathing zone concentrations of smoke suspended particulate matter, herbicide residues, and carbon monoxide were monitored on sites treated with labeled rates of forestry herbicides containing the active ingredients imazapyr, triclopyr, hexazinone, and picloram. The sites were burned 30–169 days after herbicide application. No herbicide residues (sensitivity 0.1–4.0 micrograms per cubic meter) were detected in 140 smoke samples from the 14 fires. These detection levels are several hundred to several thousand times less than any occupational exposure limit for these herbicides.

Suspended particulate matter and carbon monoxide levels monitored on these fires were highly variable, depending on fire conditions, size of tract, and worker assignment. The toxicology of combustion products (e.g., polynuclear aromatic hydrocarbons, suspended particulate matter, and carbon monoxide) and the larger issue of the EPA Particulate Air Quality Standards, proposed in 1997, are beyond the intended scope of this presentation.

In subsequent laboratory studies (McMahon and Bush 1992), herbicide recoveries in the smoke stream were compared. Upslope fires, where herbicide volatilization is likely due to heat convection, resulted in lower combustion efficiencies (high smoke production) and higher recovery of 2,4-D and picloram (5% and 0.04%, respectively). Herbicide recoveries from downslope fires were less for both 2,4-D (0.08%) and picloram (<0.02%). Thus, pre-ignition fire temperatures directly impact the extent of herbicide combustion and volatilization.

Bark beetles, especially the southern pine beetle *(Dendroctonus frontalis),* are a serious threat to forest stands and individual high-value trees throughout the South. Insecticidal control of bark beetle infestations is effective, but disposal of insecticide-treated trees could present a problem. One alternative is to burn the treated trees. In another study (Bush et al. 1987*b*), wood samples collected 4 months after treatment for pine bark beetle control were found to contain lindane and chlorpyrifos residues ranging from 0.32–35.8 milligrams per kilogram for lindane and <0.1–76.1 milligrams per kilogram for chlorpyrifos. Combustion of these samples under smoldering fire conditions resulted in 43% recovery of lindane and 28% recovery of chlorpyrifos in the smoke stream (Table 1). With rapid, flaming combustion in a well-developed fire, all lindane and chlorpyrifos residues were thermally degraded. Thus, if burning is selected as a disposal option for insecticide-treated wood, well-developed flaming fires should be used to eliminate any human exposure to residual insecticidal chemicals.

WORKER AND PUBLIC EXPOSURE ASSESSMENT

Worker exposure to herbicide residues released from burning treated vegetation was estimated in the U.S. Department of Agriculture (USDA), Forest Service, Southern Region Environmental Impact Statement (Weeks et al. 1988, USDA 1989). This analysis assumed that: (1) 30 million cubic meters per hectare of smoke is produced, (2) herbicides are applied at maximum labeled application rates, (3) herbicides degrade with time at published dissipation rates, and (4) no thermal decomposition of the parent compound occurs in the burning process.

Margins of safety (MOS's), a measure of human health risk, were developed for the herbicides used in forest management in the southern United States (Weeks et al. 1988, USDA 1989). The MOS compares a toxicological standard, the No Observable Effect Level dose (NOEL) for laboratory animals and the dose (milligrams of chemical ingested per kilogram of body weight) estimated for different herbicide application operations. The NOEL is a dose of a herbicide administered to test animals that causes no visible systemic and reproductive toxicologic effects. According to the National Research Council (1983), acceptable levels of risk for a particular herbicide can be determined with a MOS. Based on test animal NOEL's, a safety factor of 100 is used to account for variations between species (test animals and humans) and among humans (within-species variation). The NOEL divided by the exposure dose is the MOS. If the MOS >100, then the chemical is assumed to pose an acceptable risk for human exposure. The MOS does not account for hypersensitive individuals. MOS's were estimated for all registered herbicides, comparing human exposure levels from predicted smoke residue levels, based on normal "brown and burn" post-application prescribed fire, to the NOEL's for each herbicide.

All MOS's were found to be >150, except for triclopyr ester, which had a MOS of 84. For the scenario where wildfire occurs on the day of application, the MOS's were all >50, except for imazapyr applied by the aerial foliar method, which was 46. The estimated MOS's were undoubtedly lower than those likely to occur in an actual fire, where a large fraction of the herbicide residues would be destroyed during combustion (McMahon et al. 1985, Bush et al. 1987*a*). Herbicide concentrations in the air dissipate with distance from the burn site; thus, the public would be expected to have lower exposures and higher MOS's than on-site workers.

Forestry-use herbicides have been detected in the air at short ranges (<1 kilometer) after aerial applications (spray drift), but generally not after prescribed fires in herbicide-treated stands. Forestry herbicides also have not been detected in smoke adjacent to fires, regional air mass samples, or rainfall during nationwide air quality studies (Sandberg and Dost 1990, Majewski and Cadel 1995). However, agricultural herbicides have been detected in nationwide air quality studies.

Risk analysis concerning the use of herbicide-treated wood in home fireplaces conducted in the southern United States (Bush et al. 1987*a*) clearly demonstrated that under assumptions that unrealistically produced complete volatilization of pesticide residues, exposures resulting from burning herbicide-treated wood in a fireplace resulted in household air concentrations >100 times lower than the acceptable daily intake. Thus, the safety factor is high, and the exposure risk from burning herbicide-treated wood in fireplaces is very low.

MANAGEMENT IMPLICATIONS

Worker exposure assessments and field studies have shown that risk from herbicide exposure to forest workers under "brown and burn" conditions is small (MOS >50), even if the fire occurs immediately after

herbicide application, as might occur in a wildfire. Thus, use of herbicides in combination with fire in site preparation, understory vegetation management, or creating wildlife habitat and openings does not increase human health danger above the physical and smoke risks associated with fire alone. Likewise, human exposure to insecticides from wildfires in recently treated stands is not likely since rapid, flaming combustion is associated with these fires.

Private individuals, companies, and government agencies that use prescribed fire as a forest management tool need to be aware that health concerns and fears might arise among workers and the general public regarding herbicides and smoke. Those concerns or fears should not be trivialized, but dealt with as a public relations matter using the best available educational tools.

ACKNOWLEDGMENTS

This work was supported by the National Agricultural Pesticide Impact Assessment Program, U.S. Department of Agriculture, and administered by Forest Health Protection, U.S. Department of Agriculture, Forest Service, Southern Region, Atlanta, Georgia.

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