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Forest Worker Exposure to Airborne Herbicide Residues in Smoke from Prescribed Fires in the Southern United States*

Charles K. McMahon[a]
Parshall B. Bush[b]

[a]U.S. Forest Service, G.W. Andrews Laboratory, Devall Drive, Auburn University, AL 36849; [b]University of Georgia, Cooperative Extension Service, Athens, GA 30602

Occupational safety and health concerns have been raised in a number of southern states by workers conducting prescribed burns on forest lands treated with herbicides. Modeling assessments coupled with laboratory experiments have shown that the risk of airborne herbicide residues to workers is insignificant, even if the fire occurs immediately after herbicide application. However, no field studies had been conducted to confirm these findings. To bridge that gap, a field validation study was conducted in Georgia to measure breathing zone concentrations of smoke suspended particulate matter (SPM), herbicide residues, and carbon monoxide (CO) on 14 operational prescribed fires. Smoke was monitored on sites treated with labeled rates of forestry herbicides containing the active ingredients imazapyr, triclopyr, hexazinone, and picloram. The sites were burned within 30–169 days after herbicide application. Tract size ranged from 2.4 to 154 hectares. Personal monitors and area monitors employing glass fiber filters and polyurethane foam collection media were used. No herbicide residues were detected in the 140 smoke samples from the 14 fires conducted in this study. The sensitivity of the monitoring methods was in the 0.1 to 4.0 $\mu g/m^3$ range, which is several hundred to several thousand times less than any established occupational exposure limit for herbicides. The SPM and CO monitored on these fires is the first time breathing zone concentrations of these smoke constituents have been measured in the South. As expected, concentrations were highly variable depending on fire conditions and the location of personnel. Worker respirable (2.3-µm particle cut point) SPM concentrations ranged between 0.2 and 3.7 mg/m^3. Exposure periods depended on fire size and ranged from 1.2 to 6.3 hr. Area monitors that were placed in high-density smoke zones had total SPM concentrations ranging between 2.0 and 45 mg/m^3. CO breathing zone concentrations ranged from <6 to 30 ppm/hr while the fires were being worked on. These values are well below the Occupational Safety and Health Administration permissible exposure limit of 35 ppm/hr when normalized to an 8-hr work shift.

The application of herbicides to forest lands, followed weeks later by a prescribed fire (commonly known as "brown and burn"), is a widely used form of forest site preparation prior to pine regeneration. In this process, the unwanted competing vegetation is burned 30 to 180 days after herbicide treatment. The optimal time for burning is usually after herbicide translocation has peaked, but prior to resprouting when the vegetation is dry and "browned-out." The "browning" of hardwood foliage and herbaceous plants following herbicide application increases the fuel source, making late-summer burns very effective for further reduction of smaller, residual hardwoods that may have been missed by the application or were resistant to the herbicide used. Also, burning the area greatly facilitates planting operations by removing logging debris.

This forest management practice has raised forest worker and public concern about possible exposure to herbicide residues in the smoke from the fire. The roots of these concerns can be traced back to caution statements found on herbicide labels, as well as material safety data sheets. These statements refer to fire hazards and toxic decomposition products and urge the user to "wear a mask" or, "If burned, stay out of the smoke." Although these cautions are appropriate in connection with fires near concentrated forms of herbicides and containers found at mixing and storage sites, they are not intended to apply to the diluted herbicide formulation following application on forest sites. In these cases, on a given hectare, only a few grams or kilograms of herbicide are spread over several thousand kilograms of ground litter and vegetation. The litter and vegetation, along with forest harvesting residues, constitute the dominant fuels in the prescribed fire. A modeling assessment has shown that the airborne herbicide risk to forest workers is insignificant, even if the fire occurs immediately after herbicide application (as might occur

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in a wildfire).[1] To be on the safe side, the model assumes no herbicide decomposition in the fire. However, laboratory studies have shown at least 90% decomposition of the parent herbicide when it is subjected to combustion conditions typically found in prescribed burning.[2,3] Until recently, a limited pilot study employing single-point samplers provided the only field measurements of combustion products from herbicide-treated forest sites.[4] The results from that study support the model findings of no significant airborne residues, but no direct correlation to worker exposure could be made. To bridge that gap, a field validation study was conducted in 1988 to measure breathing zone concentrations of suspended particulate matter (SPM), airborne herbicide residues, and carbon monoxide (CO) through the use of small air monitors worn by personnel conducting operational prescribed fires.

The study focused on recovery of herbicide active ingredients that might become airborne during the prescribed fire. It did not attempt to monitor or identify herbicide or biomass thermal decomposition products. Under these operational and diluted field conditions, most herbicide decomposition products would not be detectable or distinguishable from the array of similar decomposition products that originate from the burning of the dominant forest biomass fuels (leaves, needles, twigs).

EXPERIMENTAL MATERIALS AND METHODS

Study Areas

The study was accomplished by cooperating with forest land managers conducting operational prescribed fires on herbicide-treated sites in the South.

During the late summer and early fall of 1988, 14 fires were monitored at two locations in Georgia. The herbicide active ingredients monitored included hexazinone, triclopyr, imazapyr, and picloram in five formulations labeled for forest site preparation in the South (Table I). A fifth herbicide, glyphosate, was used on some of the sites but was not included in the monitoring program. An earlier study by the National Council for Air and Stream Improvement[4] reported no glyphosate residues in prescribed fire smoke on forest sites in Oregon. A list of study areas and treatments is given in Table II. Prior to each fire, samples of standing foliage, ground litter, and surface soil were collected from each site and analyzed for herbicide residues. Several samples from untreated sites were also collected for use as field and laboratory blanks. Average recovery rates of the four test herbicides from spiked environmental samples ranged from 75% to 105%, except for a low recovery of 66% for imazapyr in litter samples.

Smoke Monitors

Two smoke monitoring systems were used in the study: a personal monitor worn by forest workers as they carried out their normal duties, representing a realistic operational scenario; and a portable area monitor that could be deployed by research personnel and maintained in areas of high smoke concentration to represent a worst case operational scenario. Both systems were designed to simultaneously collect smoke SPM and airborne herbicide residues.

TABLE 1. Herbicide Formulations, Active Ingredients, and Common Names of Herbicides Monitored in a Smoke Study in Georgia in 1999

Formulation	*Active Ingredient (AI)*	*Common Name*
Pronone 1 0G™A Granular herbicide 10% AI Soil active	hexazinone 3-cyclohexyl-6-dimethylamino-1 methyl-l ,3,5-triazine-2,4 (1 H,3H)-dione	hexazinone
Veipar ULW™B Granular herbicide 75% AI Soil active	hexazinone 3-cyclohexyl-6-dimethylamino-1-methyl-l ,3,5-triazine-2,4 (1 H,3H)-dione	hexazinone
Garlon 4™C Liquid herbicide 61.6% AI 44.3% AED Foliar active	triclopyr 3,5,6-trichloro-2-pyridinyloxyacetic acid, butoxylethyl ester	triclopyr
Arsenal" E Applicators Concentrate Liquid herbicide 53.1% AI 43.3% AE Foliar and soil active	imazapyr 2-(4-isopropyl-4-methyl-5-oxy-2-imidazolin-2-yl) nicotinic acid, isopropylamine salt	imazapyr
Tordon KC Liquid herbicide 24.0% AI 20.8% AE Foliar and soil active	picloram 4-amino-3,5,6-trichloropicolinic acid, potassium salt	picloram

*Pro-Serve inc.
BE.I. duPont de Nemours & Co.
CDowElanco.
DAE = acid equivalent.
EAmerican Cyanamid Co.

The sampling cartridge for both systems consisted of a 25-mm diameter, three-piece plastic cassette (No. 30015, Nuclepore Corp., Pleasanton, Calif.). In this application, the center section of the cassette was used to hold snugly a plug of polyurethane foam with a density of 0.03 1 g/m^3 behind a glass fiber filter, Thus, each cassette was loaded with a 25-mm, binder-free glass fiber filter (Nuclepore, Grade AA, No. 201618) in line with a 27-mm diameter x 35-mm long polyurethane foam cylinder (Analabs No. RCS-083, Phase Separations Co., Norwalk, Conn. This item is no longer available. Foam plugs [No. L800-B2, Jaece Industries, North Tonawanda, N.Y.] may be substituted.). The filter and plug were supported by 25-mm porous plastic support pads (Nuclepore No. 220600) to prevent movement in the cassette. The filter and plug collection media had proven successful in prior laboratory studies associated with the combustion of pesticide-treated forest fuels.[2,3] In addition, the methodology is similar in principle to EPA Method TO-4.[5]

To monitor the respirable range of SPM, the inlet to each personal monitor cassette was fitted with a 10-mm nylon cyclone (No. 456228, Mine Safety Appliance Co., Pittsburgh, Pa.). This cyclone is normally operated at 1.7 L/min to achieve a 50% collection efficiency for 3.5-μm particles (aerodynamic diameter) in accordance with American Conference of Governmental Industrial Hygienists (ACGIH) criteria for respirable particles. The authors elected to operate the sampler at 4.0 L/min to improve the detection limit for both SPM (via gravimetric methods) and herbicide residues (via chromatographic methods). At 4.0 L/min, the cyclone 50% collection efficiency is lowered to

TABLE II. Prescribed Fire Study Areas and Herbicide Treatments[A]

Fire No.	Hectares (ha) Burned	Herbicide Treatment (Formulation and Rate)	Interval[B] (days)	Herbicide Active ingredient Monitored in Smoke [C]
1	17	Pronone 1 0G™, 28 kg/ha	101	hexazinone
2	2.8	Garlon 4™, 8.2 L/ha	32	triclopyr
3	5.3	Accord™, 4.7 Uha; Ga4, 4.7Uha	32	triclopyr
4	3.2	Accord, 11.7 Uha	67	none
5	17	Arsenal™,[D] 1.2 L/ha; Accord, 3.5 L/ha	69	imazapyr
6	13	Arsenal, 1.2 L/ha; Garlon 4, 3.5 L/ha	44	triclopyr
7	81	Velpar ULW™, 5.3 kg/ha	167	hexazinone
8	154	Velpar ULW, 5.3 kg/ha	168	hexazinone
9	130	Velpar ULW, 5.3 kg/ha	169	hexazinone
10	2.4	Arsenal, 3.5 L/ha[E]	30	imazapyr
11	17	Pronone 1 OG, 28 kg/ha	158	hexazinone
12 (A)	19[D]	Arsenal, 3.5 L/ha[F]	106	imazapyr
12 (B)		Arsenal, 1.8 Uha	106	imazapyr
12 (C)		Arsenal, 1.2 Uha	106	imazapyr
13 (A)	19[E]	Garlon 4, 4.7 L/ha, Tordon K™, 4.7 L/ha	97	triclopyr, picloram
13 (B)		Garlon 4, 4.7 Uha, Tordon K, 4.7 Uha	97	triclopyr, picloram
14	2.4	No herbicides applied	—	none

[A]All fire episodes were in late summer/early fall in 1966 in Georgia.

[B]Time between herbicide application and burn date.

'Except for triclopyr and picloram, smoke monitoring procedures only allowed sampling for one herbidde when tank mixtures were used. Glyphosate (Accord) was not included in the monitoring program for this study.

[D]Three subplots (4, 6, and 9 hectares, respectively). All Arsenal treatments were with Arsenal Applicators Concentrate formulation.

[E]Two subplots (9.7 hectares each).

[F]3.5 L/ha rate applied under an experimental use permit; for research purposes, on sites 4 hectares or less. Under normal use, the maximum label rate is 2.9 L/ha.

2.3 pm, according to Blachman and Lippmann.[6] This is within the respirable size range as defined by the Environmental Protection Agency and is also the particle cut point used in prior field studies to monitor prescribed tire smoke.[7] Furthermore, it was known from earlier studies that SPM from prescribed forest fires in the South are principally spherical particles with an aerodynamic mass mean diameter below 1 .O µm.[8]

To quantify the differences in smoke particle collection efficiency for the 1.7 and 4.0 L/min flow rates, a series of small, open-burning experiments were conducted in a 85-m^3 greenhouse. When normalized to concentration values, the 1.7 L/min flow rate collected 12% more particles than the 4.0 L/min flow rate. This is consistent with the particle collection efficiencies for the two given flow rates.

For personal monitoring, a lightweight (l-kg) pump (Model 224, SKC Inc., Eighty Four, Pa.) operated at 4 L/min was worn comfortably around the waist of forest workers. The sampling cassette was connected to the pump by flexible tubing and was clipped to the worker's collar. The larger (10.5-kg) area monitor pump (Aircon 520, Gilian Corp., Wayne, N.J.) powered by a separate, 10.5kg deep cycle marine battery was operated at its maximum flow rate of 20 L/min in order to enhance the detection level for airborne herbicides. The area sampling cassette was mounted on a 1.5-m mast in order to sample the breathing zone. The area monitors were sufficiently portable to be deployed and repositioned as necessary into heavy smoke zones by the supporting research team in order to simulate a worst case operational scenario. The sampling cassette used on the area monitor was identical to the one used on the personal monitor without the cyclone. Operating the area monitor without the cyclone resulted in collection of both respirable smoke particles generated by the combustion process as well as some larger, mechanically generated soil/dust particles. To compare the collection efficiency of smoke SPM by the area monitor (at 20 L/mm) to the personal monitor with cyclone (at 4 L/min), a paired comparison test was conducted in a soil- and dust-free 85-m^3 greenhouse chamber. The chamber was filled with smoke from a tray of smoldering pine needles. Replicated paired samplers were allowed to operate for 15 min. Concentrations were not significantly different at $p < 0.001$.

The collection efficiency and laboratory recovery of pesticides from glass fiber filters and polyurethane plugs have been shown to be effective in prior laboratory combustion studies.[2,3] However, a retention efficiency experiment under the highest flow conditions used in this study (20 L/min) was performed for each of the herbicides. Recoveries are shown in Table III.

The desired detection level for smoke SPM was 0.15 mg/m^3, roughly three times the ambient SPM background for clean, rural air. For herbicide residues, the target airborne detection level was 0.001 mg/m^3. This level is well below the range of concentrations predicted by the modeling method cited in the introduction.“’ It is also several hundred to several thousand times less than the threshold limit values (TLVs) and permissible exposure limits (PELs) for herbicides. Not all herbicides have published TLVs or PELs; however, when compared to herbicides that do have a high inhalation risk, the 0.001 mg/m^3 detection level is still on

TABLE III. Percentage of Herbicide Recovered from Spiked Sampling Cassettes[A]

Herbicide	Without Aspiration (%)	with Aspiratioff (%)	Freezer Storage Period at −10°C (weeks)
Imazapyr	73 ± 20[C]	89 ± 14	12
Hexazinone	95 ± 8	92 ± 8	6
Triclopyr	125 ± 7	88 ± 2	11
Picloram	85 ± 7	71 ± 14	14

[A]20-µg spike ail samples (n = 4).
920 L/min for 1 hrat787and 55% RH.
[C]Mean (±SD).

the safe side. For example, it is 100 times below the TLV for paraquat, which has the lowest TLV of all herbicides.

Carbon monoxide (CO) color diffusion tubes (No. 800-33 19 1, Draeger type, SKC Inc.) were used to monitor breathing zone CO concentrations encountered on the fires. Although not associated with the main objective of the study, worker exposure to CO from forest fires has long been an area of uncertainty and concern. This study provided the opportunity to see if the TLV (50 ppm) or PEL (35 ppm) for CO was exceeded under operational prescribed burning conditions. CO detector tubes were clipped to the collars of the forest workers near the inlet of the personal monitor. They were also placed on the area monitors near the cassette inlet. Raw detection tube readings below 25 ppm were not quantified. Thus, for a 1-hr exposure, the CO detection limit was 25 ppm/hr and for a 4-hr exposure, 6.3 ppm/hr.

Smoke Monitoring Procedures

Five personal monitors and three area monitors were available for use on each fire. Just prior to each fire, two or three area monitors were activated to obtain a total SPM background sample. Respirable SPM background samples (personal monitors) were obtained by a miniature, real-time aerosol monitor (Miniram, Model PDM-3, MIE Inc., Bedford, Mass.). The Miniram output was correlated to respirable SPM by obtaining a series of concurrent Miniram/filter (gravimetric) collections in the same smoke environment. The Miniram was operated (with a flow cell and cyclone) for a series of 10-sec readings before each fire. In no case did the Miniram reading exceed 0.02 mg/m^3, indicating a low background of respirable particles, prior to the fire episode.

On the small to medium sites, three forest workers conducted the burning operation and were outfitted with personal monitors and CO detectors. The remaining monitors were worn by research personnel deploying the area monitors. On the three large sites, eight forest workers were used and five were outfitted with personal monitors and CO detectors. On all fires, the personal monitor pumps were activated just prior to ignition and deactivated when the crew reassembled to leave the fire site. If there were more than one fire in a day, the process would be repeated with fresh cassettes and CO detectors. Workers performed their duties by using their normal operational procedures.

In this study, herbicide detection limits dictated a need to obtain an integrated air sample over the entire fire episode rather than with specific job functions. In many prescribed fires in the South, especially those utilizing ground ignition techniques, personnel will contribute on and off to several work activities. These job functions include ignition (lighting), fire line patrol or line holding, fire suppression (when a fire jumps a fire line), and mop-up (suppression of hot spots after the main fire has passed over an area). Other work activities associated with supervision (fire boss) and heavy equipment operation (bulldozer, tractor, etc.) will also result in smoke exposure.

On each fire, three area monitors were deployed and repositioned as necessary by research personnel to areas with high breathing zone smoke concentrations. At the end of each sampling period or each fire episode, pump operating time was recorded and flow rates verified. The cassettes were capped and stored in an ice chest pending return to the laboratory for gravimetric and chromatogmphic analysis. The color changes in the CO detectors were recorded on site within 5 min after removal from the holders. On a few occasions, the CO detectors on the area monitors would be left in place through several sequential cassette changes to increase the exposure time.

Sample Analysis

Each day after the cassettes were returned to the laboratory, the tared filters were temporarily removed from the sampling cassette and allowed to equilibrate in the balance room for 1 hr before weighing. After weighing, the filters were returned to the cassettes and stored in a freezer (-1 0°C) pending further analysis for herbicide residues.

The filter and plug in the sampling cassettes and prebum soil, foliage, and litter samples were extracted and then analyzed by gas chromatographic techniques in accordance with previously reported procedures.‘“” Herbicide levels were quantified by comparing retention time and peak heights of components in the sample with analytical standards. Reagent blanks and spiked samples were analyzed with each set of samples.

RESULTS

Preburn Herbicide Residues

Residues found in the prebum surface soil, foliage, and litter samples (not corrected for recovery efficiency) are shown in Table IV. The persistence of a herbicide in a forest ecosystem is highly dependent on the properties of the herbicide, coupled with numerous site factors such as rainfall, soil properties, sunlight, and plant metabolism. The results shown in Table IV provide an approximation of site residues that could volatilize into the breathing zone during a prescribed fire. For solid formulations (pellets and granules) of the soil-active herbicide, hex&none, the highest residues were detected in the surface soil samples. The other four liquid herbicide formulations (which are foliar active) yield the highest residues in the standing foliage and ground litter. For imazapyr, the detection limit was only 0.5 mg/kg; no residues were detected at this level on the sites for Fires 5 and 12 (69 and 100 days posttreatment, respectively). However, imazapyr results obtained for Fire 10 at 1 and 30 days

TABLE IV. Herbicide Residues in Preburn Site Samples[A]

Fire No.	*Days after* Herbicide *Treatment*	Hardwood *Foliage (mg/kg)*	*Ground Litter (mg/kg)*	*Surface Soil (mg/kg)*
Hexazinone Residues				
1	101	0.08 ± 0.50	0.06 ± 0.04	0.24 50.20
7, 8	167	co.05	co.05	0.58 ± 0.54
9	169	0.12 ± 0.11	co.05	0.25 ± 0.21
Imazypyr Residues				
5	69	<0.5	co.5	CO.5
10	1[B]	4.6 ± 3.2	4.1 ± 4.0	co.5
10	30	1.5 ± 1.2	21 ± 2.6	co.5
12 A, B, C	106	<0.5	co.5	<0.5
Triclopyr Residues				
2	32	21.0f23.7	11.2 ± 10.1	0.16 ± 0.11
3	32	9.9 ± 9.8	4.3 ± 2.3	0.43 ± 0.60
6	44	10.6 ± 5.9	2.8c1.7	0.21 ± 0.29
13 A, B	97	8.4 ± 13.2	1.6 ± 1.1	0.54 ± 0.43
Picloram Residues				
13 A, B	97	1.14 ± 1.19	0.35 ± 0.28	0.21 ± 0.22

*Average ± standard deviation, n = 6. Detection limits for hexazinone, triclopyr, and picloram: 0.5 mg/kg; for imazypyr: 0.5 mg/kg. In those cases where a sample was below the detection level, one-half the detection level was used in computing the average value.

[B]Fire No. 10 burned 30 days after herbicide treatment; however, site samples were also taken 1 day after treatment.

after treatment suggest that residues would have fallen below the detection level at 69 and 100 days after treatment. The highest herbicide residues were found in the foliage from the triclopyr sites. The pattern of triclopyr residues was generally consistent with the amount applied coupled with the dates of collection.

Smoke Monitoring

No airborne herbicide residues were detected in the 140 breathing zone samples collected in this study. This included samples from 48 personal monitors worn by forest workers, 22 personal monitors worn by research personnel, and 70 area monitors. The herbicide detection limit varied with sampler flow rate and operation period andrangedfrom0.1 to 4.0 µg/m³. This range is several hundred to several thousand times below any known occupational exposure limit for herbicides. These results confirm the findings of no significant airborne herbicide residues in smoke from operational brown and bum prescribed fires as predicted via modeling methods.“’

As expected, much variability was found in the breathing zone concentrations of smoke SPM from these fires. Respirable SPM concentrations encountered by the forest workers ranged over one order of magnitude from 0.2 to 3.7 mg/m³ with a median value of 1.3 mg/m³. Background respimble SPM levels were less than 0.02 mg/m³ in all cases. This variation reflected worker location and assignment on the site as well as the inherent variability of smoke production on different fire episodes. The respirable SPM concentrations encountered by research support personnel were higher than those encountered by forest workers with a median value of 3.6 mg/m³ and a range of 1.1 to 5.5 mg/m³. These differences reflect the more focused assignment of the research personnel, who deployed the area monitors in zones of high smoke concentration.

Exposure periods for the forest workers ranged from 1.2 to 6.3 hr depending on the size of the area being burned. This can be seen more clearly in Table V, which displays results in terms of small, medium, and large fires.

On two occasions (Fires 10 and 11), the cyclone was inadvertently left off the worker monitors. As a result, the samplers collected total SPM rather than just the respirable fraction. To correct these values, a small study was conducted with personal monitors (with and without cyclones), on two prescribed fires in south Alabama. The average cyclone/no cyclone ratio of 0.54 ± 0.14 was applied to the raw values in Fires 10 and 11. The higher SPM concentrations obtained without the cyclone under these

TABLE V. Respirable[A] **Suspended Particulate Matter (SPM) Concentration Range and Average Exposure Periods for Forest Workers**

	SPM Values (mg/m³)			
Fire Size and Number	*Low*	*High*	*Median*	*Exposure Period (hr ± SD)*
Small fire episodes (3.2 hectare [ha] avg) Fires 2, 3, 4, 10, 14	0.4	2.3	1.0	1.4c0.2
Medium fire episodes (17 ha avg) Fires 1, 5, 6, 11, 12, 13	0.7	2.4	1.5	2.3 ± 0.4
Large fire episodes (122 ha avg) Fires 7, 8, 9	0.2	3.7	1.0	4.7 ± 0.8
All fires	0.2	3.7	1.3	2.8 ± 1.8

*Particle 50% out point, 2.3 pm (aerodynamic dieter). SPM values can be increased by 12% to approximate the 3.5-µm ACGIH respirable particle criteria (see explanation in the Experimental Materials and Methods section).

conditions were expected. They are associated with the inclusion of the larger, mechanically generated soil/dust particles along with the smaller, combustion-generated particles. For the fires in this study, mechanical disturbances to the soil were caused by personnel and equipment moving on or near the plowed fire lines. Additional work with cascade impactors is needed to characterize the nonrespirable component of SPM common to prescribed fires.

The area monitors were intentionally exposed to high concentrations of smoke SPM. Sampling periods ranged between 0.3 and 1.6 hr and were governed by smoke conditions and battery operating limits. In some cases, the area samples were operated sequentially over two or three time periods. The area sampler results are summarized by tire size in Table VI. The median SPM value was 6.3 mg/m^3 with a range between 2 and 45 mg/m^3. The area concentrations met the intended objective of simulating a worst case operational scenario. Again, no herbicide active ingredients were detected by the area monitors.

CO breathing zone concentrations for workers were obtained for 45 cases in this study. A total of 22 were below the detection level; 23 were quantified. Values ranged between 6 and 30 ppm/hr over exposure periods between 1 and 6 hr. The highest value was for a 1.7-hr exposure. As expected, the CO concentrations encountered by research personnel (n = 17) were higher (range 18-63 ppm/hr) over exposure periods between 1 and 3 hr. The highest value was for a 1.2-hr exposure. These higher values were associated with the research team's assignment to deploy area monitors into dense smoke zones. The area monitor CO concentrations (n = 54) ranged between 21 and 405 ppm/hr, reflecting the intentional bias to monitor dense smoke zones. Although these high concentrations frequently occur at some locations on a fire site, no worker would voluntarily tolerate the choking conditions in the upper range for more than a brief period without seeking relief by retreating to a smoke-free area.

Even with the relatively crude CO detection method used in this study, a good linear relationship of CO and SPM concentrations was found (Figure 1). The correlation of CO with respirable SPM from fires is consistent with combustion theory because both are products of incomplete combustion of carbonaceous fuels.

TABLE VI. Total Suspended Particulate Matter[A] (SPM) Concentration Range Sampled by Area Moniiors

Fire Size and Number	SPM Values (mg/m^3) Low	High	Median
Small fire episodes (3.2 hectare [ha] avg) Fires 2, 3, 4, 10, 11	2.0	12.2	5.4
Medium fire episodes (17 ha avg) Fires 1, 5, 6, 11, 12, 13	3.1	20.3	6.4
Large Fire episodes (122 ha avg) Fires 7, 8, 9	2.5	44.9	a.3
All fires	2.0	44.9	6.3

[A]20 L/min flow through a 4-mm diameter sampler inlet (50% particle cut point [aerodynamic diameter], not quantified).

DISCUSSION

The combination of low herbicide application rates, environmental degradation, and thermal decomposition, coupled with natural ventilation in the prescribed burning zone, preclude hazardous levels of airborne herbicide residues from forming. The principal inhalation hazard to workers in prescribed fire operations continues to be from smoke constituents derived from burning the natural or untreated forest vegetative fuels (branches, foliage, litter, etc.).[12] At the same time, it is appropriate to reaffirm the caution statements about fire and smoke in the vicinity of bulk storage sites of herbicides (as well as other chemicals). In these cases, the chemical is a major rather than a trace fuel component in the fire. In addition, if indoor structures are involved, the confined space and poor ventilation allow for the volatilization of the active ingredient as well as the formation of high concentrations of thermal decomposition products.

Many of the herbicides used in forest management operations contain carbon, hydrogen, oxygen, and nitrogen and some contain chlorine, sulfur, or phosphorus. Natural vegetative material (forest fuel) also contain these chemical elements (albeit in different amounts and in a different organic matrix). In a typical prescribed fire, grams or kilograms of herbicides are burned in the presence of tonnes of natural forest fuels. Thus, even trace amounts of nitrogen and chlorine in the forest fuels far outweigh the amounts added from the herbicide treatment.

The overwhelming dominance of forest vegetative fuels in a prescribed fire formed the basis of the authors' decision not to attempt to identify thermal decomposition products contributed by the trace amounts of herbicides used in this study. More importantly, this dominance of forest fuels should lead to more compelling smoke questions related to forest fires, such as, what are the worker health effects from "natural" forest fire smoke constituents and what measures are available to minimize exposure? This concern has often surfaced among workers fighting wildfires in the western United States. In contrast to prescribed fires, workers on large, long-duration wildfires may spend several days or weeks in a smoke environment on the fire line, as well as overnight in the fire camp. A major interagency initiative has been proposed to address the health hazards of forest fire smoke related to work activity and geographic area.[13]

Suspended Particulate Matter (SPM) and Carbon Monoxide (CO) Concentrations

The production of SPM and CO by forest fires has been reported in numerous studies over the past 20 yr. However, virtually all of those studies were focused on pollution emission factors and the impact of smoke on general air quality rather than worker exposure.

The results from this study are the first measurements of breathing zone concentrations of SPM and CO for prescribed fires in the South. Therefore, at this time there is no basis to compare these results with other studies. The closest occupational benchmarks are the OSHA PEL for nuisance dusts (5 mg/m^3 for the respirable fraction and 15 mg/m^3 for the total dust fraction) and the ACGIH TLV for total nuisance particles (10 mg/m^3).

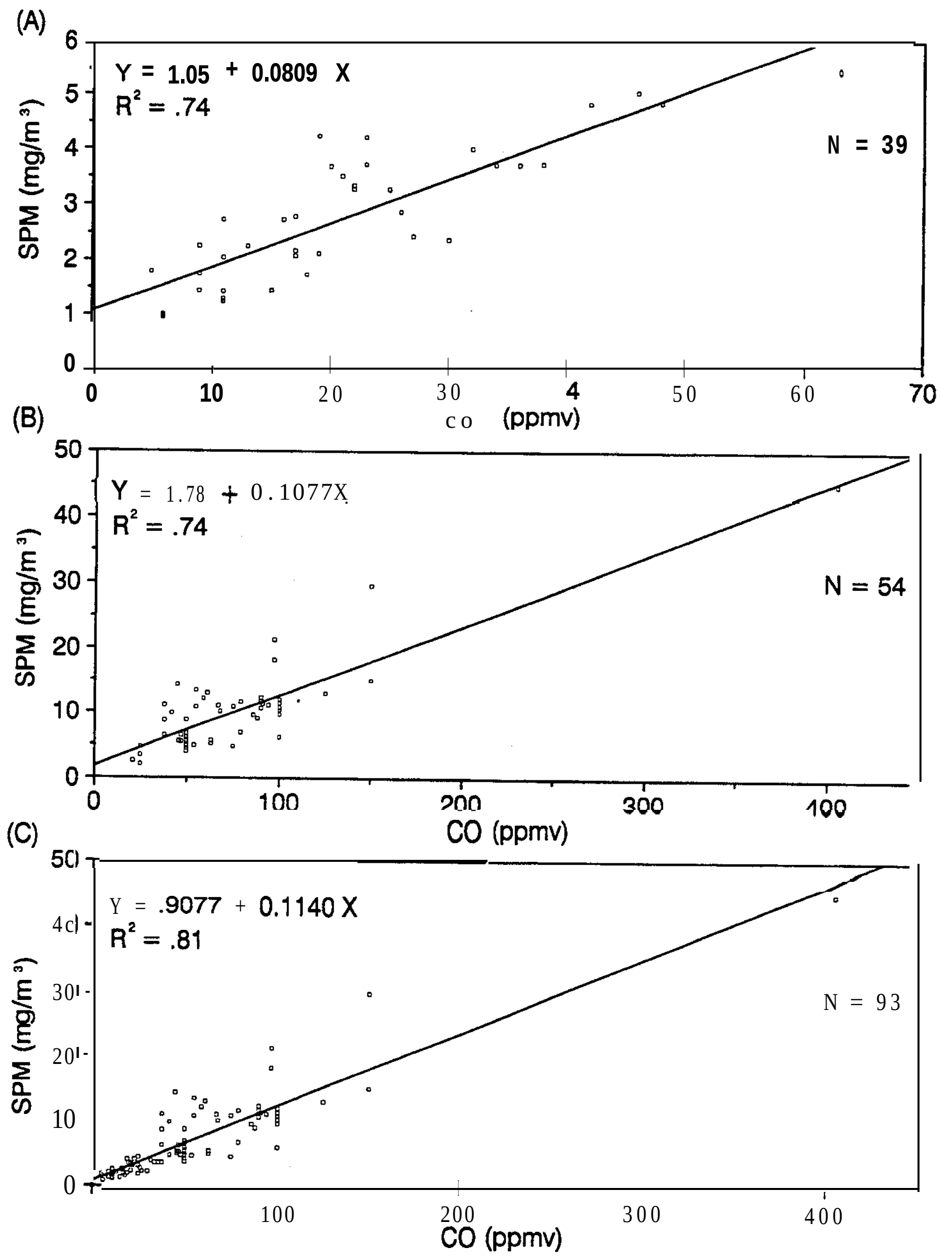

FIGURE 1. Suspended particulate matter (SPM) versus carbon monoxide (CO) concentrations for (A) personal monitors, (B) area monitors, and (C) personal and area monitors combined

The OSHA value is for particles with a mass median aerodynamic diameter of 3.5 µm. As stated earlier, the monitoring strategy in this study was geared for the detection of herbicide active ingredients. This led to a particle cutoff at 2.3 µm. As noted in the Experimental Materials and Methods section, the respirable SPM concentrations reported in Table V can be increased by 12% to approximate concentrations under the 3.5-µm ACGIH particle sampling criteria. Even with adjusted values, none of the worker exposures to respirable SPM would exceed 5 mg/m³ when normalized to an 8-hr work shift. The highest short-term worker exposure was 3.7 mg/m³ for 4.4 hr on Fire 8. Worker exposures to nonrespirable particles on a fire work site from soil and dust particles remain uncertain and will require additional study with a personal cascade impactor capable of obtaining a full spectrum of particle sizes. From a worker health and safety standpoint, characterization of the respirable fraction is more important because of the ability of these particles to reach sensitive regions of the lungs as well as scatter light and obscure visibility. In open fire episodes, the rapid sensory response of the eyes (tears) and respiratory system (coughing/breathing difficulty) to smoke-generated SPM provide a somewhat self-limiting mechanism to minimize voluntary long-term exposure to high smoke concentrations. In all of the fires in this study, workers were able to move rather freely to seek relief from high smoke zones while still carrying out their duties. The authors had no opportunity to monitor SPM concentrations or observe worker behavior in an emergency situation as might occur when a fire breaks out of control and requires arduous suppression activity.

For the 14 fires monitored in this study, none of the forest workers or research personnel approached the OSHA PEL for CO of 35 ppm/hr for an 8-hr work shift. These results are consistent with the recent findings of Brotherhood et al.[14] for prescribed fires in Australia. However, there have been recent reports of somewhat higher CO exposures on prescribed fires and wildfires in the western United States.“” The highest short-term CO exposure in this study was 63 ppm for 1.2 hr for one of the research personnel (Fire 8). The ACGIH short-term exposure limit (STEL) for CO is 400 ppm. The STEL is an average concentration over a 15-min period, which should not be repeated more than four times per work shift. The OSHA ceiling limit for CO is 200 ppm. A ceiling limit is not to be exceeded at any time during an 8-hr work shift. In addition, OSHA has an "immediate danger to life or health" (IDLH) concentration, which is a maximum level from which one could escape within 30 min without any escape-impairing symptoms. The IDLH limit for CO is 1500 ppm. The data from this study suggest that prescribed fire workers would not voluntarily expose themselves to CO concentrations of 400 to 1500 ppm for 15- to 30-min time periods because of the irritating effects of the respirable SPM contained in the same parcel of breathing air. However, a periodic exposure to 200 ppm CO would seem more plausible where personnel pass through heavy bands of smoke as they move around a site. The concern about acute CO exposure from forest tires is not so much a question of encountering "lethal" concentrations; rather it is a concern about CO-induced symptoms of "impaired judgment" which may lead to inappropriate work behavior or an increased accident frequency rate.

A complete assessment of the acute and chronic health risks of forest fire smoke will require additional research to better characterize the size distribution of all airborne particles in the breathing zone, to characterize potentially hazardous compounds in smoke, to determine exposure levels for various work practices and fire types, and to document both short- and long-term health effects. A concurrent evaluation of mitigation measures and risk management options is also needed. This includes the possible use of respirators or limiting exposure via work management techniques.

CONCLUSIONS

1. No airborne herbicide residues were detected in the smoke from the 14 prescribed fires on sites treated with herbicide formulations containing imazapyr, triclopyr, hexazinone, and picloram.
2. The suspended particulate matter (SPM) and carbon monoxide (CO) also monitored on these fires is the first time that worker exposure to these smoke constituents has been measured in the southern United States. Worker exposure to respirable SPM ranged from 0.2 to 3.7 mg/m^3 with a median value of 1.4 mg/m^3. Exposure periods depended on fire size and ranged from 1.2 to 6.3 hr. Area monitors, intentionally placed in high-density smoke zones, had short-term total SPM concentrations ranging between 2.0 and 45 mg/m^3 with a median value of 6.3 mg/m^3.
3. CO breathing zone concentrations for workers ranged from <6 to 30 ppm/hr for exposure periods of l-6 hr. All values were well below the OSHA PEL of 35 ppm/hr when normalized to 8-hr work shifts.

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