PARTICULATE SOURCE STRENGTH DETERMINATION FOR LOW-INTENSITY PRESCRIBED FIRES

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Prescribed fire is the intentional use of fire to achieve certain land management goals. Over 2 million acres of forest land in the southern United States are treated with this tool each year. The benefits from these burns can be offset by a degradation of air quality due to the improper management of combustion products. This paper reports on a portion of the overall research program at the Southern Forest Fire Laboratory which is designed to provide smoke management guidelines to land management personnel.

Included is a description of a method for determining particulate source strength emission factors for low-intensity prescribed fires. A limited amount of data regarding source strength, smoke concentration, and particulate size distribution for 9 natural environment prescribed fires is presented. Results are compared with previous data collected from fuel samples burned in the combustion room at the laboratory.

Comparability was found between the concentrations of particulates determined while sampling side-by-side with the high-volume air sampler, the Andersen sampler, and open-faced 47 mm filters.

Significant differences in particle size distributions were found between fuel types. Artificially produced fuel beds in the laboratory yielded lower particulate production rates than fires in undisturbed natural fuels in the forest. Particulate concentrations were found to be excessive near the fire, 60,000 \text{\mu g/m}^3, but decreased to less than 30,000 \text{\mu g/m}^3 10 feet away.
PARTICULATE SOURCE STRENGTH DETERMINATION FOR
LOW-INTENSITY PRESCRIBED FIRES

Introduction

Prescribed fire, a type of planned open burning, is used extensively in
the southeastern United States for applying specific resource management
treatments to our forests. In excess of two million acres of forest land
are treated annually in the 13 Southern States using low-intensity pre-
scription fires (Figure 1A). Prescribed fire has proved to be more eco-
nomical than alternative mechanical treatments and, in some cases, is the
only known practical method for achieving hazard reduction, undesirable
species control, wildlife habitat improvement, and other management re-
quirements. Along with the benefits derived from the prescribed use of
fire are combustion products, some of which degrade air quality if not
properly managed. The impact of this intentional burning on air quality
is being studied at the Southern Forest Fire Laboratory. Our mission is
to develop smoke management guidelines which will assist foresters with
their job of prescribing land management treatments. Basic to these
guidelines is knowledge regarding the rate of emission of smoke particu-
lates from the burning of various fuels under various weather conditions.

The research problem is being studied both from controlled environment
laboratory studies and through natural environment field research. This
paper will concern itself mainly with the field approach. However, for
comparative purposes the controlled environment combustion room study
results will be presented. These emission factors were derived by using
the following techniques:

1. Uniformly distributing a known oven dry weight of fuel on a
   3x4-ft wire basket fuel bed.
2. Conditioning the fuel to the desired equilibrium moisture content
   by regulating the atmospheric moisture and temperature.
3. Placing the fuel bed on a slope table located in the geometric
   center of the floor under the hood and stack in an environ-
   mentally conditioned 30-ft cubical combustion room.
4. Igniting a line of fire along the 3-ft side of the fuel bed,
   either at the top to simulate a fire backing into the wind
   (Figure 1), or at the bottom simulating a fire heading with
   the wind, burning upslope.
5. Isokinetic sampling of the emissions passing through the 24-in.
   diameter stack trapping the particulates in a standard 8x10-in.
   Type A glass fiber filter mat.

Using these techniques, particulate emission factors for the fuels burned
ranged from 6 to 158 pounds per ton of fuel consumed (Table 1). In
general, particulate production increased with increased fuel moisture
content and decreased as the rate of spread decreased. In the natural
environment this is comparable to using a fire backing into the wind
versus a head fire running with the wind. These controlled environment
studies are continuing, with emphasis being placed on particle size.

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distribution changes with fuel alterations and in determining additional emission factors for other fuel types.

Field Experimental Methods

Laboratory-derived emission factors are being checked under natural environmental conditions. We have concentrated on two major fuel types commonly burned in the Southeast. These fuels, gallberry-palmetto and slash pine (Pinus elliottii) needle litter fuels, are primarily burned using low-intensity backfires (Figures 2 and 3). The emissions from backfires generally rise on a gentle, inclined plane as the wind disperses the smoke away from the fire.

A method for monitoring smoke concentration at various horizontal and vertical spatial points downwind from low-intensity line source backfires was first developed. By positioning samplers in the vertical dimension with the top samplers above the smoke plume and by knowing the amount of air moving past this vertical array of samplers, an emission rate can be calculated for the fire.

Five 40-ft masts were constructed out of 10-ft sections of rigid aluminum conduit tapering from 2 in. in diameter at the base to 1 in. at the top. The mast is in two sections to facilitate transporting. Samplers, each containing a 47 mm Type A glass fiber filter, are positioned at various heights on the mast. A central vacuum source with a capacity of 10 cubic feet of air at 20 in. of Hg is used to service the five masts. Each mast acts as a vacuum manifold, and each filter is attached to a critical flow-limiting orifice. These are 18 gauge, 1-1/2-in. long, hypodermic needles which maintain a constant, critical flow of approximately 4 liter per minute (Lodge, et al., 1966). The hypodermic needle is inserted through a pilot hole in a 00 rubber stopper which in turn is inserted into drilled holes along the mast at the desired heights. The constant flow rate orifices are calibrated periodically, using a wet test gas meter.

A typical field test involves first sampling the fuel to determine the weight of fuel on the site. Usually equipment for monitoring wind direction and speed is operated adjacent to the planned burn area. Orientation of the fire line must be established perpendicular to the wind direction. Five masts are then outfitted with pre-weighed filters (environmentally conditioned at 50% relative humidity and 70°F) in each sampler. The towers are raised (a task easily handled by two men) and secured to 2-in. x 4-ft angle irons driven into the ground. Vacuum lines are attached to each mast and a check is made for leaks. Standard high-volume air samplers are located within 5 feet of each of the three masts nearest the fire. The larger mass of particulate matter collected by these samplers will be used for chemical extraction purposes. An 8-stage Andersen non-viable particle sampler is located near the center high-volume sampler and mast. These samplers, as explained here and in the next section, each have a specific function as well as providing a means for cross-checking results. Figure 4 is a plan view of the equipment relative to the area to be burned and Figure 4A shows the equipment in use.
Results

Particulate Concentration

Prescribed fires usually only last a few hours, the exception being fire used for reducing piled slash. In most cases, prescribed fires are used rotationally covering a given area once every 3 to 5 years. These fires are generally set from, or burn to, roadways. Usually this creates no serious visibility problem, but under certain conditions can impede travel. In developing smoke management guidelines, we are attempting to identify situations along roadways when prescribed fires can be used with little risk of reducing visibility.

The grid of masts shown in Figure 4 measure particulate concentration immediately downwind from the fires. An example of the average smoke concentration over a 20-min sample time is illustrated by the isopleth diagram in Figure 5. Thirty feet downwind, the particulate concentration 5 ft above the ground decreased from 26,000 $\mu g/m^3$ to about 7,000 $\mu g/m^3$ with a further decrease to about 3000 $\mu g/m^3$ 50 feet from the fire line.

Other fires have been sampled by taking 5-min incremental samples as the fires backed into the wind away from the masts. For one fire, samples taken at 3 and 6 ft above the ground show a maximum concentration within 5 ft of the fire of 60,000 $\mu g/m^3$. During the first 15 minutes this concentration decreased by one-half as the fire moved 10 ft away from the mast.

Particulate concentration is a function of wind speed, vertical temperature profile, fire heat yield rate, as well as the rate of emission of particulates. As more fire situations are sampled, correlations will be drawn between smoke concentration and different fire and weather variables.

Source Strength Determination

Particulate source strength data for forest fuels have been determined by burning fuel samples under hoods (Gerstle and Kemnitz, 1967)\(^2\), Tarley, et al. 1966\(^3\) and in combustion chambers (see introduction). These fuel samples in general have been artificially arranged and have not utilized naturally layered, conditioned and compacted fuels. An exception is Bouwel, et al. (1969)\(^4\) work with actual stubble and straw.

There is no need to correlate source strength data from the artificially controlled environment with those measurements of source strength made under natural environmental conditions. We still know very little about particulate production rates for fuels burned at times when only the surface layer of needles is consumed overlaying a very wet lower layer. As the forest floor dries, consumption of the fuel complex becomes greater. This results in deeper layers of partially decayed fuel being consumed, which may contribute considerable particulate matter in addition to that produced from the surface layer of fresh pine needles.

Source strength data have been obtained for a number of individual fires by using the masts to determine smoke concentration with height. Totalizing anemometers located at 6 and 20 feet above the ground are used to determine the number of feet of windrun past the mast during each sample
period. An example of the calculations is given for a fire in a palmetto-galberry fuel complex (see Table II). These calculations indicate that the fire produced 4.89 g of particulates per minute per foot of fire line. In this case, the fire line was about 1320 feet in length. The fire was yielding approximately 6.5 kg/min. The emission factor for the palmetto-galberry fuel was calculated to be 27.3 lb/ton of fuel consumed. Other fuel situations have been sampled and are summarized in Table III.

Fires in the palmetto-galberry fuel type consumed more fuel per acre and had higher spread rates than those in the slash pine litter fuels (Table III). The slash pine litter fuels were burned under two rather divergent moisture regimes with consumption and rate of fire spread significantly less under the wetter condition. Particulate production rates were much lower for the wetter fuels, but emission factors were similar under both moisture regimes. However, the difference in particulate emissions between fuel types appears to be highly significant. On the other hand, particulate emissions determined for loblolly pine litter fuels in the laboratory (Table I) showed a dependency on fuel moisture content.

**Particulate Size Distribution**

A partial description of size distribution of particulates from low-intensity prescribed fires has been obtained using the Andersen non-viable 8-stage particle sampler. Particles are sized aerodynamically (Anderson, 1966). The larger sized particles are impacted on the first stages with progressively smaller sized particles being collected on the later stages. A backup filter is used to collect particles smaller than about 0.40 μ (47 mm, Type A, glass fiber).

Each stage was covered with an aluminum disc (3.25 in. in diam) cut from household foil, which made a low tare weight collection surface. All foil discs were conditioned at 50% relative humidity and 68°F for 24 hr prior to weighing.

MacArthur (1966) reported a preponderance of particles by number of 0.1 μ diam from forest fire smoke. His analysis through electron and light microscopy indicated few particles in the 0.5 to 1 μ range or larger. His samples were collected at altitudes from 1000 to 1500 feet over terrain. Our sampling with the Andersen sampler, done in close proximity to the fire, tends to support MacArthur's findings. We found a majority of the mass of particulates to be less than 0.4 μ in size (Table IV). Our sampling showed little variation for the slash pine litter fuel type burned under two divergent moisture content conditions. However, we did find that the particle size distribution shifts with a change in fuel type. In the palmetto-galberry fuel type about 50% of the particulates by weight were aerodynamically sized less than 0.4 μ, while in the slash pine litter fuel type 70% were collected in the final filter.

**Particulate Concentration Comparability**

On several of the test fires particulate concentration was sampled using three different techniques. These methods (47 mm filter sampler, high-volume air sampler in a standard shelter, and the Andersen sampler) have produced comparable data. An example collected February 21, 1974, which is the average for three replicated test fires, is as follows:
<table>
<thead>
<tr>
<th>Method</th>
<th>Particulate Concentration ((\mu g/m^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>47 mm filter</td>
<td>8280</td>
</tr>
<tr>
<td>Andersen</td>
<td>7120</td>
</tr>
<tr>
<td>High-volume</td>
<td>8502</td>
</tr>
</tbody>
</table>

**Conclusions**

Some of the tentative conclusions are:

1. Particulate concentration decreases rapidly with distance from the edge of the prescribed fires sampled. Wind speeds of about 2 mph have diffused smoke concentration by a factor of 2 within 50 ft of the fire.

2. Particulate production appears to be higher from undisturbed fuel complexes burned in the natural environment than the emissions from artificially prepared fuel beds burned in our combustion room.

3. Aerodynamic sizing of aerosols produced from natural fuels has demonstrated a marked difference between fuel types.

4. Comparability in measuring smoke aerosol concentrations has been achieved between the Andersen inertial sampler, the hi-volume air sampler, and open-faced 47 mm filters.

More importantly, the data generated and technique illustrated can be used for determining source strength for low-intensity prescribed fires. This is providing information to meteorologists who are using models for predicting particulate concentration in the smoke plume farther downwind.

Knowing the source strength, smoke concentration, and particulate size distribution for low-intensity prescribed fires burned under different fuel and weather conditions is a major step in the development of smoke management guidelines.

**References**


Acknowledgment

The authors would like to acknowledge the loan of several hundred 43 mm filter samplers from the Department of Army, Dugway Proving Ground, Dugway, Utah.

Table I  Particulate emission factors (lb/ton) for various fuel and burning techniques.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Per cent moisture content</th>
<th>Backfire (simulated)</th>
<th>Head fire (simulated)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-50</td>
<td>-25</td>
</tr>
<tr>
<td>Loblolly pine (loose)</td>
<td>6</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>Loblolly pine (loose)</td>
<td>10</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>Loblolly pine (compacted)</td>
<td>13</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Loblolly pine (branes &amp; twigs 1/4 - 1 in.)</td>
<td>15</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Goldenrod</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed grasses (compacted)</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardwood leaves (red oak)</td>
<td>11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 11. An example of the method used for computing the particulate emission rate. Data are from the palmetto-gallberry type. Sample time was 20 minutes.

<table>
<thead>
<tr>
<th>Sampler: Mast No.</th>
<th>Partic. conc.</th>
<th>Window area</th>
<th>Wind run</th>
<th>Volume of air</th>
<th>Mass of particulate</th>
</tr>
</thead>
<tbody>
<tr>
<td>height (ft)</td>
<td>1: 2: 3 mean</td>
<td>(ft²)</td>
<td>(ft)</td>
<td>(m³)</td>
<td>(g/ft of fire line)</td>
</tr>
<tr>
<td>3</td>
<td>34.6 21.4 23.7</td>
<td>26.57 4.5</td>
<td>6500</td>
<td>828</td>
<td>22.01</td>
</tr>
<tr>
<td>6</td>
<td>30.5 23.6 21.8</td>
<td>25.50 3</td>
<td>6550</td>
<td>556</td>
<td>14.08</td>
</tr>
<tr>
<td>9</td>
<td>24.8 20.6 20.0</td>
<td>21.80 4</td>
<td>6450</td>
<td>731</td>
<td>15.93</td>
</tr>
<tr>
<td>14</td>
<td>15.3 16.1 17.3</td>
<td>16.25 5</td>
<td>6250</td>
<td>885</td>
<td>14.36</td>
</tr>
<tr>
<td>19</td>
<td>9.9 10.9 13.5</td>
<td>11.45 5</td>
<td>6030</td>
<td>854</td>
<td>9.76</td>
</tr>
<tr>
<td>24</td>
<td>7.0 7.3 10.3</td>
<td>8.20 5</td>
<td>6000</td>
<td>850</td>
<td>6.97</td>
</tr>
<tr>
<td>29</td>
<td>6.2 5.6 8.2</td>
<td>6.67 5</td>
<td>6000</td>
<td>850</td>
<td>5.67</td>
</tr>
<tr>
<td>34</td>
<td>3.7 5.8 7.3</td>
<td>5.60 5</td>
<td>6000</td>
<td>850</td>
<td>4.76</td>
</tr>
<tr>
<td>39</td>
<td>3.6 4.0 7.7</td>
<td>5.10 5</td>
<td>6000</td>
<td>850</td>
<td>4.33</td>
</tr>
</tbody>
</table>

1/ See Figure 4 for location of masts 1, 2, and 3.
2/ Average of the 3 masts (Figure 5).
3/ A window 1-ft wide parallel to the fire line is used.
4/ Volume of air passing through each window.
5/ Mass = (mean conc)(area)(wind)(0.02832 m³/ft³)
Production rate/ft of fire line = total mass/sample time
= 97.87 g/20 min
= 4.89 g/min/ft of fire line
Table III  Particulate emission rates and factors for two different fuel types burned using low-intensity backfires.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Upper: Composite consumption (tonnes/acre)</th>
<th>Fire sample (min)</th>
<th>Fire spread (ft/min)</th>
<th>Fire length (ft)</th>
<th>Per ft of fire line production (g/min)</th>
<th>Entire fire line production (kg/min)</th>
<th>Emission factor (l/min/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litter (slash)</td>
<td>23</td>
<td>84</td>
<td>3.4</td>
<td>45</td>
<td>0.39</td>
<td>250</td>
<td>0.66</td>
</tr>
<tr>
<td>Litter (pine)</td>
<td>23</td>
<td>84</td>
<td>3.0</td>
<td>45</td>
<td>0.41</td>
<td>250</td>
<td>0.66</td>
</tr>
<tr>
<td>Litter (None)</td>
<td>None</td>
<td>None</td>
<td>5.8</td>
<td>40</td>
<td>0.60</td>
<td>250</td>
<td>1.88</td>
</tr>
<tr>
<td>Litter (slash)</td>
<td>25</td>
<td>54</td>
<td>5.4</td>
<td>30</td>
<td>0.63</td>
<td>530</td>
<td>1.74</td>
</tr>
<tr>
<td>Litter (pine)</td>
<td>13</td>
<td>36</td>
<td>5.2</td>
<td>30</td>
<td>0.61</td>
<td>530</td>
<td>1.70</td>
</tr>
<tr>
<td>Palmetto-</td>
<td>17</td>
<td>82</td>
<td>5.0</td>
<td>45</td>
<td>1.38</td>
<td>660</td>
<td>1.92</td>
</tr>
<tr>
<td>gallberry</td>
<td>22</td>
<td>69</td>
<td>6.4</td>
<td>25</td>
<td>2.91</td>
<td>660</td>
<td>3.01</td>
</tr>
<tr>
<td>10</td>
<td>72</td>
<td>9.9</td>
<td>20</td>
<td>1.74</td>
<td>1320</td>
<td>4.89</td>
<td>6.452</td>
</tr>
</tbody>
</table>

1/ Upper moisture content is the moisture content as a per cent of oven dry weight of this year's needle fall. Composite moisture content is the average moisture content of those fuels consumed.
Table IV  Size distribution difference between slash pine litter fuel burned at two moisture content levels and palmetto-gallberry fuel. Data collected using Andersen sampler.

<table>
<thead>
<tr>
<th>Andersen stage</th>
<th>ECD &lt;sup&gt;1&lt;/sup&gt; (microns)</th>
<th>Slash pine&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Slash pine&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Palmetto-gallberry&lt;sup&gt;4&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11 &amp; above</td>
<td>1.0</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>0.7</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>4.7</td>
<td>0.9</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>3</td>
<td>3.3</td>
<td>0.7</td>
<td>0.9</td>
<td>1.3</td>
</tr>
<tr>
<td>4</td>
<td>2.1</td>
<td>1.7</td>
<td>1.8</td>
<td>4.3</td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
<td>4.3</td>
<td>4.6</td>
<td>6.5</td>
</tr>
<tr>
<td>6</td>
<td>0.65</td>
<td>5.0</td>
<td>9.0</td>
<td>12.3</td>
</tr>
<tr>
<td>7</td>
<td>0.43</td>
<td>12.6</td>
<td>11.7</td>
<td>19.4</td>
</tr>
<tr>
<td>Backup filter</td>
<td>---</td>
<td>73.1</td>
<td>70.0</td>
<td>53.1</td>
</tr>
</tbody>
</table>

Particulate concentration : 5,199 µg/m<sup>3</sup> : 17,834 µg/m<sup>3</sup> : 11,543 µg/m<sup>3</sup>

<sup>1/</sup> Equivalent cutoff diameter which assumes spherical particles of unit density.
<sup>2/</sup> Average of four samples. Upper moisture content = 23%, composite moisture content = 84%.
<sup>3/</sup> Single observation. Upper moisture content = 19%, composite moisture content = 45%.
<sup>4/</sup> Average of three samples. Upper moisture content = 18%, composite moisture content = 71%.
FIGURE 1A  PRESCRIBED BURN ACREAGE BY STATE FOR THE SOUTH IN 1970.
Figure 1  Test of a simulated backfire consuming loblolly pine needle litter fuel in a 3x4-ft wire basket on a weight-loss sensing slope table.
Figure 2  A typical prescribed fire backing into the wind through a palmetto-gallberry fuel complex.

Figure 3  A typical prescribed fire backing into the wind through a slash pine needle fuel complex.
FIGURE 4: PLAN VIEW OF RELATIVE LOCATIONS OF THE EQUIPMENT USED FOR A TYPICAL TEST FIRE.

AREA TO BE BURNED

FIRE LINE

FIRE DIRECTION

LEGEND

- MASTS (1 - 5)
- HIGH-VOLUME AIR SAMPLER
- ANDERSEN PARTICLE SAMPLER
- METEOROLOGICAL MAST WITH TOTALIZING ANEMOMETERS AT 6 AND 20 FT
- RECORDING WIND DIRECTION AND SPEED SENSORS AT 5 AND 20 FT
- VACUUM SUPPLY PUMP

NO SCALE
Figure 4A Masts with 47 mm filter holders, high-volume air samplers, and Andersen sampler in position.
FIGURE 5  ISOPLETH LINES CONNECTING POINTS OF EQUAL CONCENTRATION (MG/M³) FOR A PRESCRIBED BACKFIRE BURNING IN A PALMETTO-GALBERRY FUEL TYPE.