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A SOURCE STRENGTH MODEL FOR PRESCRIBED FIRE IN CONIFEROUS LOGGING SLASH

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ABSTRACT

Emission reduction has become an essential part of the effort to reduce air pollution from forest slash burning. The State of Washington has set a goal of reducing emissions by 35 percent by 1990, leaving the choice of emission reduction techniques to forest managers. Several thousand harvested areas are burned each year in the Northwest, encompassing a wide variety of physical and meteorological factors that determine the mass and duration of each pollutant source. Each burn is somehow unique; and no emission reduction technique is uniformly effective.

A source strength model has been developed to combine what is known about the factors that control biomass consumption and combustion efficiency in Douglas-fir and hemlock logging slash. Particulate matter and carbon monoxide emission rates are predicted from a set of eighteen or more input parameters. Default values or inference techniques are available for most inputs. An interactive computer model has been written. The output can be used to load a dispersion model, or used to compile a daily emissions inventory. Iterative model solution has been used to evaluate the effectiveness of emission reduction techniques.

INTRODUCTION

Emission reduction is an essential part of reducing air pollution from prescribed forest fires. The State of Washington has set a goal of reducing emissions by 35 percent by 1990, leaving the choice of reduction techniques to forest managers. Prescribed fire is a difficult source of pollutant emission to characterize: each fire is unique and each reacts differently to mitigation efforts. For the past 15 years, 4000 prescribed fires per year in western Washington and western Oregon has been scheduled to avoid identifiable intrusion of smoke into a few smoke-sensitive areas. Wind direction and weather conditions have been the most important criteria on which decisions were made, but only a rough estimate of fuel (biomass) consumption and an approximate emission factor (pounds of pollutant per ton of fuel consumed) were needed.

Recent emphasis on air quality in Federal Class I areas and on the problem of regional haze has created new smoke-sensitive areas in proximity to and downwind from forested areas where fire is prescribed. Some of these new areas can tolerate limited intrusion of smoke, provided the smoke is diluted to an acceptable concentration. Hence, new approaches of air resource management are needed, approaches requiring more accurate knowledge about the rate of emission, called source strength, and its dispersion.

The Forest Fire and Atmospheric Sciences Research (FFASR) team of the USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, is completing a 4-year program to characterize emissions from slash burns and to evaluate techniques that reduce emissions. As part of the program, the FFASR team developed a source strength model with a design accuracy of ±35 percent. The model has four major uses. (1) A cooperative effort between FFASR, the U.S. Environmental Protection Agency, and the States of Washington and Oregon is working toward reducing emissions from prescribed fires and evaluating progress toward that goal. The effort will improve compilation of annual inventories of emissions; the source strength model will be used to estimate those emissions. (2) Inventories of daily emissions compiled by the model will be used by the PANORAMAS1/ study group to compare apportionment of sources from source inventories to that from receptor models during episodes of regional haze. (3) A screening system proposed by Pierovich 2/ uses a dispersion model to predict downwind pollutant concentrations to insure adequate dilution. Prediction of pollutant source strength and heat release rate at one hour intervals may be required for the dispersion model. (4) Forest managers also need a source strength model. They must design a mix of several techniques that reduce emissions to meet annual goals that meet daily dispersion requirements by reducing source strength. The effectiveness of each technique varies with many factors, so the design is not a simple one. The source strength model can aid the manage in the design.

This paper discusses the concept of the source strength model, how it operates, and how the model can be used. The source strength model packages a series of mathematical algorithms that represent our current knowledge of the factors that control biomass consumption and pollutant formation. Some of the algorithms will be revised slightly in the next several months, so not all are included in this paper.

1/PAcific NOrthwest Regional Aerosal Measurement/Apportionment Study, a joint study of regional haze by the U.S. Environmental Protection Agency, Region 10; State of Washington Department of Ecology; State of Oregon Department of Environmental Quality; and State of Idaho Air Quality Bureau. Seattle, WA: U.S. Environmental Protection Agency. Draft project plan.

2/Pierovich, John. Smoke management screening system process: user's guide. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. Manuscript in preparation.

MODELING PRESCRIBED FIRE

The source strength model is limited to broadcast burning in coniferous logging slash in Washington and Oregon, west of the Cascade Range. Broadcast burning is the in-place ignition of scattered residues as opposed to creating large piles or windrows for burning. We chose coniferous slash because it provides the best opportunity for emission reduction through increased utilization, although we realize that burning of hardwood slash and the prescribed burning east of the Cascade crest are nearly as important to the air resource manager. We simply didn't have the time or money to do both jobs.

Fuel Consumption

Areas to be broadcast burned are commonly ignited in many successive strips, either by hand or by dripping ignition sources from a helicopter, over a period of one to several hours. Sizes of burns from 3 to 600 acres are common. The flames spread in the fine fuels between strips at a rate controlled by fuel loading and environmental conditions. Heat from adjacent strips may reinforce each other, accelerating fire spread. Occasionally, areas are lit so quickly (mass ignition) that several strips coalesce, producing violent, intense fire behavior that alters the amount of fuel consumed.

Forest fuels always burn in two reasonably distinct combustion stages, flaming and smoldering. The duration of the flaming stage at one point within a burn is usually 10 to 20 minutes. Smoldering persists for several hours, but the emission rate from smoldering fuels has been shown to diminish exponentially over time (Ward and Hardy, 1984), and the exponential decay constant is predictable. The proportion of fuels that is consumed during the flaming stage can vary from much less than half to over 90 percent.

Coniferous slash fuelbeds are a mixture of at least five components: fine fuels (less than 1 inch in diameter), small fuel (1-3 inches in diameter), large woody pieces (greater than 3 inches in diameter), live vegetation, and duff (decayed material on the forest floor). The total loading (mass per unit area) typically ranges from 20 to 200 tons or more per acre, of which 5 to 100 tons per acre may be consumed by fire.

The range in fuel consumption is wide because moisture contents of large fuel (12 to 50 percent or more ovendry weight) and duff (20-300 percent) varies widely and because a special effort is sometimes made to remove large fuels before burning. Ottmar (1983) reported on the proportion of woody fuel and duff consumed in each stage, and provided predictive algorithms for fuel consumption.

In addition to broadcast slash, there is usually a concentration of yarded, but unmerchantable material at landings, where logs are processed and loaded. Landings can contain 1-10 tons per harvested acre and may be burned or left unburned according to choice and circumstances.

Each of the fuel components has a distinct role in the combustion process, and its consumption is limited by different factors. In general, the fine and small fuels, and live vegetation govern fire behavior and combustion efficiency. The objective of most prescribed fires is to fully consume these fuels, which usually consititute 5-15 tons per acre. The large fuels and duff tend to smolder inefficiently. Although 6-70 tons per acre may be consumed, their consumption is seldom desirable. Reducing the biomass consumed in the large fuel and duff components offers the best possibility for mitigating air pollution from slash burns.

Emissions

Because of the two combustion stages, a single emission factor does not adequately describe broadcast burning. A set of emission factors for flaming and smoldering forest fuels has been reported by Ward and Hardy (1984), but no distinction was made in emission factors for the five fuelbed components because all fuelbed components at one spot flame together, then smolder. They showed that the flaming emission factor for carbon-bearing pollutants may double when an abundance of live fuels are present.

Source Strength

The model first uses Ottmar's (1983) and Sandberg and Ottmar's (1983) predictive algorithms and heuristics (placing bounds on predicted values) to compute fuel consumption (tons per acre) for each fuelbed component. Then the proportion burned in the two combustion stages is computed for each fuelbed component and multiplied by predicted fuel consumption. The mass of fuel burned in all components is summed to estimate total fuel consumption, W (tons per acre), in the flaming (W_F) and smoldering (W_S) stage. Those values are multiplied by fire size, A (acres), and the appropriate emission factor, EF_F, EF_S (pounds per ton), to compute emission yield, E_F, E_S (pounds or kilograms[3] of pollutant), from each stage of the burn. A rate equation (proportion of fuel consumed per minute) is derived for each stage. The average rate proportion for each 10 minutes is multiplied by emission yield to predict flaming and smoldering source stengths, $E_{F.t}$ $E_{S.t}$ (pounds of pollutant per minute or grams per second), which are then summed to estimate total source strength, E_t. The subscript, t, denotes the time (minutes) since ignition begins.

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[3] The mixture of English and metric units is intentional. Foresters commonly use English units, but dispersion models commonly require metric inputs. Air resource managers use a mixture of units, which we attempt to duplicte here. Equations included in this paper dispense with conversion factors.

The rate equation to apportion flaming consumption over the burning period is a simple one. If ignition proceeds uniformly, source strength increases uniformly for the 10-20 minutes until the first strip begins to smolder (t = TFLAM, minutes). Flaming source strength remains nearly uniform at a rate:

$$\dot{E}_{F.t} = A\ W_F\ EF_F/TIGN, \quad \text{when } TFLAM<t<TIGN, \qquad (1)$$

until ignition is completed (t = TIGN), and finally decreases uniformly to reach zero when the last strip begins to smolder (t = TIGN + TFLAM) (fig. 1).

As the first and successive strips begin to smolder, the smoldering area increases more or less uniformly. Smoldering emissions during that period are always increasing, such that at time, t (minutes after ignition begins):

$$\dot{E}_{s.t} = A\ W_s\ EF_s\ \{1-\exp\ [TFLAM - (t/EDR)]\}, \quad \text{when } TFLAM<t<(TFLAM + TIGN) \qquad (2)$$

where EDR (minutes) is the exponential decay constant, or the length of time required for the emission rate to diminish to a proportion equal to 1/e of its original value. The emission decay rate appears to be proportional to the mass of duff consumed, although the relationship requires verification. After all flaming ceases, smoldering emissions source strength diminishes exponentially such that:

$$\dot{E}_{s.t} = \dot{E}_{smax}\ \exp\ [(TIGN + TFLAM - t)/EDR], \quad \text{when } t>(TIGN + FLAM) \qquad (3)$$

where $\dot{E}_{smax}$ is the maximum value of $\dot{E}_{s.t}$ from equation 2, that is at t = (TIGN + TFLAM) (fig. 2).

Considering the burn area as a whole, flaming and smoldering always occur simultaneously. Within the first few minutes after ignition, when time, t, is less than TFLAM, no smoldering occurs. As ignition progresses (t >TFLAM), an increasing proportion of the area smolders until 10-20 minutes after ignition is complete (t = TFLAM + TIGN), when the entire souce is smoldering. Because the combustion efficiency is lowest during the smoldering stage, the instantaneous emission factor for the total burn area increases during the course of the burn. The average emission factor for an entire burn period varies according to the overall proportion of flaming and smoldering fuel consumption.

INPUTS TO THE SOURCE STRENGTH MODEL

The model is currently maintained on the University of Washington CDC Cyber 170-750 computer. It is written in extended ANSI-77 FORTRAN for compatibility with an FTN5 compiler. It utilizes 55,700 octal locations of central memory for storage costs approximately $1.73 to compile and approximately $4.94 to execute with one set of input values.

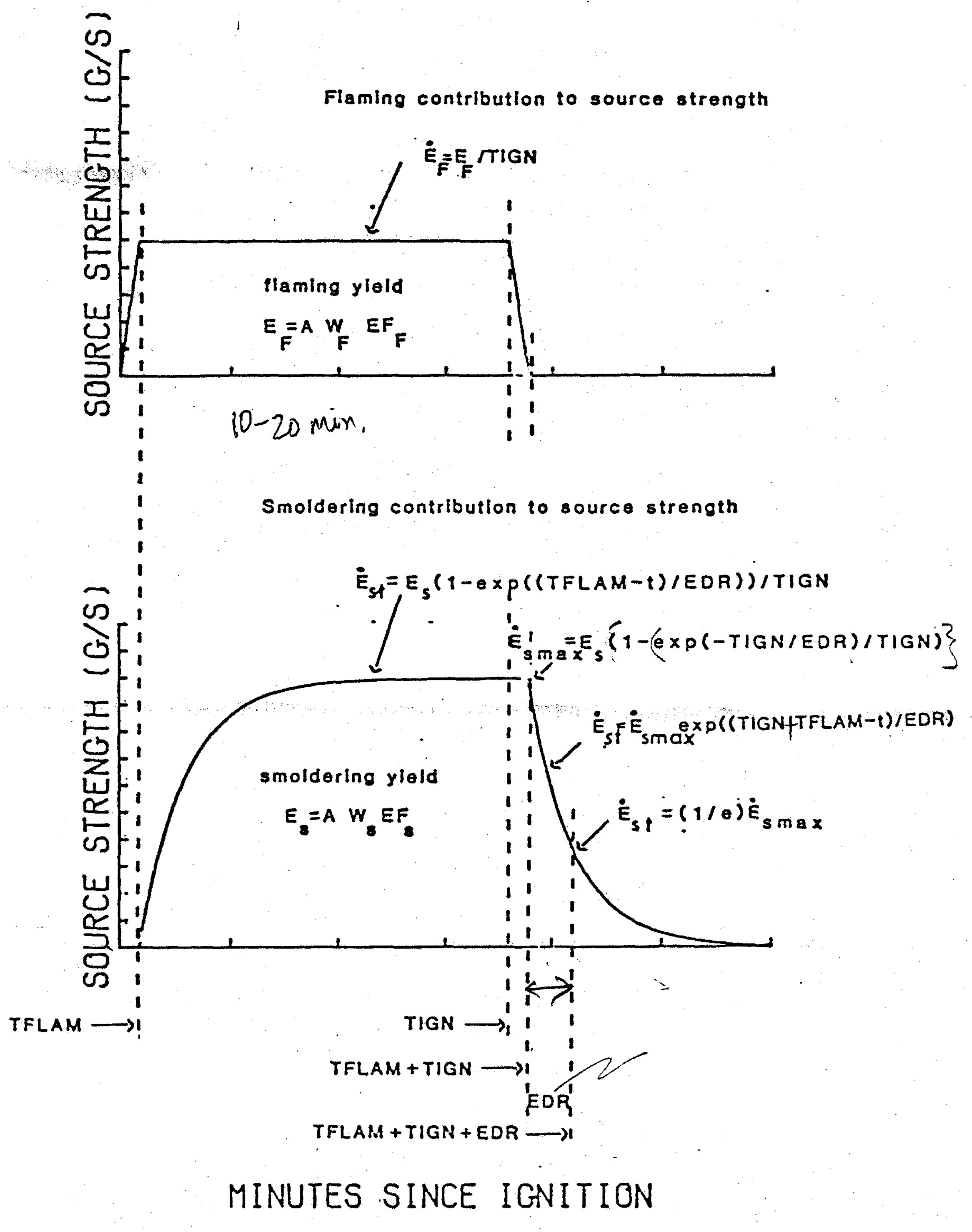


Figure 1. Generalized emissions source strength model for broadcast burning of logging slash. Two combustion stages occur simultaneously. Emission yield, E_F and E_S, for the flaming and smoldering stage, respectively is the product of burn area, A, fuel consumption, W_F and W_S, and the pollutant emission factor, EF_F and EF_S. Emission source strength, $\dot{E}_t$, is the sum of the flaming and smoldering source strength, $E_{f.t}$ and $\dot{E}_{s.t}$ at time, t, after ignition begins.

The model is written in a user-friendly format, provided the user is familiar with prescribed burning techniques and terminology. At the beginning of an interactive session, the user can choose to obtain explanations of any or all of the input variables that will be required. This section can be skipped altogether by experienced users. The inputs are verified for the user, and the user is given an opportunity to change any of the values (fig. 2). When the user is satisfied with the values, the model works-whether they fall within a reasonable range for that variable. If a value does not fall within this range, the user is informed that the value may be unreasonable and is again given an opportunity to change the value. It is not obligatory that the value be changed; in some cases, out-of-range values can be informative.

At least 18 input variables have been shown to influence source strength and are used by the model to predict fuel consumption, select emission factors, or solve rate equations. Default values that represent regional averages (for continuous variables), or the most frequent value (for discontinuous variables), or in some cases, a best guess can be substituted for any of the inputs. We continually change the default values as new information is revealed. If default values are selected for all 18 inputs, the output represents our current characterization of a "typical" broadcast burn. There is no "average" broadcast burn because so many of the input variables are discontinuous, have nonlinear effect on source strength, or are correlated with other input values.

Sample Input

To illustrate the types of information the model produces, we will use the model with default values. The result will be a source strength estimate for a I-acre broadcast burn on a Douglas-fir/western hemlock clearcut on Federal land, harvested to a minimum diameter of 8 inches. (One acre is not a typical burn size, but it reduces the output to a per-acre basis.) The area will be ignited by hand over a 3-hour period. Fuel loadings per acre are: .2 tons of fine fuel, 5 tons of small branchwood, 23 tons of large fuel, 5 tons of rotten logs, no live fuel, and more than 4 tons of duff. Landing piles will not be burned. No firewood will be removed before burning. Fuel moisture content for large (3- to 9-inch diameter) fuels averages 32 percent, and fuel sticks(1/4- to I-inch diameter) contain less than 12 percent moisture. It has been 15 days since more than 1/2 inch of rain has fallen, so the duff is still moist.

Sample Output

Sample output for the typical broadcast burn, using default values, is shown in figure 3. The matrix of source strength and heat release rate predictions are in a format structured for input to the dispersion model. The summary following the matrix provides information that can be used to compile an emission inventory or be compared with other outputs to evaluate options for emission reduction.

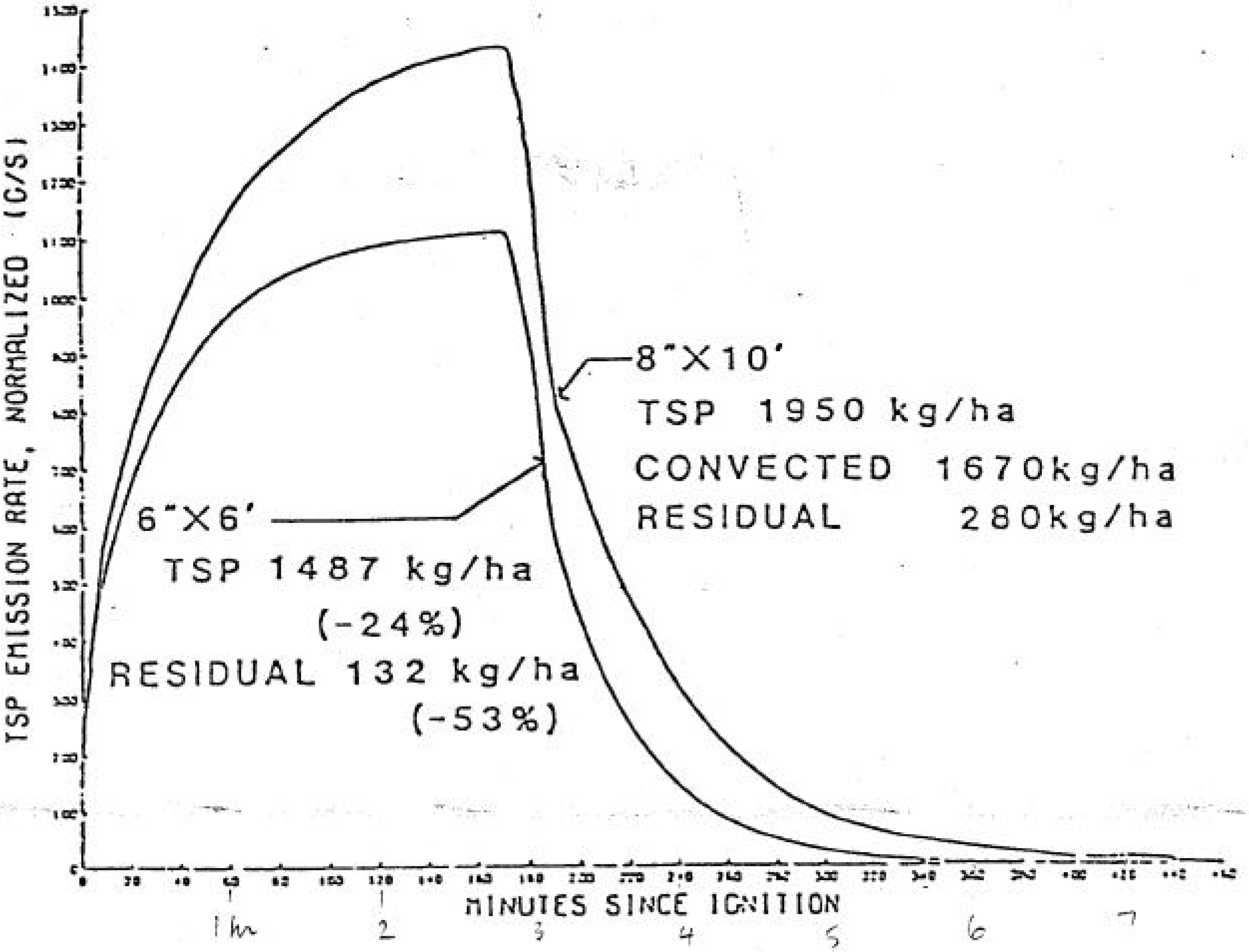
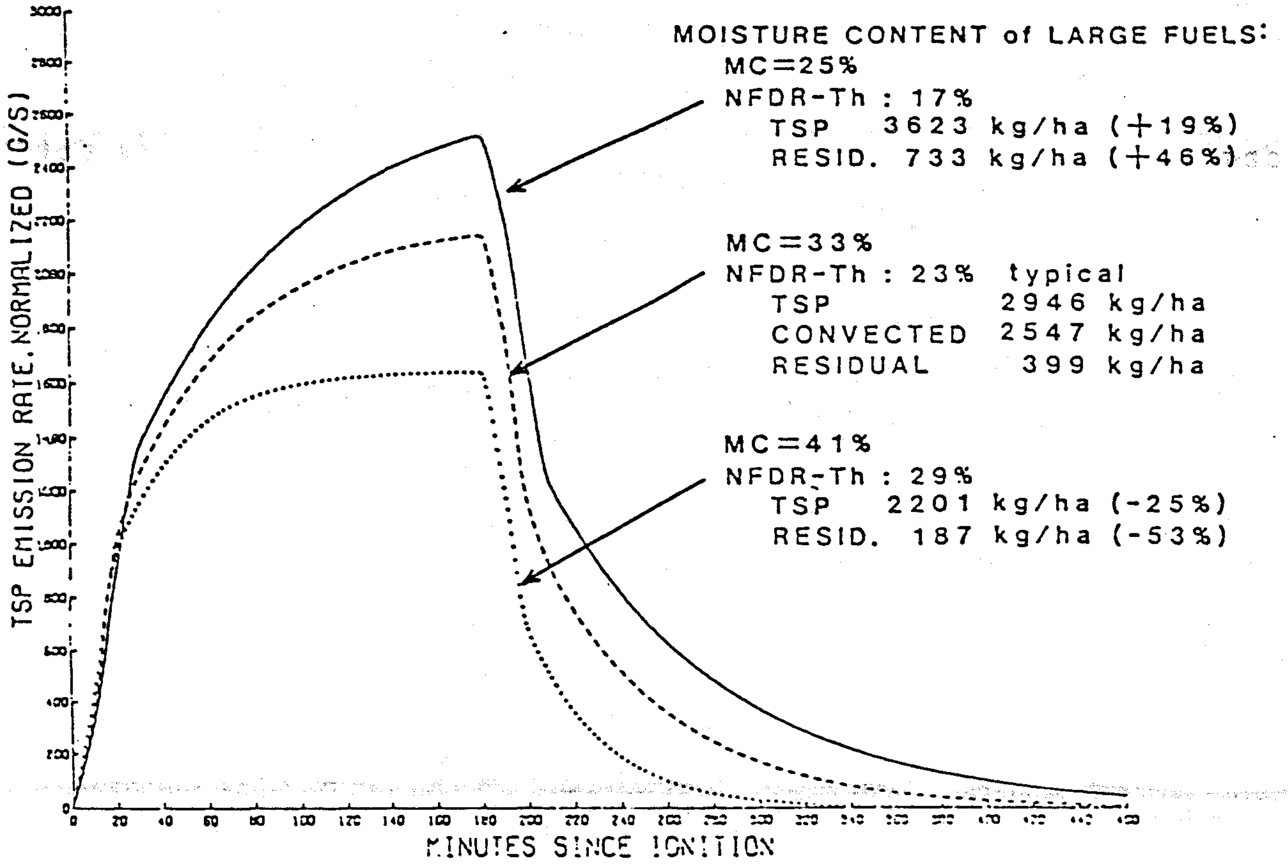


Figure 4. Average total suspended particulate emission rates (TSP) from a series of 8 prescribed-fire demonstrations in the Willamette and Mount Hood National Forests. Pieces on three units were yarded to an 8-inch diameter by 10-foot length minimum size, and pieces on five units to 6 inches by 6 feet. Measured emission rates were normalized to a 20-acre size unit and a 3-hour ignition time to compensate for differences in the size and ignition pattern between units.



MOISTURE CONTENT of LARGE FUELS:
MC=25%
NFDR-Th : 17%
TSP 3623 kg/ha (+19%)
RESID. 733 kg/ha (+46%)

MC=33%
NFDR-Th : 23% typical
TSP 2946 kg/ha
CONVECTED 2547 kg/ha
RESIDUAL 399 kg/ha

MC=41%
NFDR-Th : 29%
TSP 2201 kg/ha (-25%)
RESID. 187 kg/ha (-53%)

Figure 5. Simulated emission rates from prescribed fires in a fuelbed similar to the average of three demonstration units yarded to a minimum piece size of an 8-inch diameter and 10-foot length. Each curve represents the predicted emission rate on a 20-acre unit ignited over a 3-hour period. NFDR-Th is a moisture index value commonly used in fire danger rating (Ottmar, 1983).

Input Requirements

The number and complexity of real (not default) input variables depends on what use will be made of the output. Few input values are needed to compile a daily or an annual emissions inventory. A large random error is acceptable provided that systematic errors can be eliminated. No source strength estimates are required, so the variables that compute EDR, TIGN, and TFLAM are unnecessary. Average (default) values for continuous variables, (for example, fuel loading), are adequate unless the average value is expected to change from one inventory period to the next. Required input values are:

1. Number of acres to be burned;
2. Designation of harvest method (clearcut, partial cut);
3. Land ownership (Forest Service, private, other public) to select default values for fuel loadings; and
4. Fuel moisture content of large fuels (3- to 9-inch diameter), meteorological algorithm that provides fuel moisture values by inference.

5. Date

The FFASR team is examining input options to improve emissions inventory in Washington and Oregon. Additional input values such as species, duff loading, utilization standards, volume of landing piles, and whether mass ignition were achieved would certainly improve the accuracy of an emissions inventory, but it is not clear that the improvement would be worth the extra effort.

The output and rate equations required by the dispersion model used in the screening system require the most inputs in order to meet the accuracy requirements of the daily burn/no burn decision. We envision the dispersion model needing the same inputs as the inventory system, plus:

5. Ignition time, TIGN, for the rate equations and to infer whether mass ignition will occur;

6. Duff thickness (to the nearest inch) if less than 3 inches and
7. Days since rain (greater than 1/2 inch) to, in some cases, predict duff consumption;

8. Number of months, if less than 3 since harvest and
9. Measured (or compared with photographs) loading of large fuels in three size classes to predict fuel consumption and, in some cases, duff consumption;

10. Loading of live fuels (presence or absence of 0-5 tons per acre and whether live fuels are heat source or sink) and
11. Moisture content of fuel sticks (1/4- to 1-inch diameter) and
12. Loading of small (1- to 3-inch diameter) fuels, to predict fuel consumption and to select appropriate emission factors;

13. Volume of landing piles and
14. Whether firewood harvest or secondary utilization will alter the volume or piece size distribution in piles or broadcast fuels

The screening system is being tested on in the Olympic National Forest, Washington, and will soon be using the source strength model for input. An input density somewhere between that for the inventory system and the dispersion model is required for evaluating techniques to reduce emissions. Input requirements will vary according to whether the evaluation is site-specific or applied to a category such as land ownership, species, or elevation. The basic rule is to use default values for the category, then provide actual values for the inputs that can be changed to reduce emissions.

MODELING TECHNIQUES OF EMISSION REDUCTION

Several techniques have been shown to reduce emissions from slash burning (Sandberg, 1983). A series of demonstrations in the Willamette and Mount Hood National Forest in Oregon measured emission rates from 8 units harvested to a variety of utilization standards. Units harvested to a minimum piece diameter of 6 inches end length of 6 feet emitted 24 percent less smoke than those harvested to an 8-inch diameter and 10-foot length, for example (fig. 4). Fuel moisture contents were similar in all units. The results can be extrapolated to other conditions using the source strength model.

The model was used to examine the emission reduction that could have been achieved by rescheduling the burning of the average demonstration unit over a range of moisture conditions (fig. 5). Moisture content for large fuels used as input to the model was allowed to vary from 25 to 41 percent. Average fuel loading for units harvested to 8 inches by TO feet was also input. The model projected total' "suspended particulate ITSP): emissions of 2946 kg/ha (2628 lb/acre) at the mid-range fuel moisture and projected a possible emission reduction of 25 percent by rescheduling when fuel moisture was the highest. Delaying the burn to the driest condition would have increased emissions by 677 kg/ha (604 lb/acre), or 19 percent, according to the simulation.

Modeling more than one emission reduction technique is valuable because the results are not additive. Iterative solution of the model has helped us project trends in emissions and gain a better understanding of the source of emissions. For example, results of an extensive inventory of logging residues (Howard, 7981) are stratified by size class of residues so the end result of yarding to a specified size piece can be calculated. Four fuel loads representing Howard's "current practice" and three yarding levels (8 by 10, 6 by 6, and 4 by 4) (20 cm by 3 m, 15 cm by 2 m, and 10 cm by 1.3 m), and three sets of fuel moisture contents for large fuels (25, 33, and 40 percent) were processed by the model to generate a family of curves similar in format to those in figure 5. Results of those 12 simulations are summarized in figure 6 to project the amount of emission reduction that could be expected by changing from current logging practices to various yarding requirements set for public lands west of the Cascade Range (fig. 6).

Current logging practices yard pieces to a variety of sizes. The most common size is an 8-inch diameter by 10-foot length minimum, but some units are yarded to other specifications. We estimate that removal to 8 inches by 10 feet from all public land units would reduce TSP emissions by as much as 15 percent, or 404 kg/ha (360 lb/acre). If the specification were 4 inches by 4 feet, TSP emissions would be reduced by as much as 48 percent, or 1289 kg/ha (1150 lb/acre).

The effect of extra yarding effort to reduce emissions is greatest if burning is done in early summer, when moisture content of large fuels (3- to 9-inch diameter) are moderate--about 33 percent or when the NFDR-Th[4] index value is near 23 percent. Wetter or drier conditions reduce the effectiveness of the extra yarding effort.

SUMMARY

An interactive source strength model was developed for prescribed fires in coniferous logging slash in western Washington and western Oregon. The model packages research results from 4 years of field experiments by the USDA Forest Service FFASR team in Seattle. The model is necessary for consistent and accurate source strength estimates because the fuelbed and combustion processes are too complex to describe otherwise. Source strength estimates are used to compile daily and annual emission inventories, and to provide inputs to a dispersion model being proposed as an adjunct to the smoke management program in the two States. The source strength model is being used to evaluate several emission reduction techniques, alone and in combination. It is available to forest managers to assist in choosing techniques to reduce emissions in site-specific cases, or to design a mix of techniques to achieve overall emission goals.

The FFASR team hopes to attract funding to expand the capability of the source strength model for use with other timber types--including hardwood slash, brush conversion, eastside mixed conifers, and long-needled pine species. Eventually we hope to extend the model and the concept of emission reduction from prescribed fires to other regions. We welcome the readers' comments and advice regarding this goal.

The authors invite inquiries regarding the source strength model. The model is primarily useful as a research tool at present, but we will make the computerized version available to anyone with need.

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[4] National Fire Danger Rating-1000 hour timelag fuel moisture index value. Defined by Ottmar, 1983.

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