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EMISSION REDUCTION FOR PRESCRIBED BURNING

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Introduction

Prescribed burning is an effective tool widely used in forest management. Several strategies are employed to minimize pollution from prescribed fire, including systems to avoid polluting sensitive areas or to ensure adequate dilution between the source and the receptors. Success in using avoidance and dilution strategies has overshadowed emerging techniques for reducing emissions at the source. In this paper, I will cite examples of research and present some hypotheses regarding the effectiveness of techniques for reducing emissions.

Fire Use

Prescribed burning is used to treat fuels on an estimated 118,300 ha per year in the United States, primarily in the West and Southeast;[1] and its use is not expected to diminish soon. In the West, fire is usually prescribed after timber harvest for silviculture and for preventing wildfire. Use of prescribed fire on industrial forest land has increased by 10% per year in recent years, and most forest managers do not expect a decrease in the next decade.[2] In the South alone, about 81,000 ha per year are burned. Most of the area is beneath a pine overstory where fire is used to remove the fuel supply on the forest floor, so that a wildfire would not spread to the tree crowns. The use of fire for other purposes, such as to return its natural influence on ecosystems or to manage wildlife habitat, is becoming more common in all regions.

About 37 million metric tons of fuel are consumed annually by prescribed fire.[3] Half of this amount is consumed in the western states, where fuel consumption per unit area averages at least an order of magnitude greater than in the South.[4] Prescribed burns contribute 0.62 million metric tons of total suspended particulate matter (TSP), or about 0.5% of the national total. Emissions of hydrocarbons and carbon monoxide are about 2.7% and 2.0% of the national total, respectively.[3] Prescribed fires can be the major source of TSP in timber-producing regions for several weeks each year; for example, the TSP contribution is about 5% of the annual total from all sources in Oregon, but the activity is compressed into a few weeks. Because most of the particles are of submicrometer size, the fine particulate contribution is 13%.[5] A 13% contribution, concentrated in one month, would contribute 64% of total emissions during that month.

Control Strategies

Avoidance. Forest managers, controlling a remote and temporary source of air pollutants, have enjoyed more flexibility than the managers of most industrial sources. Avoidance, dilution, reduction of emissions, and alternative treatments are all ways to manage smoke from prescribed fires. Smoke-management plans in the Pacific Northwest rely heavily on wind direction or atmospheric layering to avoid incursions of smoke into designated smoke-sensitive areas. A team of qualified meteorologists and foresters review burning plans daily to insure that plume trajectories will

not impact urban areas or areas of concentrated recreational use. The program has almost eliminated identifiable incursions and has reduced complaints from citizens, but has not led to appreciable reduction in area burned or mass of pollutants released.[6]

Dilution. A guidebook published by the USDA Forest Service Southern Forest Fire Laboratory (SFFL)[7] improves on the avoidance approach with a quantitative system that screens weather and fuel conditions to ensure dilution of air-pollutant emissions so that they are within the National Ambient Air Quality Standards at a designated area. The dilution strategy is a scheduling process that may or may not reduce emissions. The system calculates an allowable emissions rate which, in turn, constrains the length of line or area of fire per unit time. Application of the guidebook is most useful in the Southeast where terrain is not a factor in dispersion and fuels are reasonably uniform; however, the approach is now being evaluated in several Western States, and it shows promise.

Emission reduction. Reducing emissions will likely become a more important control strategy for reaching new air quality goals. In some areas of the country, avoidance and dilution approaches are already used to their full potential. In those areas, controlling emissions is the only way left to control pollution or to enable expansion of prescribed-fire programs. Particularly where rural air quality or visibility impairment is a problem, the opportunity for avoidance and the advantage of being remote have diminished. The State of Washington is recommending a goal of reducing emissions from prescribed burning by 35% over several years, although the area burned is expected to increase.[8] In Oregon, the Bureau of Land Management is planning to reduce emissions enough to at least offset a planned increase in the area treated by fire.[9]

Qualitative guidelines for reducing emissions from prescribed fires have been published. The Southern Forestry Smoke Management Guidebook[7] listed practices that would minimize production of TSP from forest burning in the South. Sandberg and Ward[10] presented guidelines for reducing emissions from fire prescribed to control vegetation. Performance of managers, however, has seldom been evaluated by considering reduction of emissions, and incentives for the practice have not been offered by the regulatory agencies. Improved forest practices have resulted in considerable improvement in reduction of emissions, but not because of a strategy to reduce them.

Alternative treatments. One way to reduce emissions is to treat fuels and prepare seedbeds using methods other than fire, including the option of no treatment. It was widely assumed a decade ago that alternative methods would have greatly reduced fire use by now. Prescribed fire has become more expensive and more tightly regulated in recent years; yet its use has increased.[6] Forest managers are apparently influenced more by the growing evidence of the benefits from use of fire. Marcus and others[2] conclude that mechanical, checmical, and no-treatment options should not be considered true alternatives to fire because they do not accomplish the same results. We expect the use of alternate methods to continue to offset the effects of increased use of prescribed fire to some extent; but no longer expect an overall decrease in emissions to result from their use.

Methods

Source-Strength Modeling

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Forest fuelbeds are a mixture of components, including recently deposited foliage, or litter; partially decomposed material, or duff; fine live fuels, including grass and light brush; coarse live fuels, including older brush or undesirable trees; small (less than 7.6 cm) woody fuels; and large, woody fuels. The combustion process, too, is complex. Understanding source strength from prescribed fires requires a model more complicated than the steady-state models used for many industrial and transportation sources.

Ward[11] described the structure of three models representing emissions from a point within prescribed fires with different ignition patterns. He pointed out that the emission rate at any time is the product of the fuel consumption rate and an emission factor appropriate to the fuel type and fire behavior at that time. Following the approach first reported by Ryan and McMahon,[12] he divided the combustion process into flaming and smoldering stages which are reasonably distinct and have different emission factors.

A similar approach can be used to describe emissions from the total burn area by integrating the point source model over the area burned (Figure 1).

The source strength of emissions is the sum of the smoldering and the flaming emission rates from all fuels in that combustion stage within the burn area. At time = 0, ignition begins. For a short period, TFLAM (determined by the size and condition of fuel elements), all combustion is in the flaming stage. As ignition continues, until time = TIGN, an increasing proportion of the combustion takes place in the smoldering stage, until no flame remains (time = TIGN+TFLAM). Smoldering combustion continues to emit pollutants, probably at a rate that can be described by an exponential decay constant, TSMOL (also determined by the size and condition of fuel elements), which represents the time it takes for the rate to decay to 1/2 its maximum value.

The first objective of any technique to reduce emissions is to reduce the mass of pollutants, represented by the area under the curve in Figure 1. This could be accomplished by reducing the mass of fuel consumed, by lowering the emission factors, or by creating a fire environment in which a greater proportion of the fuel is consumed in the more efficient flaming stage.

Application of emission-reduction techniques might also achieve secondary air quality objectives. For example, an area within a prescribed fire that is burned rapidly enough to create a strong convection column will loft pollutants in a way analogous to building a tall stack. A greater or lesser portion will be entrained according to the lighting pattern used (especially TIGN) and the smoldering duration (TSMOL). Building a tall stack is an avoidance approach which often complements but sometimes antagonizes the objective of reducing emissions. Most techniques for reducing emissions will also achieve the objective of a dilution approach by reducing the peak emission rate, but sometimes they are counterproductive in that regard.

The source-strength model is useful for breaking down proposed emission-reduction techniques into causative elements. First, the model must be adapted to fit a specific fuel type. Then the influence of each technique in terms of effect on the functional parameters TFLAM, TLIGHT, and

TSMOL; and the mass of emissions from the flaming and smoldering stages can be described. In the remainder of this paper, I will review reports of the effectiveness of techniques for reducing emissions. 83-45

Results

Simple fuelbeds

The simplest fuelbeds are composed solely of pine-needle litter and/or fine, live fuels. These fuels burn with short residence times in the flaming stage (TFLAM) and in a virtually nonexistent smoldering stage, as in Figure 2. In this case, TIGN is the length of time it takes for a line of fire to spread across the burn area. The fires may spread by "heading" with the wind or "backing" into the wind.

Source strength. Typical TSP emission rates range from 30 g s^{-1} for backing fires in grass or pine-litter fuelbeds to 500 g s^{-1} for heading fires in 2-year-old rough palmetto-gallberry. These rates assume an 800-m-long fireline and would be proportionally larger for larger fires. TSP emissions average 17 kg ha^{-1} from grass, 168 kg ha^{-1} from pine-litter and/or light brush, and 84 kg ha^{-1} from young palmetto-gallberry stands.[7]

Emission reduction. Opportunities to reduce emissions from simple fuelbeds include (1) burning techniques which reduce flaming emission factors, and (2) scheduling for meteorological conditions which will result in reduced fuel consumption.

The practice of producing lower emission factors has been refined to a considerable degree through research at the SFFL. Backing fires were found to emit 67% less TSP than did heading fires.[12] Ward and others[13] demonstrated as much as a 50% reduction in emission factors from heading fires by maintaining an optimum (200 to 300 kw m^{-1}) fireline intensity. They also showed that emission factors were lowest when reaction intensity (kw m^{-2}) was highest, regardless of the type of fire. Sandberg[14] found a similar tendency in simple Douglas-fir slash fuelbeds; that is, those that contained only small, woody fuels and foliage.

Meteorological scheduling may also be used to reduce emissions. In pine forests of the South, Southwest, and West, the fuel moisture in litter and duff layers (which dry at the same rate as small fuels) determines the rate of consumption.[15] Depending on the consumption objectives, litter and duff are burned when moisture content ranges from less than 10% to more than 200% on a dry-weight basis. Prediction equations for pine litter in the Southeast[16] reveal that a 40% increase in litter/duff moisture reduces consumption by about 0.22 kg m^{-2}. Assuming no increase in smoldering occurs, that would reduce emissions by approximately 30%.

Complex Fuelbeds

Complex fuelbeds include components which have longer residence times, or are consumed mainly by smoldering. Large (greater than 7.6 cm in diameter) woody fuels, short-needled conifer duff, and coarse brush or weed trees are just a few examples.

Southern rough, such as a palmetto-gallberry understory older than 2 years, is a common complex fuelbed. It has been estimated that 50% of the consumption occurs in the smoldering stage, and that the emission factor during smoldering is 3 to 5 times as great as during flaming.[7] Backing fires were shown to minimize the smoldering stage. Options for reducing emissions for southern rough include the use of backing fires or burning on a shorter rotation; i.e., maintaining a simple fuelbed. Either technique could reduce emissions by more than 50%. 83-45.3

Logging Slash

Nationwide, nearly half the emissions from prescribed fire evolve from logging slash--another complex fuelbed. Figure 1 is typical of western logging slash, where litter and small fuels make up a small fraction of the fuel mass consumed by fire.[4] Roughly 1/2 to 2/3 of the consumption and 3/4 of the emissions occur in the smoldering stage, according to unpublished data. Emission factors are 2 to 2-1/2 times as great during the smoldering stage.[11] Typical TSP emission rates from slash fuels range from 1500 g s^{-1} for pine logging slash[7] or for small (approximately 9 ha.) western units to 15000 g s^{-1} from large (approximately 100 ha.) clearcuts in the Pacific Northwest. TSP production ranges from 800 kg ha^{-1} for pine slash to 2700 kg ha^{-1} for Douglas-fir slash. Although the following values vary greatly from fire to fire, flaming duration is typically 18 to 24 minutes, lighting time 120 to 180 minutes, and TSMOL roughly 80 minutes.

Techniques for reducing emissions from logging slash include increased utilization of residues, scheduling fire to avoid consumption of large fuels and duff, and using burning techniques that limit consumption of fuels or improve the efficiency of combustion.

Increased Utilization. The most attractive technique for reducing emissions from logging slash fuelbeds is increased utilization of large residues. Useful fiber is recovered, and adverse fire effects are mitigated. Burning is done more safely and at lower cost because there are fewer large pieces to extinguish.

The benefits to air quality from increased utilization are great in proportion to the amount of material removed. Duff usually is too moist to burn alone, so it burns only in conjunction with the surface fuels (logging slash). Removing residues reduces consumption of duff by a like amount, so a twofold reduction in fuel consumption occurs.[17,18] Large woody fuels and duff also burn predominantly in the smoldering stage. Emissions are reduced by improving the ratio of the mass of flaming to smoldering emissions. If usable residues comprise 15% of the total fuels, removing them decreases total fuel consumption by 30%. Emissions are reduced by 30% to 50%, depending on the conditions which promote flaming or smoldering combustion. Increased utilization is less effective in very dry periods, when duff will smolder independently of surface fuel combustion.

The USDA Forest Service Pacific Northwest Forest and Range Experiment Station (PNW) is currently evaluating the emission reduction possible by working with logging contractors to remove smaller pieces of residue from Douglas-fir clearcuts. The standard, but by no means universal, practice on federal lands in the Pacific Northwest is to remove material greater than 20 cm in diameter by 3 m long. A demonstration effort, partly reported on

at this conference last year,[19] compared emissions on a standard unit to those on one from which material larger than 16 cm x 2 m and 41 cm x 0.7 m had been removed. The experiment was designed to demonstrate the maximum reduction of emissions possible at that level of utilization. Flaming and smoldering emissions were 29% and 35% lower respectively on the demonstration unit (Figure 3). The smoldering duration (to 1/2 of the maximum emission rate) is thought to have been reduced from 85 minutes to 58 minutes. 83-45.

Sandberg and Ward[20] used a characterization of an "average" clearcut in western Washington and Oregon to project the improvement in air quality that could be made by universally applying various levels of removal. They estimated that removal of material 20 cm x 3 m or larger would reduce TSP by 409 kg ha^{-1}, or 15%, for units burned in midseason (June). Removing material larger than 5 cm x 3 m would reduce TSP by 1800 kg ha^{-1}, or 67%. The technique would be less effective in drier or wetter months.

Prescribing Fuel Conditions. Emissions can also be reduced by careful scheduling of prescribed fire to minimize consumption of large fuels and duff. Forest managers prescribe weather conditions individually for each prescribed burn. Consideration is given to desired fire behavior and the degree of fuel consumption required to meet forest management objectives, as well as to production and dispersion of smoke. Fires that consume small woody fuels with moisture contents in the 8% to 20% range usually achieve those objectives. Although an increase in small-fuel moisture content lowers the combustion efficiency, emissions are not greatly increased. Small, woody fuels comprise only about 20% of a typical slash burn in Western States.[4]

The moisture content of large, woody fuels ranges from about 30% to 45% at the beginning of a burning season and 10% to 20% at the dry end. Each 1% increase in moisture of large fuel decreases fuel consumption by 2% in the Pacific Northwest.[21] Burning when large fuels are moist provides the same out-of-proportion improvement as increased utilization, so emissions are decreased by roughly 3% (based on unpublished data at the PNW). In the extreme case, emissions from slash burning could be reduced by 75% simply by rescheduling burns for periods when large fuels are moist but small fuels are dry. Not all burning can be so drastically rescheduled; but if the average large-fuel moisture were shifted by 5%, an overall 15% reduction in emissions is possible. The major obstacle to seasonal shifting is the already small number of burning days available under current smoke management (avoidance) plans.

Alternative Burning Techniques. The forest manager controls the combustion process to some extent by altering the manner in which fire is applied. The emission factor, the fuel consumed, and the duration of the fire can be manipulated.

It is possible, though yet unproved, that emission factors are reduced in complex fuelbeds when higher fire intensities are achieved. Intense fires are commonly created by mass-igniting the fuels in a logged unit. It is also possible that intense fires lose so much heat to convective heating of the atmosphere that a smaller amount of the large fuel and duff is dried out sufficiently to burn. Mass ignition may reduce emissions by 25%, according to an untested hypothesis by PNW scientists.

Prescribed fires are usually followed by mop-up, a lengthy process of extinguishing flaming pockets of fuels or smoldering duff and logs and applying water to the burning pieces. Mop-up is primarily a fire-control device, but it is occasionally used to control emissions. Roughly 40% of

particulate emissions from slash burns occur after ignition (according to unpublished data at PNW). If the mop-up effort were increased so that TSMOL were reduced by one-third, say from 80 minutes to 53 minutes, total emissions would be reduced by more than 10%.

Discussion

Emission Reduction and Forest Management

There is a growing awareness that many techniques for reducing emissions, instead of impeding forest management, actually enhance forest productivity. The costs of techniques for reducing emissions are seldom justifiable solely on the basis of improving air quality. The challenge is to find techniques that enhance other values so the cost can be shared. For example, the fiber value of forest residues, by definition, is not sufficient to offset the cost of their removal. Certainly, the value of improved air quality is not sufficient. The combined value to both resources, however, should justify some increment of increased residue utilization. Similarly, short-rotation periodic underburning is desirable to provide control of vegetation, release plant nutrients, and minimize overstory damage; but it also has value in reducing smoke from the inefficient combustion of coarse live fuels. Backing fires in fine fuels concentrate the heat near the root collars of weed species; they also produce lower emission factors. More complete mop-up and mass-ignition techniques have reduced the risk of slash-fire escape; they also interrupt smoldering consumption. There is no best universal control technique which can be applied to all situations, but certainly there are more individual opportunities than are now being used.

The ultimate technique for reducing emissions is to select an alternative fuel treatment method, or to not treat fuels at all. Mechanical treatment methods have steadily become more effective, especially as utilization standards improve. Unfortunately, physical limitations and the environmental damage caused by mechanical treatment methods still limit their use to a small percentage of sites. From an environmental standpoint, chemical methods are opposed more strongly than is burning.[10] The no-treatment option simply compromises other objectives of forest management.[2]

Conclusions

Techniques for reducing emissions from prescribed fires have been known for several years but have not been systematically applied. Current research at SFFL and PNW is evaluating the effectiveness of many of the most promising techniques. Scientists at both locations will be concentrating their efforts during the next two years on reducing emissions from the smoldering stage of prescribed fire. Research to date has evaluated only techniques for reducing emissions from single burns, rather than from an overall strategy of reducing emissions. No one knows the answer to the larger questions, "What percentage of burns can be rescheduled to wetter periods?" and "To what degree is increased utilization justified?" Already,

utilization is vastly improved over a decade ago, and burns have been rescheduled as forest management practices improve. No one has evaluated the credit due the forest industry for those measures. These questions, along with an effort to determine the value of clean air and the cost of reducing emissions, would be good topics for future research. Backing fires, high reaction intensities, or burning when litter moisture content is high can reduce emissions from a single burn on simple fuelbeds by 30% to 70%. Backing fires are also effective in some complex understory fuels, especially in the Southeast.

Nationwide, nearly half the emissions from prescribed fire evolve from logging slash. Increased utilization of large, woody fuels could reduce emissions from slash burns by 15% to 67%. Burning when the moisture contents in large fuels and duff are higher could reduce emissions by up to 75% in the extreme case, and 15% on the average. Although not shown by research, mass ignition and increased mop-up effort might reduce emissions by 25% or more.

Using more than one technique to reduce emissions from a given burn does not necessarily produce an additive effect. Meteorological scheduling to minimize smoldering in logging slash, for example, largely negates the value of utilizing fuels that produce smoldering emissions. Scheduling burns in pine-needle fuelbeds for periods when litter moisture content is high may render backfiring impossible.

Every technique I have reviewed for the reduction of emissions requires the flexibility of scheduling burning to maximize effectiveness. Backing fires require moderate winds and very dry fine fuels. Moist large fuels and duff coincide with dry small fuels on a limited number of days per year. Even the effectiveness of increased utilization is marginal during very dry or very wet weather. Smoke management by avoidance (and dilution) eliminates many days that are optimal for reducing emissions.

The results reviewed in this paper indicate that reducing emissions by 35% over the next several years is a realistic goal in the Northwest, and probably elsewhere. In some instances, however, a choice must be made between avoidance, dilution, and emission-reduction approaches. Greater flexibility for meteorological scheduling of prescribed fire would enhance efforts to reduce emissions, but reducing the days available to burn would frustrate them. Forest managers and air resource managers must first agree on the balance of objectives to be met with the three approaches and then begin to incorporate techniques for reducing emissions into their air quality strategies.

NOTE TO EDITORS

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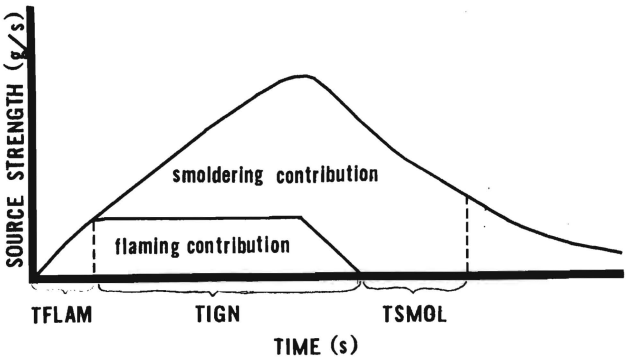

Figure 1. Generalized model of emissions source strength for prescribed fires.

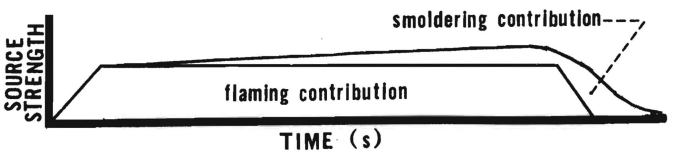

Figure 2. Idealized model of emission source strength for fuelbeds composed solely of litter, fines, and light brush consumed predominantly in the flaming stage.

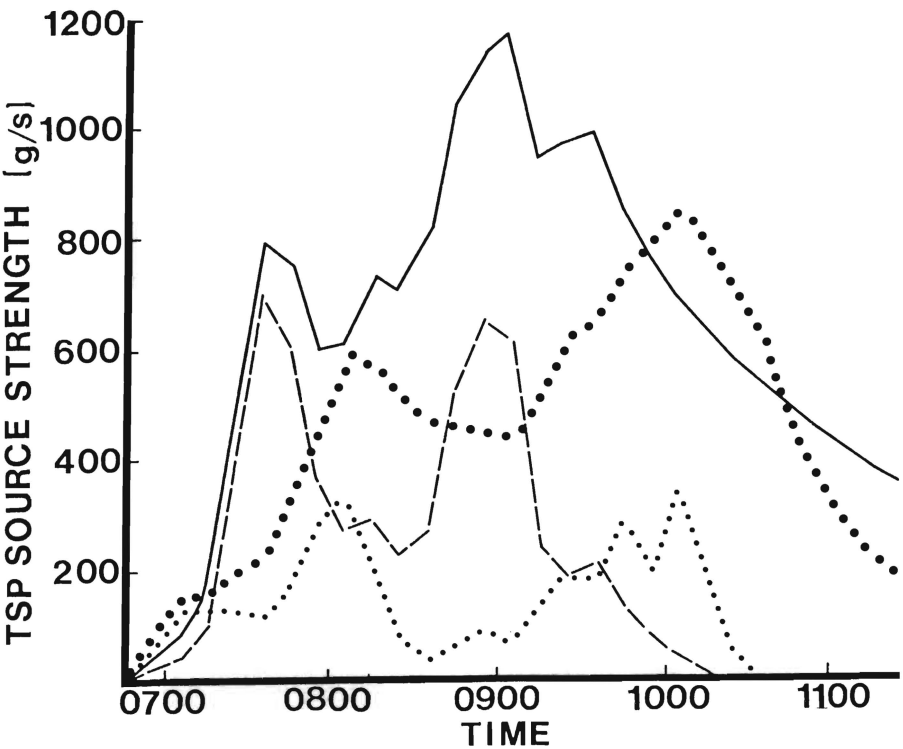

Figure 3. TSP source strength from two prescribed fires in western Oregon logging slash. The solid line represents a standard unit from which woody material larger than 20 cm x 3 m was removed. Emissions from the flaming stage on the same fire are represented by the broken line. The bold dotted lines represent a demonstration unit where material larger than 61 cm x 2 m and 41 cm x 0.7 m was removed. Small dots represent emissions from the flaming stage.