#76-2.2

AN UPDATE ON PARTICULATE EMISSIONS FROM FOREST FIRES

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~~For Presentation~~ Presented at the 69th Annual Meeting of the

Air Pollution Control Association

Portland, Oregon June 27-July 1, 1976

763

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Abstract

Recent estimates of particulate production from forest fires in the United States have ranged from 500,000 to 54,000,000 tons annually. This has been due partly to disparities in estimates of fuel that is consumed during the combustion process, but more to the choice of emission factors used to compute particulate production.

This Paper reviews the published data, and proposes new National estimates for two main categories of fires:

	Emission Factor	Annual Production
	-lb/ton-	-tons-
Wildfires	150	3,500,000
Prescribed fires	50	430,000
Total		3,930,000

The wide range of currently quoted emission factors, between 10 and 200 lb per ton for different fire behavior and fuel characteristics, is discussed. Grouped with the prescribed fire category are both low-intensity fires (used primarily in the South to reduce understory litter) and fires used for disposal of logging debris (slash fires). In addition, estimates summarizing particulate production on a seasonal-regional basis are also presented in order to underscore the need to recognize the cyclic and intermittent nature of the forest burning source.

AN UPDATE ON PARTICULATE EMISSIONS FROM FOREST FIRES

Introduction

The contribution of forest fires to the annual load of particulate matter emitted into the Nation's atmosphere is significant, but the magnitude of this contribution is quite uncertain. Reports of particulate production from forest fires have been from 500,000 to 54,000,000 tons/yr--an exceedingly wide range. One objective of this report is to present data from recent studies to refine National estimates of particulate emissions from forest fires.

Fire behavior, fuel moisture, and fuel arrangement affect emissions from a fuel bed. Heading fires, high fuel moisture, and fuel beds where the elements are tightly packed each cause an increase in emissions. Rather than propose the use of a single emission factor for all burning forest fuel, broad categories of forest burning have been identified and emission factors assigned to each. In addition, the cyclic nature of forest fire emissions by region and season is presented. The emission values proposed are derived from small-scale experiments in a combustion laboratory, as well as field experiments with relatively low-intensity prescribed fires.

Categorizing Forest Burning

Fire in forests of the World has been a naturally occurring phenomenon as a result of lightning long before man's activities made any significant contribution. The extent of these fires was determined by fuel conditions, the wind field, proximity to natural barriers (lakes, rivers, etc.), and the advent of rain.

The type of vegetative cover that developed throughout the country was determined largely by fire frequency and intensity. Examples of fire plant communities are the development of the extensive Douglas-fir stands in the West and the pine areas of the South. These are referred to as fire-climax communities. Without much fire, other species (such as oak-hickory in the South) would have occupied these areas.

Before man constructed improvements in the forest and utilized products therefrom, forest fires could not be considered damaging to property or environment. When forest management was undertaken, fire protection was put into effect and fire as a natural part of the environment became a gradually increasing counter force. Today, we recognize both the need for fire protection and the need for fire, or a true substitute, as a tool in land management. For this reason, there are two general types of fire now occurring in the Nation's forests--wildfire and prescribed fire.

Wildfire

Modern man has considerable economic investment in today's forests. Cost of land preparation and forest regeneration can be high and the investments are long term. He has built homes and other improvements within the forests. When inadvertent fires now occur, whether natural or man caused, they pose an economic threat in millions of dollars to man's property; and are usually extinguished as quickly as possible. They have been responsible for loss of life.

Wildfires can be categorized into two classes, two- and three-dimensional fires. The two-dimensional (relatively low intensity) fires include all flame fronts that back against the wind, those heading fires in which spotting is no problem, and fire intensity is governed by the wind field. The second class, three-dimensional fires, are large, fast-moving fires where depth of the flaming zone can be hundreds of feet, long-distance ignition by firebrands is a major source of fire spread, and the fire energy exceeds that of the wind field. Emissions have been studied only from actual or simulated two-dimensional fires.

Effective fire control and prevention programs have reduced the National (exclusive of Alaska) acreage loss per year from 45 million acres in the early 1930's to less than 4 million acres in the middle 1970's. This reduction represents not only a tremendous saving of property loss but also has significantly improved air quality. Extensive use of prescribed fire has been partly responsible for the decrease in acreage burned by wildfire. However, part of the reduction in particulate emissions from wildfires has been somewhat offset by the emissions from the prescription burns.

Prescribed Fire

Considerable burning in the Nation's forest takes place according to planned decisions made by forest managers. When fire is used in a forest to achieve a planned silvicultural objective, within a defined area, under exacting weather and fuel conditions, the process is called prescription burning--sometimes referred to as managed or controlled burning. Properly planned prescription burns are not a threat to property.

The major uses of prescribed fire are the reduction of hazardous fuel accumulations (a form of fire prevention), wildlife habitat improvement, disease control, and disposal of logging debris (slash) preparatory to forest regeneration. There is increasing interest in prescribing fires in wilderness areas to maintain near-natural conditions.

Recent Estimates on Forest Fire Particulates

Recently, a number of review articles have appeared which cite National or global estimates of forest fire particulates. We have noticed a hundredfold disparity in these estimates and felt compelled to review the source data to try to explain the variation.

Fluctuation in the number of acres burned each year causes some variation in the estimates, but this is certainly not an adequate explanation of the variability shown in Table I.

Table I. Annual forest fire particulate production (tons/yr).

Reference	USA Estimate	Global Estimate
Vandegrift[1]	54×10^6	
Hidy and Brock[2]	15×10^6	150×10^6
AP-73[3]	6.7×10^6	
AP-115 (for 1969)[4]	2.0×10^6	
Robinson and Robbins[5]	0.7×10^6	3×10^6
Yamate[6]	0.5×10^6	

To put these figures in a proper perspective, the estimate of 54×10^6 tons/yr for forest fires alone may be compared to the 27.3×10^6 tons/yr of particulates for all primary sources, including forest fires given by EPA[4] for the year 1969.

All the reports listed in Table I represent comprehensive indepth investigations. Each contains explanatory narrative sections in addition to the summary tables from which we have selected the Table I values. Each made the best use of data available at that time. Unfortunately, data from summary tables are often quoted out of context or cited without carrying forth the associated text. Misunderstanding is the likely result.

Particulates in the atmosphere come from a variety of sources and can possess a very wide variety of physical and chemical characteristics. For the most part, reports which consider particulates within an air quality context usually consider only those particulates that are small enough to remain suspended in the atmosphere for a significant period of time (one or more days). This restriction generally limits considerations to particulates smaller than 5 to 10 microns in diameter. More recently, the term "fine particulates" has been assigned to material smaller than 2 to 3 microns in diameter. These particulates are responsible for most air pollution problems related to visibility, health effects, and atmospheric interactions.

Only recently have definitions of particulate size classes been widely recognized and accepted. Consequently, when reviewing the literature on this subject, one has to carefully examine the definitions and size distribution reported.

In the Vandegrift report, the 54×10^6 tons/yr is subdivided into:

1. Wildfire — 37×10^6 tons/yr
2. Controlled fire
   a. accumulated litter — 11×10^6 tons/yr
   b. slash burning — 6×10^6 tons/yr.

These values can be traced back to a U. S. Forest Service estimate which, as Vandegrift states in his report, "included a sizeable weight of firebrands and other large debris commonly entrained in the convection column of a large wildfire." Furthermore, the estimates were based on indirect inference from gaseous emission data rather than from laboratory or field measurements of particulates. Therefore, we conclude that these estimates should not be used in discussing particulates and air quality.

Hidy and Brock's[2] estimate was based on an assumption that an acre of burning forest produces 2 x 10^{22} particles. This value was combined with U. S. Forest Service data which show 4.2 x 10^6 acres burned by wildfire in 1968. Assumptions were then made that these particles averaged 0.05μm radius or 1.3 x 10^{-16}g, and the United States accounted for 10% of the worldwide forest fires. Thus, this estimate was based more on theoretical considerations than measured emission values.

The estimates in AP-73[3] differ considerably from those in AP-115[4]. Average emission factors (not stated in the reports) were applied to quantities of combustible materials estimated from U.S. Forest Service reports on annual occurrences of wild and prescribed fires. It appears that the major reason for the variance between AP-73 and AP-115 is a reevaluation of available fuel per acre rather than a reevaluation of average emission factors. AP-115's restated figures for 1968 for miscellaneous sources (including forest fires) total only 1.7 x 10^6 tons, whereas AP-73 reported those same miscellaneous sources as producing 7.2 x 10^6 tons in 1968.

The Robinson and Robbins[5] estimate was based on forest wildfire acreage in the United States for 1967 (4.5 x 10^6 acres). Since the United States value was assumed to be 25% of the global fire area, the World total was 18 x 10^6 acres burned annually. Average fuel burned per acre was assumed to be 18 tons. Particulate emissions were assumed to be 17 lb per ton based on the available estimates for particulate emissions from the open burning of landscape and agricultural refuse[7]. Particles larger than 10 microns in diameter were excluded.

The Yamate[6] estimate was based on extensive search for, and evaluation of, available data on forest fire emissions in the United States and its territories. An extensive review of the fuel consumed by fire for the various geographic areas was also presented. However, a single, averaged emission factor of 17 lb/ton was applied to all the data. This estimate was recognized by the authors as "conservative." They also expressed the need to review and update their findings as more information on emission factors by fire and fuel type became available.

It is clear that existing National or global summaries of production rates for forest fire particulates are open to misinterpretation. For various reasons associated with particle size, fuel loading, and emission factors, the figures to date vary by a factor of over 100. We have updated these estimates by applying new knowledge on forest fire emission factors.

Major Updating Emission Factors

An emission factor for particulates from forest fires is defined as the mass of particulates produced when a fire consumes a given amount of forest fuel (usually 1 ton of ovendry weight). With this factor, the total weight of particulate matter introduced into the atmosphere by fire can be predicted if fuel quantity is known. In addition, if the rate of fuel consumption is known, the rate of particulate production can be estimated. This value is generally considered as the emission rate (source strength) for the burning operation.

Prior to 1974, most investigators that reported on forest fire particulate emissions employed an "average" emission factor of 17 lb of particulate for each ton of fuel consumed. This factor was applied to all fire and fuel conditions and was derived principally from several laboratory studies of agricultural(8), (9) and landscape(10) refuse burning. Recent experimental results suggest that these early reports represent low values for most forest fires, especially high-intensity wildfires.

Emission measurements from field burns represent the real world. Unfortunately, such fires are most difficult to measure with accuracy and precision. Determination of emission factors and emission rates from burning fuels in their natural environment is time consuming and costly. Operational difficulties increase as fire intensity increases. Fuel loading, fuel moisture, and other factors that affect particulate production vary considerably in the field. Laboratory procedures that simulate the field burning phenomena have been developed slowly. Such procedures are satisfactory for the rather uniform pine needle fuels found in some forest plantations in the South. They are not satisfactory for live fuel complexes consumed in high-intensity fires.

A variety of techniques have been employed for determining emission factors for forest fire particulates. We are now in a position to begin to evaluate techniques and to arrive at realistic emission factors through what might be termed as convergence of evidence. This convergence of evidence from field and laboratory fires, coupled with basic combustion technology principles, offers the greatest promise for determining accurate emission factors.

Table II shows emission factors found in recent studies. Values given are total suspended particulate (TSP) that are less than 10 microns in diameter. There is growing evidence that well over 90% of forest fire particulates that are transported long distances are less than 2 to 3 microns in diameter(14), (15).

The values shown in Table II clearly illustrate the problem of trying to use a single emission factor for a National estimate. They also strongly suggest that the currently used emission factor of 17 lb/ton is much too conservative for most fires. More realistic emission factors for various types of fires are:

Wildfire	100 to 200 lb/ton
Prescribed fire	
Understory litter (backfires)	25 to 50 lb/ton
Logging debris	28 to 107 lb/ton:

Table II. Examples of current particulate emission factors for forestry fuels.

Fuel Type	Method	Emission Factor[a] (lb/ton)	Reference
1. Logging residue (Western)	Lab	6 - 24	11
2. Logging residue (Western)	Field	28 - 107	11
3. Logging residue (Eastern)	Lab	b	12
4. Live understory fuels (Southern)	Lab	24 - 97	13
5. Live understory fuels (Southern)	Field (backfire)	15 - 30	14
6. Pine needle litter (Southern)	Lab (backfire)	17 - 28	14
7. Pine needle litter (Southern)	Field (backfire)	45 - 55	14
8. Pine needle litter (Southern)	Lab (head fire)	40 - 158	12, 14
9. Pine needle litter (Southern)	Lab (head fire) Flaming Combustion	14 - 50	12
10. Pine needle litter (Southern)	Lab (head fire) Smoldering Combustion	65 - 180	12

a Only particles less than 10 microns in diameter.

b Value to be supplied at time of presentation.

The values for wildfire are simply extrapolations of the laboratory results for the head fires. The values assigned to the understory litter reflect the most current measurements derived from actual field fires(14). The logging debris estimates reflect recent but very limited data. Additional field measurements are needed to refine this estimate.

For a National estimate of forest fire particulates, we suggest the following average values:

Wildfires	150 lb/ton (National estimate)
Prescribed fires	50 lb/ton (National estimate).

The selection of 50 lb/ton for prescribed burning requires some explanation. This value combines the existing data on all types of prescribed burning and is, therefore, only useful when applied to a regional or National scale.

We must emphasize here that we do not recommend the use of these National values in a local situation where specific information on fuel characteristics and fire behavior are readily available. In that situation, we recommend the use of specific emission factors such as recommended in the "Southern Forestry Smoke Management Guidebook"(16).

Effects of Fuel Characteristics and Fire Behavior

Forest fires are different from other types of burning in that the fuel occurs naturally and is consumed in place. All forest fuels are made up principally of cellulose and lignin, although other constituents such as waxes, resins, and oils are present in quantities that depend upon fuel type. The differences between types in fuel quantity, density, and moisture content can be great. Differences in fuel types, both within and between the Nation's regions, strongly suggest the need to look at each region and fuel type separately when estimating fire behavior and emissions.

Since all fuels are seldom consumed in a forest fire, estimating the amount of fuel actually consumed (available fuel) is often difficult. Consider a light fuel complex such as a pine needle litter area in the southern forests. In a prescribed backing fire (advancing slowly against the wind or downslope) only the upper layers of pine needles are consumed, and fuel available for burning may be only 3 tons/acre(17), (18). In that same fuel complex a wildfire, which is most often moving rapidly with the wind or upslope, will often burn more deeply into the lower layers of decomposing needles--as well as into the tree crowns. The fuel now available to a wildfire may be much higher (9 tons/acre on the average)(17), (18). Likewise, with the disposal of logging debris (slash), the amount of fuel consumed will be a function of fuel moisture, fuel arrangement (piled or scattered), and fire behavior. In many broadcast (scattered) slash disposal fires, only the light fuels (needles, leaves, and light twigs) are totally consumed in the fire. Larger branches, etc., are only partially burned (often less than 50% weight loss) and the largest materials (logs, etc.) are often just slightly charred. If the material is piled and dried before burning, much more of it is consumed.

Some general statements about emissions can be made for all fuel types. Dry fuels burn more rapidly than moist fuels under like conditions of weather and emit less particulate per ton of fuel consumed. Drier fuels have been shown to have an emission factor one-half to one-third that of more moist fuel[14], [19]. Likewise, when living plants, with their relatively high moisture contents, are included in the combustion process, the burning reaction is slowed and particulate emissions increase.

The amount of fuel available for combustion per unit area of land also affects the amount of emissions that will be released during the passage of the flaming front, while heavy fuel loadings are only partially consumed. The rest smolders with intermittent glowing and low-flaming combustion until the fire goes out.

Particulate emissions from the smoldering fuel can be a factor of two to ten higher than from the flaming fuel. These results have been reported in studies of grass burning in California[20]. Similar results have also been observed when burning pine needle beds in a combustion room at the Southern Forest Fire Laboratory[12].

Whether a fire moves with the wind (a heading fire) or against it (a backing fire), greatly influences the amount of particulate emissions that will be released. Backing fires, those usually prescribed, move slowly, 1 to 3 ft per min, and most of the fuel (about 90%) is consumed in the flaming zone of the fire. Heading fires spread forward 10 to 30 times faster and frequently less than 50% of the fuel is consumed in the fire's flaming zone. The rest is consumed in a rather inefficient smoldering combustion with considerably higher particulate emissions per unit of fuel consumed. The net effect of heading fires is usually to produce two to three times as much particulate as backing fires in the same fuel[12], [14].

Particulate Production by Region and Season

The most recent fire statistics by state were compiled in 1975[6]. We made three minor additions to the prescribed fire statistics for Arizona, Colorado, and New Mexico. The authors of that report applied an emission factor of 17 lb/ton to all the data.

We applied the new emission factors proposed here to produce new National values: wildfires - 3,500,000 tons/yr and prescribed fires - 430,000 tons/yr, for a total of 3,930,000 tons/yr, as shown in Table III. Totals are displayed for geographic regions in Figure 1. This geographic grouping is now used by the U. S. Forest Service in compiling statistics on forest fires.

Unlike most sources, forest fires produce particulates intermittently rather than continuously. Patterns of production in each region are seasonal (Figure 2), depending upon weather and fuel conditions.

In the northern regions, fires do not occur in winter because heavy snow covers the fuel. During the summer lack of rainfall, high temperatures, and low humidities cause fuel moisture to decline and combustibility to increase. These conditions are reflected in fire occurrence and particulate emissions.

Table III. Acres burned, fuel consumed, and particulate yield by geographic region on an annual basis

States by Region	WILDFIRES Area Burned Acres(6)	Fuel Consumed(6) Tons/Acre	Particulate Yield[a] Tons	PRESCRIBED FIRES Area Burned Acres(6)	Fuel Consumed(6) Tons/Acre	Particulate Yield[b] Tons
PACIFIC REGION						
California	162,070	18	218,794	12,104	70	21,182
Oregon	43,658	60	196,461	26,125	33	21,553
Washington	35,917	61	164,320	66,777	34	56,760
TOTAL	241,645		579,575	105,006		99,495
ROCKY MOUNTAIN REGION						
Arizona	38,051	10	28,538	25,956	8	5,191
Colorado	11,106	30	24,988	2,594	8	519
Idaho	120,892	60	544,014	27,906	65	45,347
Kansas	292,279	3	65,763	0	0	0
Montana	27,102	49	99,600	47,000	45	52,875
Nebraska	88,911	3	20,005	0	0	0
Nevada	24,643	8	14,786	No data avail.**	**	**
New Mexico	26,483	10	19,862	7,136	8	1,427
North Dakota	2,096	3	472	1,998	2	100
South Dakota	15,891	4	4,767	**	**	**
Utah	16,707	8	10,024	Negligible*	*	*
Wyoming	18,538	6	8,342	0	0	0
TOTAL	682,699		841,161	112,590		105,459
NORTH CENTRAL REGION						
Illinois	13,881	11	11,452	*	*	*
Indiana	10,812	11	8,920	0	0	0
Iowa	4,200	6	1,890	0	0	0
Michigan	9,314	11	7,684	3,831	3	287
Minnesota	37,347	11	30,811	**	**	**
Missouri	319,530	5	119,824	**	**	**
Ohio	6,247	11	5,154	0	0	0
Wisconsin	8,322	11	6,866	**	**	**
TOTAL	409,653		192,601	3,831		287
EASTERN REGION						
Connecticut	1,982	7	1,041	0	0	0
Delaware	307	2	46	950	2	48
Maine	3,696	9	2,495	0	0	0
Maryland	2,699	7	1,417	0	0	0
Massachusetts	10,184	11	8,402	0	0	0
New Hampshire	760	8	456	0	0	0
New Jersey	31,325	10	23,494	20,000	3	1,500
New York	7,331	11	6,048	0	0	0
Pennsylvania	15,609	11	12,877	0	0	0
Rhode Island	1,311	7	688	0	0	0
Vermont	366	8	220	0	0	0
West Virginia	82,475	12	74,227	0	0	0
TOTAL	158,045		131,411	20,950		1,548
SOUTHERN REGION						
Alabama	151,150	9	102,026	208,505	3	15,388
Arkansas	139,970	9	94,480	54,736	3	4,105
Florida	703,490	6	316,571	718,877	4	71,888
Georgia	61,123	9	41,258	724,616	3	54,346
Kentucky	75,750	11	62,494	*	*	*
Louisiana	108,107	9	72,972	220,791	3	16,559
Mississippi	116,479	9	78,623	168,890	3	12,667
North Carolina	111,209	9	75,066	117,175	3	8,788
Oklahoma	514,772	3	115,824	**	**	**
South Carolina	64,645	9	43,635	388,704	3	29,153
Tennessee	41,003	9	27,677	**	**	**
Texas	42,482	6	19,117	83,255	3	6,244
Virginia	14,910	5	5,591	30,964	5	3,871
TOTAL	2,145,090		1,055,334	2,716,513		223,009
Total Continental USA	3,637,132	--	2,800,082	2,958,890		429,798
Alaska	783,994	11	646,795	*	*	*
TOTAL USA	4,421,126		3,446,877	2,958,890		429,798

a Based on 150 lb/ton emission factor.
b Based on 50 lb/ton emission factor.

* Negligible.
** No data available.

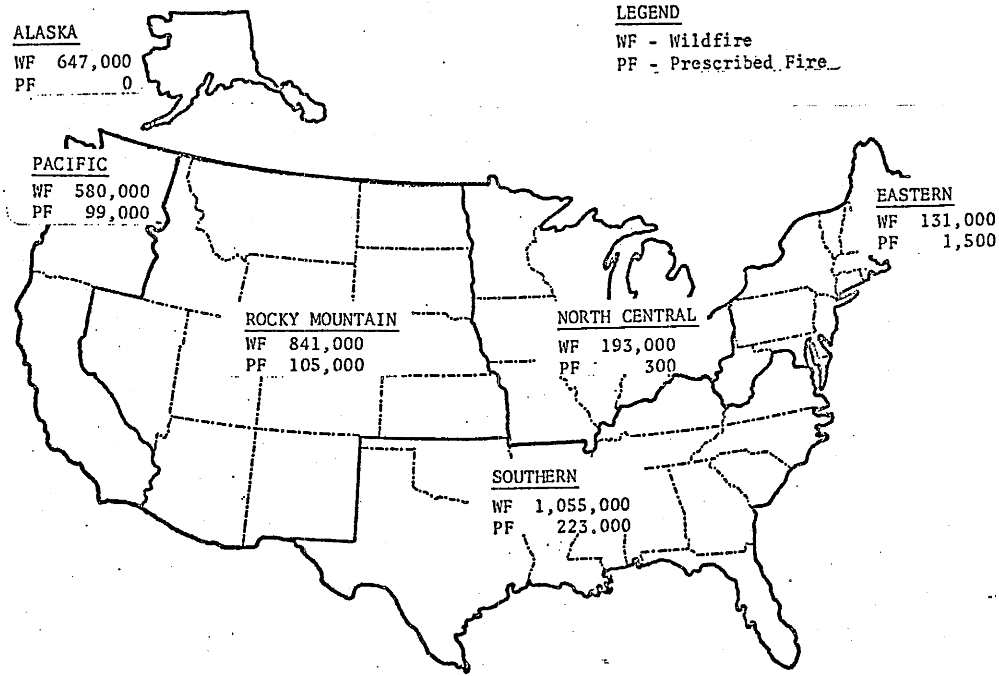

Figure 1. Annual forest fire particulate production by geographic region (tons).

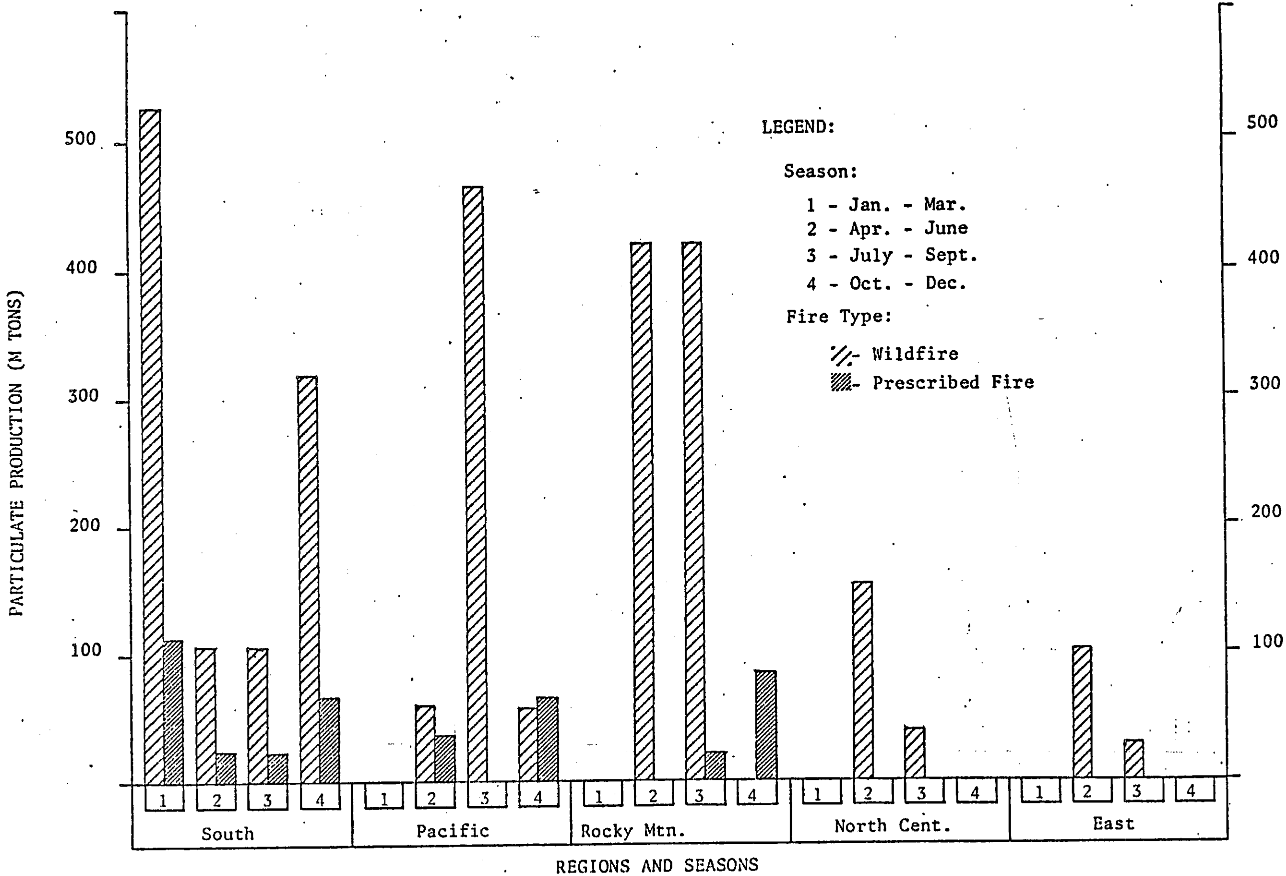

Figure 2. Forest fire particulate production by region and season.

In the Southern Region most forest burning takes place in the Coastal Plain during late fall, winter, and early spring when the fuels are most flammable, winds are most persistent, and relative humidity is the lowest. During this period, most of the aerial portions of the grasses and forbs on the forest floor are dead and become dry. Together with fallen needles from a pine overstory, they form a highly flammable fuel bed. During late spring, summer, and early fall considerable ingrowth of lush, green vegetation and frequent rain lower the fuel combustibility, and the incidence of wildfires.

Conclusions

The recent literature reports on forest fire particulates have been critically reviewed and found to vary by a factor of 100. Estimates range from 0.5×10^6 tons/yr to 54×10^6 tons/yr.

New National emission factors for forest fires have been proposed to replace the currently used value of 17 lb/ton. The new values proposed are as follows:

Wildfires	150 lb/ton of fuel consumed
Prescribed fires	50 lb/ton of fuel consumed.

These emission factors are useful for National estimates only. For a local area and a given fire and fuel situation, the use of more specific emission factors is encouraged.

Annual forest fire particulate production, by geographic region and season, are presented, and total particulate production from forest fires in the United States are estimated to be 3,930,000 tons/yr total.

References

1. A. E. Vandegrift, et al., "Particulate Pollutant System Study. Volume I--Mass Emissions," PB-203-128, Natl. Tech. Inf. Serv., U.S. Dep. Commer., Springfield, VA 22151, 1971.

2. G. M. Hidy and J. R. Brock, "An Assessment of the Global Sources of Tropospheric Aerosols," Pap. ME-26A, Second Int. Clean Air Congr., Washington, DC, Dec. 1970.

3. A. J. Hoffman (ed.), "Nationwide Inventory of Air Pollutant Emissions 1968," AP-73, Div. of Applied Technol., Bur. of Stationary Sources Pollut. Control, Office of Air Programs, Environ. Prot. Agency, Research Triangle Park, NC 27711, 36 p., July 1971.

4. J. H. Cavender, D. S. Kircher, and A. J. Hoffman, "Nationwide Air Pollutant Emission Trends 1940-1970," AP-115, Office of Air and Water Programs, Office of Air Quality Planning and Stand., Environ. Prot. Agency, Research Triangle Park, NC 27711, 52 p., Jan. 1973.

5. E. Robinson and R. C. Robbins, "Emissions, Concentrations, and Fate of Particulate Atmospheric Pollutants," API Pub. No. 4076, Stanford Res. Inst., Menlo Park, CA 94025, 1971.

6. G. Yamate, J. Stockham, W. Vatavuk, and C. Mann, "An Inventory of Emissions from Forest Wildfires, Forest Managed Burns, and Agricultural Burns," Pap. No. 75-36.6 presented at the 68th Annual Meeting of the Air Pollut. Control Assoc., Boston, MA, June 15-20, 1975, 12 p.

7. R. L. Duprey, "Compilation of Air Pollutant Emission Factors," PHS Pub. No. 999, AP-42, Environ. Health Series, Air Pollut., 1968.

8. E. F. Darley, et al., "Contribution of Burning of Agricultural Wastes to Photochemical Air Pollution," J. Air Pollut. Control Assoc. 16: 685-690 (1966).

9. R. W. Boubel, E. F. Darley, and E. A. Schuck, "Emissions from Burning Grass Stubble and Straw," J. Air Pollut. Control Assoc. 19(7): 497-500, (1969)

10. R. W. Gerstle, and D. A. Kemnitz, "Atmospheric Emissions from Open Burning," J. Air Pollut. Control Assoc. 17: 324-327, (1967).

11. D. V. Sandberg, "Measurements of Particulate Emissions from Forest Residues in Open Burning Experiments," Ph.D. Thesis, College of Forest Resour., Univ. of Washington, 1974.

12. United States Department of Agriculture, Forest Service, unpublished data related to emission factors of forestry smoke particulates. Material on file at the Southern For. Fire Lab., Macon, GA.

13. P. W. Ryan, "Quantity and Quality of Smoke Produced by Southern Fuels in Prescribed Burning Operations," Proc. of the Natl. Conf. on Fire and For. Meteorol., Am. Meteorol. Soc. and Soc. of Am. For., Lake Tahoe, CA, April 2-4, 1974.

14. D. E. Ward, et al., "Particulate Source-Strength Determination for Low-Intensity Prescribed Fires," Proc. Spec. Conf. Control Technol. for Agric. Air Pollut., South. Sect. Air Pollut. Control Assoc., Memphis, TN, March 1974.

15. P. W. Ryan and C. K. McMahon, "Some Chemical and Physical Characteristics of Emissions from Forest Fires," Pap. No. 76-2.3 to be presented at 69th Annual Meeting of the Air Pollut. Control Assoc., Portland, OR, June 1976.

16. H. E. Mobley, et al., "Southern Forestry Smoke Management Guidebook," Manuscript in progress and on file at Southern For. Fire Lab., Macon, GA.