Correspondence

Section 11.1 Forest Wildfires

Emission Factors for Forest Wildfires

by

G. Yamate and J. Stockham
IIT Research Institute
10 West 35th Street

and

W. Vatavuk
Environmental Protection Agency
Research Triangle Park, N.C.
27711

Acknowledgement

This study was supported by the U.S. Environmental Protection Agency under contract 68-02-0641. The co-operation of personnel in the U.S. Forest Service and cooperating universities who contributed documents, data, demonstrations, and many valuable hours of discussion is gratefully acknowledged.

ABSTRACT

Emission factors have been developed for estimating atmospheric emissions from forest fires, particularly wildfires. The emission factors cover five pollutants: particulates, hydrocarbons, carbon monoxide, nitrogen oxides, and sulfur oxides. The factors, expressed as pounds of pollutant released to the atmosphere for each acre of forest land burned, were developed using pollutant yield data, pounds of pollutant released per ton of forest fuel consumed, and estimates of the fuel consumed per acre by a wildfire. Fuel consumed estimates were developed from available fuel inventories prepared by regional foresters. Pollutant yield data were obtained from measurements made on laboratory, burning tower, and field experimental and managed fires. Each ton of forest fuel consumed yields 17 lbs of particulates 140 lbs of CO, 24 lbs of hydrocarbons, as methane, and 4 lbs of nitrogen oxides. These yields appear independent of the type of fuel. Sulfur oxide yields are negligible. Emission factors are presented for each of the 9 forest regions, the 5 forest groups, and for the United States. Hawaii is excluded. Emissions from wildfire for the year 1971, the last year for which published wildfires statistics are available, are presented.

TABLE OF CONTENTS

LIST OF TABLES

1. INTRODUCTION

The Office of Air Quality Planning and Standards, Monitoring and Data Analysis Division of the U.S. Environmental Protection Agency (EPA) is responsible for developing and reporting emission factors for both natural and man-made pollutant sources. The objective of this study was to develop improved emission factors for estimating atmospheric emissions from forest fires, especially wildfires. Forest fires produce considerable quantities of pollutants into the atmosphere. In 1970, nationwide estimates[(1)] indicate forest fires account for about 1% of the nitrogen oxides and hydrocarbon emission, 2.7% of the carbon monoxide, and 5.3% of the particulates. Emission trends, Table 1, shows that the emissions have consistently declined over the past 30 years; in 1970, emissions were 14% of the 1940 levels. The reduction in emissions is probably in part due to the highly successful fire prevention programs of the U.S. Forest Service. However, fire in the nation's forest lands is not necessarily all evil; many benefits occur from fire. Included in the benefits are the prolongation of the familiar fire resistant, seral, species we recognize in our forests, hazard reduction through litter removal, and insect and disease control.

The EPA defines the emission factor as a statistical average of the rate at which a pollutant is released to the atmosphere as a result of some activity, such as combustion or industrial production, divided by the level of that activity. The level of activity specified by the EPA for forest wildfires was the number of acres burned, a more convenient activity level indicator in this instance than weight of fuel consumed. The EPA has published a collection of emission factors.[(2,3)]

Table 1

Nationwide Estimates of Emissions
from Forest Fires

Pollutant	Emissions, 10^3 tons per year					
	1940	1950	1960	1968	1969	1970 (1)
sulfur oxides	neg. (2)	neg.	neg.	neg.	neg.	neg.
particulates	5930	2910	1680	1220	1960	835
carbon monoxide	17700	8670	5000	3640	5750	2460
hydrocarbons	1410	693	405	291	460	197
nitrogen oxides	699	343	198	144	230	98

Source: Nationwide Air Pollutant Emission Trends, 1940-1970, U.S. Environmental Protection Agency. Research Triangle Park, N. C. Publ. AP-115, January 1973.

(1) Includes prescribed burning.

(2) Negligible (less than 50,000 tons/year.)

Four elements of information were essential to the objective of this study. These were:

1. Pollutant yields.
2. Fuel consumed.
3. Environmental effects on fire.
4. Wildfire statistics.

Pollutant yields, as a function of forest fuel type, were sought for five pollutants: particulates, hydrocarbons, nitrogen oxides, carbon monoxide, and sulfur oxides. Yields are expressed as the weight of pollutant released to the atmosphere per unit weight of forest fuel consumed. The fuel consumed per acre of burned-over land was needed to develop the emission factors using the expression:

$$(EF)_p = Y_p \times F_c$$

where

$(EF)_p$ = emission factors for pollutant, p, in lbs/acre,

Y_p = yield factor for pollutant, p, in lbs per ton of forest fuel consumed

F_c = the tons of forest fuel consumed by the wildfire per acre of forest.

Fire behavior is influenced substantially by the environment. Information on how terrain, wind, and humidity effect emission was sought. The effect of these variables was to be expressed as adjustments to the emission factors. Finally, statistics of wildfires, particularly the acreage of forest lands consumed by wildfires,were needed to estimate emissions using the expression:

$$E_p = (EF)_p \times A_c$$

where

E_p = the pounds of pollutant, p, emitted to the atmosphere from forest fires

A_c = the acreage of forest land burned-over by forest fires.

Information on each of the above elements was sought in the open literature, sequestered reports, documents with limited distribution, results of on-going experiments and studies, and from discussions with key personnel working in forest fire science and environmental engineering.

2. WILDFIRE STATISTICS

The U.S. Forest Service, Division of Cooperative Forest Fire Control, U.S. Department of Agriculture is the principal source of wildfire statistics. Data are reported for each administrative unit in the Forest Service. The Forest Service is divided into 5 groups, 9 regions, and 8 experimental stations. The geographical boundaries of the regions and stations are shown in Figure 1.

Wildfire statistics for 1971 [4] are summarized in Table 2. In 1971,108,398 fires burned over 4,278,472 acres of forest land. Approximately 46.5% of the fires occurred in the Pacific Group. About 94% of the fires were small; burning less than 100 acres each. Only 0.3% of the fires burned 1000 or more acres apiece. These few large fires, however, consumed about 52.5% of the total acres burned.

3. FOREST FUELS

The determination of fuel consumed in a forest fire was crucial to the task of developing improved emission factors. The Forest Service considers fuel assessment to be of major importance. However, the service is primarily concerned with fire ignition potential, rate of spread, intensity, and containment and not emissions and air quality.

The Rocky Mountain Experiment Station is presently developing the National Fire Danger Rating System (NFDR) [5]. This system uses fuel models to plan fire control activities.

ADMINISTRATIVE REGIONS AND EXPERIMENT STATIONS, U.S. Forest Service

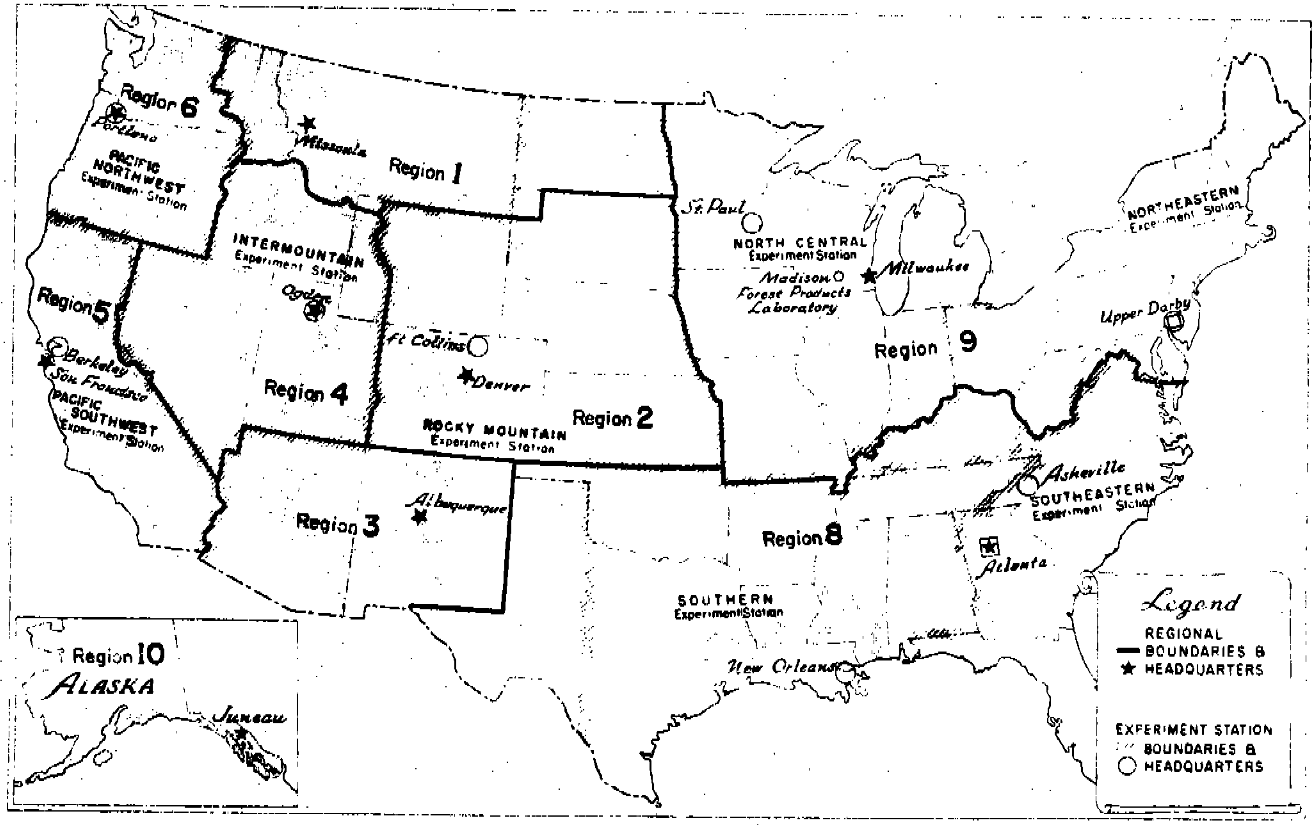

Figure 1

Table 2

Wildfire Statistics, 1971

Forest Group	Rocky Mountain	Pacific	Southern	North Central	Eastern	United States
Forest Region	1. Northern 2. Rocky Mountain 3. Southwestern 4. Intermountain	5. California 6. Pacific Northwest 10. Alaska	8. Southern	9. Eastern	9. Eastern	
Forest area, M acres	454,033	452,167	250,767	90,073	79,162	1,326,202
Percent protected (1)	95	85	96	96	100	92
Number of fires	14,088	9295	60,157	11,832	13,026	108,398
Area burned, acres	774,405	1,162,728	1,992,339	232,749	116,251	4,278,472
Number of Wildfires by size class (2)						
A-0.25 acres and less	7647	7168	7729	2669	5277	30,490
B-0.26 - 9	4191	1556	37886	5572	6626	55,831
C-10 - 99	1237	361	11682	1698	971	15,949
D-100 - 299	215	84	1071	185	106	1,661
E-300 - 999	147	52	318	35	35	587
F-1000 - 4999	74	41	100	7	10	232
G-5000 and more acres	27	33	28	1	1	90
Acres burned by size class (2)						
A-0.25 acres and less	124	56	8	55	155	398
B-0.26 - 9	12414	3527	188,897	15006	13400	233,244
C-10 - 99	39736	13572	342,986	49933	25817	472,044
D-100 - 299	37455	14266	170,123	28904	18124	268,872
E-300 - 999	91741	29014	163,273	18793	16607	319,428
F-1000 - 4999	183,565	97733	194,522	8238	21,148	505,206
G-5000 and more acres	399,445	1,004,560	312,278	9320	21,000	1,746,703

(1) Protected by the Cooperated Fire Control Program, the U.S. Forest Service, Bureau of Land Management, National Park Service Bureau of Indian Affairs, Fish and Wildlife Service, Tennessee Valley Authority.

(2) Protected area only.

The models organize forest fuel information and environmental factors as inputs into nine fire spread models which were first introduced by Rothermel [6]. The fuel models are not based on cover types, but on how much fuel, by classes, is present and how it is arranged. Rather diverse cover types are grouped together because they have similar fuel properties. The fuel loadings for various types of fuels are given in Table 3.

Classifying forests other than by botanical descriptions or geographical demarcations is a relatively recent development. Schroeder [7] divided the country into homogeneous areas based on the combination of fire climate and fuels. Komarek [8] proposed seven lightning, bio-climate regions for North America. The Rand Corporation, [9] while investigating the possible extent of wildland fires that might result from a large scale nuclear attack, reduced wildland vegetation to 15 fuel types. Fahnestock [10] characterized forest fuels using two keys: fire spread potential and crowning potential. Region 6 has a guide for fuel type identification; [11] but, unfortunately, fuel loading estimates are not included.

Deriving fuel consumed figures from fuel loading estimates is not straightforward. A precise definition of the word "fuel loading" is lacking and it has not received consistant usage in fire science. The term has been used to describe forest fuels vastly different in physical and combustion properties. In the NFDR system, concerned with ignition and spreading potential, the smaller sized fuel particles are emphasized. Adding to the confusion, is the fact that wildfires seldom, if ever, consume all the combustible material in the fire path. Light surface fires consumed only the top litter layer brush fires typically consume most of the litter and brush high intensity fires and crown fires burn all litter, fine fuel particles, and the entire organic soil mantle.

Table 3

Fuel Loadings in the National Fire Danger Rating Systems

Fuel Type	Fuel Loading Tons/Acre
Grass, short	3/4
Grass, tall	3
Brush, not chaparral	6
Chaparral	25
Timber, grass and understory	4
Timber, litter	15
Timber, litter and understory	30
Hardwood, litter	15
Logging slash, light	40
Logging slash, medium	120
Logging slash, heavy	200

However, material over 4 inches in diameter is seldom consumed completely. Davis [12] reports about 33% of Ponderosa pine duff was consumed in a prescribed burn in the Coconino National Forest. Fosberg and Davis [13] report that about 2/3 of the chaparral fuels were consumed during a fire behavior study. Kilgore [14] studied a managed burn in a Sequoia-mixed Conifer forest. Before the burn, 50 tons/acre of total litter and duff fuels were measured. After the burn, 7.7 tons/acre remained. There was a 75% reduction in litter fuels and a 85% in duff fuels. Log fuel weights decreased from 12.8 to 2.8 tons/acre (78% reduction). As a first approximation the fuel loadings designated in the NFDR models would be totally consumed in a wildfire. Also, fuel loadings are not constant but vary over time.

In many areas of the United States accumulation rates exceed decomposition rates. Unless removed by fire, forest fuels can accumulate to hazardous levels. Dodge, [15] reports annual accumulation rates of 0.45 to 1.3 tons/acre in the Southern California Chaparral and 0.89 to 2.8 tons/acre in the central Sierra Nevada. Litter from Eucalyptus accumulates in most forests at a rate of 1/2 to 1 ton/acre per year for at least 25 years [16]. Pace [17] measured the litter production under chaparral in center Arizona. He found annual accumulation rates of 1.03 tons/acre on the north slopes and 0.93 tons/acre on the south slopes. Beaufait [18] referring to a study by Bray and Gorham indicates the organic mantle is encriched at a rate of 3 to 4 tons per acre per year in the North Temperate Zone. Weather extremes can greatly effect accumulation rates. The cold 1972-73 winter in the California Bay Area killed and injured 2-3 million Eucalyptus trees and caused litter levels amounting to 50 tons/acre. Only when applied to broad land masses can the fuel loadings be considered constants.

Although fuel assessment is an inexact it presents the best approach toward developing fuel consumption figures. Trained foresters can make reasonable and consistent estimates. A more reliable and periodic fuel inventory should be forthcoming as the Forest Service adopts their nationwide uniform fuel identification system. Eventually, fuel loadings should reflect the breakdown given for acreage burned by states as in the Wildfire Statistics. For the present, regional foresters were requested to supply information on "available fuel" loadings by fuel types for their region. Available fuel was defined as fuel that would be consumed under usual fire conditions that prevail for that fuel type and region during the fire season. The fuel loading values obtained from the regional foresters along with supportive evidence in the literature were combined with acreage figures by fuel type and used to calculate average fuel loading values for each region, Table 4. Information for each forest region is summarized in the following sections.

3.1 Region 1, Northern Region

The Northern region has 16.8 million acres of commercial forest land dominated by pine, western larch and Engelman spruce. One study [19] of logged areas in Western Montana indicates that logging debris, dead and down material, including duff on site before logging ranged from 50 to 150 tons/acre, averaging just over 100 tons/acre. Another study [20] indicates that the total organic matter of Douglas fir slash, non-commercial residue, and duff averaged 64 tons/acres.

3.2 Region 2, Rocky Mountain Region

Table 5 is a broad subjective estimate of fuel loadings by type prepared by Sanderson and Phillips [21]. Based upon the distribution of forest type throughout the 22 million acres of forest land in this region, an average fuel loading of 30 tons/acre is estimated.

Table 4

Estimated Regional Fuel Consumed Values

Group or Region (2)	Estimated Available Fuel (1) tons/acre
Rocky Mountain Group	37
Northern Region 1	60
Rocky Mountain, Region 2	30
Southerwestern, Region 3	10
Intermountain, Region 4	8
Pacific Group	19
California, Region 5	18
Pacific Northwest, Region 6	60
Alaska, Region 10	16
Southern Group	9
Eastern & North Central Groups, Region 9	11

(1) available fuel and fuel consumed are synonymous

(2) there is no Region 7

Table 5

Fuel Loadings, Region 2, Rocky Mountain Region

NFDR Fuel type	Estimated millions of acres	Fuel Loading tons/acre
Unburnable	1.0	-------------
A	2.5	1-3
C	7.8	20-40
G	4.8	50-100
H	5.0	100-150
All others	0.9	5-20

Table 6

Fuel Loadings, Region 3, Southwestern Region

NFDR Fuel Type	Principal Vegetation	Fuel Loading tons/acre
A	grass and herbaceous plants	0.5
A	grass, herbaceous plants and less than 1/3 pinyon pine, juniper ponderosa pine	1
B	Chaparral	20
B	coniferous slash with needles attached	100
C	open ponderosa pine	8
C	ponderosa pine	20
C	pinyon pine or juniper	5
G	spruce	20
H	mixed conifer	50

Table 7

Fuel Loadings, Region 4, Intermountain Region

Principal Vegetation	millions of acres	Fuel Loading tons/acre
Pinyon - juniper	9.3	5.0
Mountain brush (Gambel Oak)	1.0	8.8
Other non-commercial	0.6	5.0
Aspen	1.3	12-20
Fir - spruce	1.0	20
other conifers	1.7	8-20

3.3 Region 3, Southwest Region

The fuel loadings for the Southwest Region, Table 6, were prepared by Hurst [22]. We estimate the average fuel loading for this region at 10 tons/acre. The forest area in Arizona covers 20.6 million acres, Pinyon-juniper and Chaparral cover 12.2 million and 4.4 million acres, respectively. Commercial forests, dominated by Ponderosa pine, occupy 4 million acres; about 1/3 is commercial forest. Ponderosa pine (69%) and Douglas fir (16%) dominate the commercial forest. Of the non-commercial forest land, pinyon-juniper dominates, 89% or 11.2 million acres. The rest is chaparral. The forest floor under Arizona ponderosa pine was measured by Ffolliott [23] at a mean weight of 9.3 tons/acre. Under chaparral the forest floor varied from 4.1 to 12.1 tons/acre [17].

3.4 Region 4, Intermountain Region

Qualitative data on Region 4 fuels are not readily available [24]. The best available estimates are based on Region 3 data, Table 7. An average fuel loading for this region is estimated at 8 tons/acre.

3.5 Region 5, California Region

Region 5 covers the states of California and Hawaii. One-half of California is covered by vegetation: coniferous forest, woodland savanna, chaparral, and grassland. It is estimated that 15-24 million acres of brush, 8 million in chaparral, exist in California. Countryman [25] reported on chaparral fuels in Southern California: Light chaparral fuel contained 12.5 tons/acres of which 49% was duff and litter and 18% living; medium chaparral fuel contained 21.1 tons/acre of which 29% was duff and 46% was living, and heavy chaparral fuel contained 39.4 tons/acre of which 21% was duff and 73% was living. Kilgore [14] found 50 tons/acre of total litter and duff fuel and 12.8 tons/acre of log fuel weights in a sequoia-mixed conifer forest.

In Region 5, the NFDR fuel models do not describe the fuel types accurately, especially in uneven aged timber stands with significant amounts of logging debris. Lundeen [26] provided the fuel loading estimates for this region, Table 8. The NFDR tonnage figures have been adjusted to give a better estimate of the fuel consumed in a wildfire. An average fuel loading of 18 tons/acre is estimated for this region.

3.6 Region 6, Pacific Northwest

Region 6 recently completed a summary of the total acres for each NFDR fuel model found in the region [27]. This data is presented in Table 9. Fuel loading estimates were not available. However, by applying representative values obtained from other sources an average fuel loading of 60 tons/acre appears reasonable for this Region.

3.7 Region 8, Southern Region

The Southern Region is divided into three areas: Plains, Mountain, and Intermediate. A list of fuel types described by the NFDR fuel models was provided by Ruziska [28]. The principal fuel models were: A, C, D, E, and H. In the central hardwoods of Tennessee forest floor litter average 4 tons/acres, about 1/5 of that found in a pine forest [29]. The Region is highly skilled in the use of managed fires as a pine management tool.

Fuel loadings have been measured as part of extensive prescribed burning studies [30, 31, 32, 33]. These managed fires consume about 2 to 4 tons/acre of fuel. Only the brushy fuel and upper litter layer are removed however in these managed fires. We estimate the average fuel loading for the Southern Region at 9 tons/acre.

3.8 Region 9-Eastern Region

Region 9 is unique in that it covers two Forest Groups, the North Central and the Eastern. A broad classification of fuel models used in the Eastern Region National Forest and

Table 8

Fuel Loadings, Region 5, California Region

Fuel Model	Vegetation	Fuel Loading Tons/acre
A	Grass	3
B	Brush	10
C	Open pine timber	
	West side of Sierra Nevadas	40
	East side of Sierra Nevadas	20
D	Young brush	12
G	dense conifers	80
I	logging slash	
	light	30
	medium	35-70
	heavy	80-150

Table 9

Forest Acreage by Fuel Model, Region 6, Pacific Northwest

Fuel Model	Acreage, Millions
A	1.93
B	1.43
C	5.50
D	2.59
E	0.04
F	0.15
G	12.0
H	0.08
I	1.32

their respective fuel loadings is given in Table 10. The information was provided by Heilman (34) who also estimates the fuel loading for the Northeast mixed conifers at 7 to 12 tons/acre and for Northeast mixed hardwood at about 12 tons/acre. The average fuel loading for the region is estimated at 11 tons/acre.

3.9 Region 10, Alaska Region

Region 10's forests are divided into two sub-regions for inventory purpose, Coastal and interior. The Coastal forest of 13.3 million acres is an extension of the rain belt forests of Oregon, Washington, and California. Western hemlock and Sitka spruce account for 96% of the Coastal Forest Area; Douglas fir is not found. The Coastal Forest is well protected from fire by the heavy rainfall. The interior forests cover 106 million acres and are a mixture of white spruce, paper birch, asper, and balsam poplar. The timber stands are similiar to those found in the Great Lake States.

Accurate information on fuel loadings is difficult to obtain because of the remoteness of the forests. We projected the fuel loading estimate (60 tons/acres) from the Pacific Northwest Region to the Coastal Forests and the Great Lakes States estimate (11 tons/acre) to the Interior Forests. Taking into account the forest area for each sub-Region, an average fuel loading for Region 10 is 16 tons/acre.

4. POLLUTANT YIELDS

Pollutant yields from forest wildfires, have not been measured. However, data are available from the burning of forest and agricultural fuels in the laboratory, burning towers, and managed field fires. Experienced fire scientist caution against scaling such data to wildfires. Their doubts require consideration. Wildfire behavior, except for grass and stubble fuels, has not been closely simulated by laboratory or small scale field burns. Experimental studies usually entail an

Table 10

Fuel Loadings, Region 9, Eastern Region

National Forest	NFDR Fuel Model (1)	Fuel Loading tons/acre
Allegheny	H	3.0
Chequamegon	H, C	5.5
Chippewa	C, A	3.75
Clark	E	2.5
Green Mountain	H	3.0
Hiawatha	C, H	5.5
Huron-Manistee	C	2.5
Mark Twain	E	2.5
Monongahela	H, E	5.5
Nicolet	H, C	5.5
Ottawa	H	3.0
Shawnee	E	2.5
Superior	C, H, I	5.5
Wayne-Hoosier	E, C	5.0
White Mountain	H	3.0

(1) first model is the predominant model

artificial selection and arrangement of fuels, and atypical burning conditions. Intuitively, these conditions lead experienced observers to conclude that wildfire emissions are underestimated by such tests. Where burning conditions can be closely simulated, such as grass and stubble, field and laboratory studies correlate quite satisfactorily. Despite the reservations the laboratory and field studies represent the best approximations of pollutant yields available at this time.

Original published data on experimentally measured emissions from burning forest and related fuels are given in Table 11. The reported data is relatively meager and incomplete; no investigator has tested the complete spectrum of emissions of concern to the EPA. Many good review articles are available [35, 36, 37, 38, 39, 40, 41, 42] but most reference the test data in Table 11. Analysis of the measured emissions indicate that they generally vary within one order of magnitude. When one considers the dependence of the measured values on the temperature, residence time, pyrolysis-combustion relationships, and point of sampling the reported values are remarkedly consistent. A rule of thumb for particulate yields is: the total weight of solid particulate matter emitted is 1-2% of the fuel weight. Reactive and non-reactive hydrocarbons have only been categorized for brush and grass fuels [44, 46, 48].

Two investigators, Dr. Ellis Darley at the U. of California, Riverside, and Dr. Robert Cooper at the Southern Forest Fire Laboratory, have ongoing, comprehensive studies to determine the atmospheric emissions from forest fuels. Results from these studies are unreported. During informal discussions at the 13th Tall Timbers Fire Ecology Conference (1973), references were made to the close agreement among the emission measurement made by the Darley and Cooper teams and an Australian research team.

Table 11

Published Pollutant Yields

Geographical Area	Fuel Type	Pollutant Yield, lbs/ton (1) Particulates	HC (2)	CO	NO_2	Reference
California Bay Area	-	24	196	600	-	Feldstein (43)
California Bay Area	Fruit Pruning, 11% MC (3)	-	5.6	46	-	Darley (44)
	Fruit Prunings, 35% MC	-	12.9	66	-	
	Native Brush, 5% MC	-	6.3	65	-	
	Native Brush, 13% MC	-	5.9	55	-	
	Fir Chips, 5% MC	-	3.7	35	-	
	Redwood	-	2.9	70	-	
California San Joaquin Valley	Native Brush, dry	-	6.3	70		Darley (44)
	Native Brush, dry & green	-	20.3	81	-	
	Native Brush, green	-	26.5	134	-	
California	Agricultural & Forest Fuels dry, Range	-	5.3-24	40-140	-	Darley (45)
	Agricultural & Forest Fuels dry, Av.	-	18.7	92	-	
	Grass	16	-	-	-	
	Woody Material	11-17	-	-	-	
Oregon Williamette Valley	Straw and Stubble Residue, Grass, Range	10-17	5.3-25.4	56-147	-	Boubel (46)
	Straw and Stubble Residue, Grass, Av.	15.6	16.4	101	-	
	~~Field stud~~ies on above Av.	15.6	14.1	132.2	-	
Washington	Hemlock, laboratory burn	4.0	3.2	76	-	Fritschen (47)
	Douglas fir, laboratory burn	4.6	4.3	64	-	
	Red Cedar, laboratory burn	4.0	5.9	114	-	
Washington	Landscape refuse	17	65	-	4	Gerstle (48)
Montana	Douglas fir Lumber, Ponderosa Pine Sticks	5.5	-	-	-	Philpot (49)

(1) Sulfur oxide emission are negligible
(2) Total hydrocarbons as methane
(3) moisture content

Table 12

Pollutant Yields from the Burning of Forest Fuels

Pollutant	Pollutant Yield lbs/ton of Fuel
Total particulates	17
Carbon monoxide	140
Total hydrocarbons (as methane)	24
Oxides of Nitrogen (as NO_2)	4
Oxides of Sulfur (as SO_2)	negligible

Average yields for the 5 pollutants are reported in Table 12. Unpublished results and opinions of Darley and Cooper were weighted heavily in arriving at these values. Because of the reservations voiced by fire scientists that results from experimental burns underestimate wildfire emissions yields the higher values were chosen in the range of values reported by Darley.

Table 13

Summary of Emission Factors and Emissions

Forest Unit	Area Consumed by Wildfires 10^3 acres (1)	Fuel Consumed tons/acre (2)	Emission Factors, lbs/acre (3) Particulates	CO	HC	NO_x	Emissions, 10^3 tons (1) Particulates	CO	HC	NO_x
Rocky Mountain Group	774	37	629	5180	888	148	244	2006	344	57
Northern, Region 1	352	60	1020	8400	1440	240	179	1477	253	42
Rocky Mountain, Region 2	163	30	510	4200	720	120	42	342	59	10
Southwestern, Region 3	207	10	170	1400	240	40	18	145	25	4
Intermountain Region 4	53	8	136	1120	192	32	4	30	5	1
Pacific Group	1162	19	323	2660	456	76	188	1544	265	44
California, Region 5	47	18	306	2520	432	72	7	59	10	2
Alaska, Region 10	1047	16	272	2240	384	64	142	1172	201	33
Pacific N. W. Region 6	68	60	1020	8400	1440	240	35	284	49	8
Southern Group, Region 8	1992	9	153	1260	216	36	152	1255	215	36
Region 9	349	11	187	1540	264	44	33	269	46	8
Northcentral Group	233	11	187	1540	264	44	22	179	31	5
Eastern Group	116	11	187	1540	264	44	11	90	15	3
Total United States	4278	17	289	2380	408	68	618	5089	872	145

(1) for the year 1971

(2) see Table 4

(3) uses pollutant yields listed in Table 12

Note: minor errors are due to rounding, SO_2 emissions are negligible.

5. EMISSION FACTORS, EMISSIONS, AND ENVIRONEMTNAL EFFECTS

Emission factors and emissions for each forest group and region for the year 1971 are presented in Table 13. The emission factors were developed using the pollutant yields in Table 12 and the fuel loadings given in Table 4. Because of the variability in fuel loadings,each region and group has an independent emission factor. However, an estimated emission factor for the entire United States is given. The emissions were calculated using the wildfire statistics for 1971 reported in Table 2.

Our extensive literature search did not uncover any reliable data on the effect of environmental variables on emissions. While such variables as wind, humidity and topography, on fire ignition, spread, and containment are well appreciated and documented, their effect on emissions is only qualitative at this time. Some qualitative observations are: the burning of dry fuels produce relatively little smoke compared to burning green fuels, about 1/3 as much; head fires burn dirtier than back fires because flaming combustion predominates over glowing combustion. The literature indicates that the fuel properties are the main factors governing wildfire emissions and environmental factors are secondary. Also, some environmental factors such as humidity and moisture levels are already incorporated into the NFDR fuel models. We conclude that our understanding of how environmental factors affect emissions is insufficient at this time to develop correction or adjustment factors to the emission factors. Their use would only serve to complicate emission calculations without improving their reliability.

Literature Cited

1. Nationwide Air Pollutant Emission Trends, 1940-1970, U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publ. AP-115, January 1973.

2. Compilation of Air Pollution Emission Factors (Revised), U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publ. AP-42, February 1972.

3. Supplement No.1 for Compilation of Air Pollutant Emission Factors, Second Edition, U.S. Environmental Protection Agency, Research Triangle Park, N.C. July 1973.

4. 1971 Wildfire Statistics, USDA, Forest Service, Washington, D.C., 1972.

5. Deeming, J, Lancaster J, Foshberg M, Furman R, and Schroeder M. National Fire Danger Rating System, USDA Forest Service Research Paper RM-84, February 1972.

6. Rothermel R, A Mathematical Model for Predicting Fire Spread in Wildland Fuels, USDA Forest Service Research Paper INT-115, January 1972.

7. Schroeder, M. Synoptic Weather Types Associated with Critical Fire Weather, Pacific Southwest Forest Range Station, 1964.

8. Komarek,E. Lightning and Lightning Fires as Ecological Forces, Tall Timbers Fire Ecology Conference No. 8, 1968.

9. Huschke, R. The Simultaneous Flammability of Wildland Fuels in the United States, The Rand Corporation, Santa Monica, California,1966.

10. Fahnestock, G. Two Keys for Appraising Forest Fire Fuels. USDA Forest Service Research Paper, PNW-99, 1970.

11. Guide for Fuel Identification, U.S. Forest Service, Region 6, 1968.

12. Davis J, Ffolliott,P., Clary W., A Fire Prescription for Consuming Ponderosa Pine Duff. USDA Forest Service Research Note RM-115, 1968.

13. Foshberg M, Davies J. Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colorado. Personal Communication, 1973.

14. Kilgore , B. Impact of Prescribed Burning on a Sequoia-Mixed Conifer Forest, Tall Timbers Fire Ecology Conference, No. 12, 1972.

15. Dodge M. Forest Fuel Accumulation-A Growing Problem, Science, 177, 139, 1972.

16. Mount A., Eucalypt Ecology as Related to Fire, Tall Timbers Fire Ecology Conference, No. 9, 1969

17. Pace, C., Litter Production by Oak-Mountain Mahogany Chaparral in Central Arizona, USDA Forest Service Research Note. RM-214, 1972.

18. Beaufait, W., Fire and Smoke in Montana Forests. Forest Land Use and Environment, Montana Forest and Conservation Experiment Station, School of Forestry, U. of Montana, Missoula, Montana, 1971.

19. Beaufait, W. Scheduling Prescribed Fires to Alter Smoke Production and Dispersion. Prescribed Burning and Management of Air Quality Seminar, Southwest Interagency Fire Council, Tucson, Arizona, 1968.

20. Steele R., Beaufait W. Spring and Autumn Broadcast Burning of Interior Douglas-Fir Slash, Bulletin 36, Montana. Forest and Conservation Experiment Station, School of Forestry, U. of Montana, Missoula, Montana, 1969.

21. Sanderson J. Phillips D. USDA Forest Service, Denver, Colorado. Personal Communications, 1973.

22. Hurst W. USDA Forest Service, Albuquerque, New Mexico. Personal Communication, 1973.

23. Ffolloitt,P., Clary W, Davis, J., Some Characteristics of the Forest Floor Under Ponderosa Pine in Arizona, USDA Forest Service Research Note, RM-127, 1968.

24. McBride R, USDA Forest Service, Ogden, Utah, Personal Communication, 1973.

25. Countryman C. Mass Fires and Fire Behavior, USDA Forest Service Research Paper, PSW-19, 1964.

26. Lundeen C. USDA Forest Service, San Francisco, California. Personal Communication, 1973.

27. Wilson K, Beal C. USDA Forest Service, Portland, Oregon, Personal Communication, 1973.

28. Ruziska, W. USDA Forest Service, Atlanta, Georgia. Personal Communication, 1973.

29. Thor, E. and G. M. Nichols. Some Effects of Fire on Litter, Soil and Hardwood Regeneration in Middle Tennessee. Talk Presented at the 13th Tall Timbers Fire Ecology Conference, Tallahassee, Florida, 1973.

30. Cooper, Robert W., 1971. The Pros and Cons of Prescribed Burning in the South. Forest Farmer 31 (2) 10-12, 39-40, 1971.

31. Sackett, Stephen S. and D. D. Wade. Prescribed Burning at Night. Forest Farmer 29 (5) 11, 18, 1970.

32. Wade, Dale D., Research on Logging Slash Disposal by Fire. Tall Timbers Fire Ecology Conference No. 9, 229-234, 1969.

33. Fahnestock, George R. and W. K. Key,. Weight of Brushy Forest Fire Fuels from Photographs, Forest Science 17 (1) 119-124, 1971.

34. Edward G. Heilman; Personal Communication. Region 9, U.S. Forest Service, Milwaukee, Wisconsin 53203, 1973.

35. Dieterich, John H. Prescribed Burning and Air Quality. 29th Annual Forestry Symposium, Southern Pine Management-Today and Tomorrow. Crow A. Bigler, editor, Louisiana State University, Baton Rouge, La., 168 pp. 1971.

36. Hall, J. Alfred,. Forest Fuels, Prescribed Fire, and Quality. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 44 pp, 1972.

37. Murphy, J. L., L. J. Fritschen, and O. P. Cramer. Research Looks at Air Quality and Forest Burning. J. of Forestry 68 (9), 530-535, 1970.

38. Komarek, E. V., Sr. Controlled Burning and Air Pollution: An Ecological Review. Tall Timbers Fire Ecology Conference No. 10, 141-173, 1970.

39. Ward, D. E. and R. C. Lamb,. Prescribed Burning and Air Quality-Current Research in the South. Tall Timbers Fire Ecology Conference, No. 10, 129-140.

40. Burckle , J. O. and J. A. Dorsey,. Air Pollution and Open Burning in Forestry Operations. Joint Meeting of the Southern Fire Chiefs and I&E Chiefs, Houston, Texas 14 pp.

41. Southwest Interagency Fire Council,. Prescribed Burning and Management of Air Quality - A Seminar, Tucson, Arizona, 81 pp.

42. Robinson, E. and R. C. Robbins,. Emissions, Concentrations, and Fate of Gaseous Atmospheric Pollutants. Air Pollution Control, Part II, edited by W. Strauss, Wiley-Interscience, (1-93), 1968.

43. Feldstein, M., S. Duckworth, H. C. Wohlers, and B. Linsky,. The Contribution of the Open Burning of Land Clearing Debris to Air Pollution. J. of Air Pollution Control Association 13 (11) 542-545, 564, 1963.

44. Darley, E. F., F. R. Burleson, E. H. Mateer, J. T. Middleton, and V. P. Osterli. Contribution of Burning of Agricultural Wastes to Photochemical Air Pollution. J. of Air Pollut. Contr. Assn. 16, 685-690, 1966.

45. Darley, E. F., H. H. Biswell, G. Miller, and J. Goss. Air Pollution from Forest and Agricultural Burning. Presented at the Spring Meeting, Western States Section/ The combustion Institute, Seattle, Washington, 10 pp, 1972.

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

47. Fritschen, L., H. Bovee, K. Buettner, R. Charlson, L. Monteith, S. Pickford, J. Murphy, and E. F. Darley. Slash Fire Atmospheric Pollution. USDA Forest Service Research Paper PNW-97, 42 pp, 1970.

48. Gerstle, R. W. and D. A. Kemnitz. Atmospheric Emissions from Open Burning. J. of Air Pollution Control Assn. 17, 324-327, 1967.

49. Philpot, C. W., C. W. George, A. D. Blakely, G. M. Johnson, and W. H. Wallace, Jr. The Effect fo Two Flame Retardants on Particulate and Residue Production. U. S. Forest Service Research Paper INT-117, 1972.