Development of Emissions Inventory Methods for Wildland Fire

Final Report

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Contents

Page

Contents (continued)

Page

Figures

Page

Tables

Page

Tables

Page

List of Acronyms

EIIP	Emission Inventory Improvement Project (sponsored by the U.S. EPA)
FCC	Fuel Characteristic Class (developed by the FERA)
FEJF	Fire Emissions Joint Forum (part of the WRAP)
FEP	Fire Emissions Project (part of the GCVTC)
FERA	Fire and Environmental Research Applications Group (in the Forest Services Pacific Northwest region)
FMI	Fire Modeling Institute (part of the U.S. Forest Service)
GCVTC	Grand Canyon Visibility Transport Commission
NEI	National Emissions Inventory (developed by the U.S. EPA)
NFDRS	National Fire Danger Rating System
SIP	State Implementation Plan
WESTAR	Western States Air Resources Council
WFIG	Wildland Fire Issues Group (part of the GCVTC)
WRAP	Western Regional Air Partnership

1. Introduction

Wildland fires are important sources of airborne fine particulate matter ($PM_{2.5}$)* emissions in the western United States. These fires include wildfires and prescribed fires in forests and rangelands. Fires release $PM_{2.5}$ directly to the atmosphere, and also produce gaseous pollutants that can react in the atmosphere to form secondary $PM_{2.5}$. These precursor pollutants include nitrogen oxides (NO_X), volatile organic compounds (VOC), and ammonia (NH_3). Small amounts of sulfur dioxide (SO_2) are also released.

Emissions from fires contribute to elevated ambient concentrations of $PM_{2.5}$, and impairment of visibility. Section 169A of the Clean Air Act establishes a national goal to improve and protect visibility in mandatory Class I Federal areas where visibility is an important value.** Section 169A also calls for regulations to ensure "reasonable progress" toward the national visibility goal.

EPA has been working with the Western Regional Air Partnership (WRAP) to develop strategies for minimizing adverse environmental impacts of prescribed burning. The WRAP was formed to implement the recommendations of the Grand Canyon Visibility Transport Commission (GCVTC).[1] The GCVTC was mandated by Congress through Section 169B of the CAA to conduct research to identify and evaluate sources and source regions of both visibility impairment and regions that provide predominantly clean air to Class I areas on the Colorado Plateau. The WRAP is a coalition of state air pollution control agencies, tribal representatives, federal agencies, and other stakeholders (industry and public interest groups). The WRAP is composed of standing committees, forums, work groups, and boards. One of the ten WRAP forums is the Fire Emissions Joint Forum (FEJF). The FEJF was formed to address the GCVTC report's recommendations for fire emissions and visibility.

Effective planning of prescribed burns will require improved emissions data bases and models to analyze the impacts of burning. In addition, improved wildfire emissions estimates are needed in order to estimate ambient $PM_{2.5}$ impacts. Improved emissions databases and methodologies must address two distinct needs: (1) development of baseline inventories (1999 and 1996) for model evaluation, and (2) development of future year projections and inventory updates for years when detailed data are not available.

Emissions estimates for wildland fire emissions are needed as part of State Implementation Plan (SIP) particulate matter emissions inventories, and to evaluate the impact of

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* $PM_{2.5}$ is the portion of particulate matter smaller than 2.5 microns aerodynamic diameter.

** Areas designated as mandatory Class I Federal areas include national parks exceeding 6000 acres, wilderness areas and national memorial parks exceeding 5000 acres, and all international parks in existence as of August 7, 1977. Visibility has been identified as an important value in 156 of these areas.

proposed increases in prescribed burning. Inventories will also be useful for internal program review, demonstrating conformity, and assessing relative impacts of wildfire and prescribed fire. The purpose of this document is to provide background information to state and tribal air pollution agencies developing inventories of wildland fire emissions. The document describes the tools and databases available for developing for estimating emissions for wildland fire, and the choices available for different levels of spatial and temporal resolution. In addition, the report details recent test data on criteria pollutant and hazardous air pollutant (HAP) emissions. This report is not intended to provide guidance on mechanisms for tracking trends in fire emissions.

1.1 Previous Large-scale Fire Emissions Inventories

Previous large-scale fire emissions inventories can provide a framework for on-going emissions inventory development. A number of recent fire emissions inventory efforts were reviewed in order to identify potential methodologies for future inventories (see Table 1). The first of these efforts was an inventory of prescribed fire emissions prepared in 1993 by the Forest Service (Peterson and Ward) for the EPA.[2,3] This inventory addressed historic emissions in 1989.

Table 1. Summary of Previous Emissions Inventories for Wildland Fire

Inventory	Sponsoring Agency	Types of Fires	Year of Emissions	Coverage
Peterson and Ward (1993)	U.S. Forest Service for the U.S. EPA	Prescribed	1989	National
GCVTC (mid 1990's)	GCVTC	Wildfires	1986 - 1992	10 western states
FEP	GCVTC	Prescribed	1990, 1995, 2015 and 2040	10 western states
FMI	WESTAR	Wildfires		11 western states
NEI	EPA	Wildfires and prescribed	1985 - 1995	National - Uses Peterson & Ward for prescribed fires, GCVTC for wildfires in the western states, independent estimates for wildfires in the east.

In the mid 1990s, the GCVTC developed a comprehensive emissions inventory for ten western states, including separate inventories for wildfire and prescribed fire. The GCVTC wildfire inventory covered the period 1986 through 1992.[4] For prescribed fires, the initial GCVTC inventory was based on Peterson and Ward's 1989 estimates. The GCVTC also initiated a Fire Emission Project (FEP) to investigate strategies for managing emissions from prescribed fire.[5] Under the FEP, prescribed fire emissions inventories were developed for 1990 and 1995, and also for expected conditions in 2015 and 2040.

In 1998, the Forest Service's Fire Modeling Institute (FMI) used data and methods developed in the FEP, along with additional data, to estimate the wildfire emissions in the western states.[6] This project was sponsored by the Western States Air Resources Council (WESTAR).

Emissions from wild and prescribed fires are also included in EPA's National Emissions Inventory (NEI). NEI emissions estimates for prescribed fires are based largely on the Peterson and Ward inventory. For wildfires, the NEI draws heavily on the GCVTC inventory for the western states. Independent estimates are developed in the NEI for wildfires in the east.

1.2 Calculation of Emissions from Fire

Figure 1 summarizes the steps required to evaluate emissions from a fire. First, information is needed on the fuel consumption, which is dependent upon the land area burned, the amount of fuel materials per unit area (pre-burn fuel loading), and the characteristics and condition of the fuel. In the context of wildfire and prescribed fire, the term "fuel" refers to the materials typically burned. Ideally, this is restricted to downed trees, fallen branches, decaying leaves and needles (duff), and small trees and shrubs. The amount of fuel actually burned in a fire will depend on fuel loading and condition, the type of fuel, climactic and meteorological factors, and the intensity of the fire. Various empirical models have been developed to estimate fuel consumption. (These will be discussed in Section 3.)

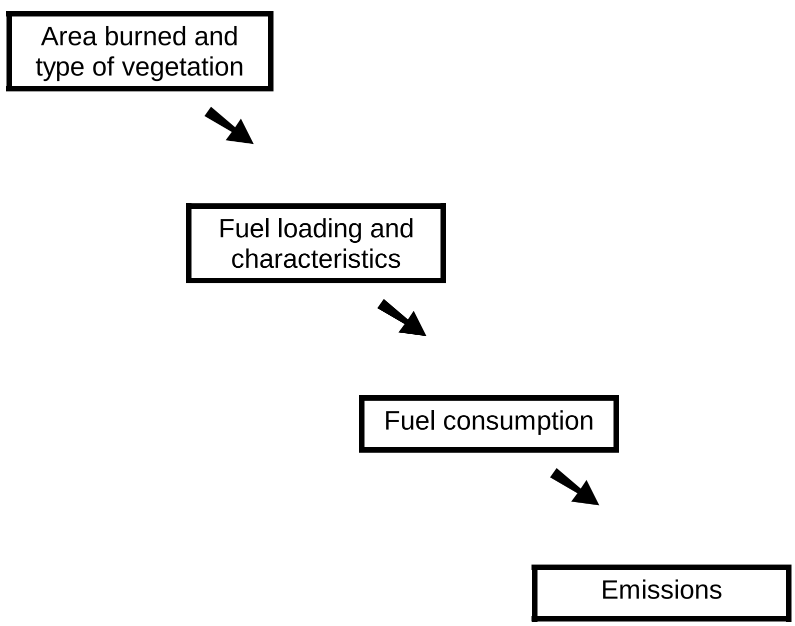

Figure 1. Steps Required to Evaluate Fire Emissions

Once the fuel consumption has been determined, measured emission factors can be applied in order to compute air pollutant emissions. However, these emission factors are also dependent on fire conditions. In particular, empirical measurements have shown that emissions of some pollutants are much higher under smoldering conditions than under flaming conditions. Fuel consumption models generally include empirical factors for predicting the relative amounts of smoldering and flaming for various fuel and fire conditions.

The overall methodology for computing emissions from fire can be summarized as follows:

$$\text{Total fuel consumption (Mg)} = \text{Area burned (acres)} \times \text{Fuel consumption per unit area (mass/acre)} \qquad (1)$$

$$\text{Fuel consumption per unit area} = \sum_i \left(\text{Mass of fuel type i per area} \times \text{Fraction burned for fuel type i} \right) \qquad (2)$$

$$\text{Emissions (kg)} = \text{Total fuel consumption (Mg)} \times \text{Emission factor (kg/Mg)} \qquad (3)$$

where: Emission factors depend on the relative prevalence of smoldering and flaming combustion, which is a function of the type of fuel and other factors.

Measures taken to mitigate emissions from prescribed fires can impact the fuel consumption in equation 2, or decrease the amount of smoldering, thereby reducing the emission factor in equation 3. (See Appendix A.)

These calculations can be made on a fire-by-fire basis, or for a collection of fires occurring in a given season or year. In large scale emissions inventories, emissions are often calculated on an annual basis. These emissions may then be allocated to seasons or other timeframes for the purposes of estimating ambient air pollution impacts. It must be noted, however, that presctibed fire and wildfire have different seasonal patterns. Therefore, seasonal allocation methodologies must take into account these differences.

1.3 Available Methodologies for Estimating Fire Emissions

A number of different options are available to develop each of the inputs needed to calculate wildland fire emissions. Table 3 summarizes potential sources of emissions inputs for wildfires. The table lists options available to estimate area burned, vegetative cover, fuel loading and characteristics, fuel consumption, emission factors, factors that may mitigate emissions, and the temporal distribution of emissions. Table 2 provides a similar list for prescribed fires. For each parameter, the options are listed in order of increasing level of detail, from left to right. For instance, at the lowest level of detail, the acreage burned can be determined from Forest Service and Department of Interior summary reports on annual fire activity (at the state or regional level). More detailed estimates can be obtained using fire incident data bases, satellite data, and individual fire incident reports.

Table 4 summarizes options that have been used in previous large scale emissions inventories. The table also shows the level of detail that can be obtained using data from EPA's Compilation of Emission Factors (AP-42). For national and regional inventories, AP-42 is typically used to calculate emissions from source categories that have not reported their emissions.

The remaining chapters of this report discuss options available for determining: (1) the area burned and vegetative cover, (2) pre-burn fuel loading and characteristics, (3) fuel consumption, (4) emission factors, and (6) temporal distribution of emissions. In each case, we identify available options and discuss their strengths and weaknesses. We also discuss the methodologies used in previous large scale inventories, and identify questions and potential issues for future inventories. The final section discusses the overall structure of large scale emissions inventories for fire. Appendix A provides information on available emission control measures.

Table 2. Options for Obtaining the Inputs Needed for Wildfire Emissions Inventories

Parameter	➔ ➔ ➔ ➔		**Increasing level of detail and accuracy**		➔ ➔	➔ ➔
Area burned	DOI and FS summary reports		Federal and state incident databases	Federal and state incident databases with auditing and quality assurance	Satellite data with auditing and quality assurance	Ground-truthing with land surveys, aerial surveys, etc.
Vegetative cover	Regional defaults	Estimates from existing inventories		Satellite data	Survey land managers	Ground-truthing with land surveys, aerial surveys, etc.
Fuel loading and characteristics	General estimate	Land manager determination of NFDRS fuel classes	Land manager determination of fuel type, with emission model defaults	Fuel characteristics classification system		
Fuel consumption	Regional defaults		Fuel consumption models with dry fuel assumption	Fuel consumption models with crown adjustment		Models with input from land managers and crown adjustment
Emission factors	General defaults	Regional defaults	Separate factors for flaming and smoldering	Emission models or correlation with CO or CE	Emission models with input from land managers	Vegetation-specific emission data
Temporal distribution of emissions	Default seasonal and/or hourly profiles	Allocation using actual seasonal fire frequencies		Fire-specific emission calculations		Fire-specific hourly modeling

Table 3. Options for Obtaining the Inputs Needed for Prescribed Fire Emissions Inventories

Parameter	➔ ➔ ➔ ➔ Increasing level of detail and accuracy ➔ ➔ ➔ ➔					
Area burned	Previous inventory estimates	State incident databases	State incident databases with auditing and quality assurance	Survey land managers for different ownership categories	Satellite data with auditing and quality assurance	Ground-truthing with land surveys, aerial surveys, etc.
Vegetative cover	Regional defaults	Estimates from existing inventories		Satellite data	Survey land managers	Ground-truthing with land surveys, aerial surveys, etc.
Fuel loading and characteristics	General estimate	Land manager determination of NFDRS fuel classes	Land manager determination of fuel type, with emission model defaults	Fuel characteristics classification system	Photo-series correlation	Transect measurements
Fuel consumption	Regional defaults		Vegetation-specific defaults	Fuel consumption models with default inputs		Models with input from land managers
Emission factors	General defaults	Regional defaults	Separate factors for flaming and smoldering	Emission models or correlation with CO or CE	Emission models with input from land managers	Vegetation-specific emission data
Impact of mitigation measures	Default emission factors for activity fuels	Account for activity fuels in fuel consumption modeling		Account for impacts of fuel moisture		Situation-specific emission data
Temporal distribution of emissions	Default seasonal and/or hourly profiles	Allocation using actual seasonal fire frequencies		Fire-specific emission calculations		Fire-specific hourly modeling

Table 4. Summary of Options Used in Previous Large Scale Inventories and Inputs Available in EPA's AP-42

Parameter	Options used in previous large scale fire emissions inventories					Factors available in EPA's AP-42	
	Peterson and Ward prescribed fire inventory	GCVTC wildfire inventory	FEP prescribed fire inventory	FMI wildfire projections	NEI prescribed fire and wildfire	Prescribed	Wildfire
Area burned	Survey of land managers	Survey of land managers	Federal and State databases	Projections from Federal and State databases	Previous inventories, DOI and FS reports	na	Previous estimates
Vegetative cover	Survey of land managers	Survey of land managers	Survey of land managers	Survey of land managers	Carried from previous inventories	Regional default	Regional default
Fuel loading and characteristics	NFDRS classes	Classification by land managers	Classification by land managers	Classification by land managers	"	na	Regional default
Fuel consumption	Expert judgement	Consume model	Consume model	Consume model	"	na	Regional default
Emission factors	Consume model factors	Consume model factors	Consume model factors	Consume model factors	"	Forest-type defaults (a)	General factor
Factors mitigating emissions	"	Separate factors for activity fuels	na	na	"	Separate factors for activity fuels	na
Temporal distribution	Annual	Allocation using actual seasonal fire frequencies	Allocation using actual seasonal fire frequencies	Allocation using actual seasonal fire frequencies	na	na	na

(a) AP-42 factors for prescribed fire take into account variations in average combustion efficiency among different forest types.

2. Area Burned and Type of Vegetation

The area burned is one of the more difficult parameters to determine in developing an inventory of wildland fire. In many states, data are only available for wildfires on Federal land. Double counting can occur in fire reports where a fire moves from land management jurisdiction to another, or where two fires burn together and are renamed. In addition, the area reported for a given fire generally reflects the total area within the fire's perimeter. In most cases, not all of the area within the perimeter of a wildfire is actually burned. (For instance, studies of fires in Yellowstone National Park indicated that only two thirds of the area within the fire perimeter was burned.[7])

In prescribed fires, managers often report the *planned* area of a burn, which may be much larger than the actual accomplished size. In addition, there may be ambiguity between the "area treated" and the area burned. A large watershed may be considered to be "treated" by a prescribed fire that covers only a fraction of the watershed's total area.

Reported fire locations and types of vegetation are also subject to considerable uncertainty. Typically, the fire location is reported at the date of detection or of breakout. This location probably will not reflect the center of the fire. The type of vegetation reported at the outset of the fire also may not be representative of the bulk of vegetation burned. The reported coordinates must also be checked for accuracy. For instance, in the GCVTC wildfire inventory, about 12% of the geographic locations obtained from existing fire databases proved to be invalid.[4]

2.1 Available Databases and Tools

2.1.1 Area Burned in Wildfire

Table 5 summarizes options for estimating the area burned in wildfires. The options are listed in order of increasing level of detail, from left to right. The table also lists advantages and disadvantages or potential issues associated with each option. For state-level or regional calculations, the National Interagency Fire Center (NIFC) compiles state and regional summaries of the acreage burned in wildfires.[8, 9] In previous years, the Department of Interior (DOI) and Forest Service have produced annual reports of state level fire activity. (As discussed in the following section, these have been used in the NEI to estimate emissions for some states.)

For more detailed inventories, the Forest Service and DOI maintain extensive databases of wildfire incidents on federal lands.[10,11,12] Many states also maintain databases of wildfire incidents on state and private lands. The fire incident databases contain information on the location, acreage burned, start date, and duration of each fire. Although the databases provide a good source of information on historic fire activity, the data for any given fire is not based on rigorous measurements. As noted above, the databases double-count many fires, and reported locations are often erroneous. Therefore, auditing and quality assurance of these databases is

Table 5. Options for Estimating the Area Burned in Wildfires

	Increasing level of detail and accuracy				
Option	DOI and FS summary reports (State level)	Federal and state incident databases	Federal and state incident databases with auditing and quality assurance	Satellite data with auditing and quality assurance	Ground-truthing with land surveys, aerial surveys, etc.
Advantages	Easy to use for general calculations	Good spatial and temporal detail	Improved accuracy	Superior spatial and temporal detail Good accuracy is expected	Best accuracy
Disadvantages	Lack of spatial and temporal detail	Incomplete coverage Double counting Reported area typically exceeds blackened area Errors in location data	Analyzing reports is resource intensive	Processing of satellite data is resource intensive Processed data sets are not yet available	Resource intensive

Table 6. Options for Estimating the Area Burned in Prescribed Fires

	Increasing level of detail and accuracy					
Option	Previous inventory estimates	State incident databases	State incident databases with auditing and quality assurance	Survey land managers for different ownership categories	Satellite data with auditing and quality assurance	Ground-truthing with land surveys, aerial surveys, etc.
Advantages	Easy to use for general calculations	Good spatial and temporal detail	Improved accuracy	Good accuracy is expected	Superior spatial and temporal detail Good accuracy is expected	Best accuracy
Disadvantages	Lack of spatial and temporal detail	Not always available Errors in location data Reported area may overstate burned area	Analyzing reports is resource intensive	Considerable effort required	Resource intensive Processed data sets are not yet available	Resource intensive

required. The perimeter-areas reported in the databases should also be adjusted to reflect the actual areas burned. This work could be focused on larger fires, but would still be very labor intensive. In addition, the fire reports specify the location of the fire start or breakout, and not the center or shape of the fire.

Work is underway to map fire incidence using remote sensing data and Geographic Information Systems (GIS). The resulting databases are expected to provide more temporal and spatial resolution than fire incident reports, since they will map the movement of individual fires as they spread and as previously-burned areas are extinguished. In one project, California fires are being mapped by Center for the Assessment and Monitoring of Forest and Environmental Resources (CAMFER) at the University of California in Berkeley.[13] The goal of this project is to produce day-specific databases of fire location, covering the period 1985 through 2000. In a second project, CAMFER is collaborating with the Forest Service Fire Sciences Laboratory to prepare a broader database covering all of North America.[14] It must be noted that many wildfires are confined largely to the forest floor and understory, so their areas may be difficult to ascertain from satellite photos. Improved accuracy can be obtained from aerial surveys and ground surveys.

For future projection inventories, acreage burned in wildfires can be estimated either using averages based on the historical fire incident databases, or using estimates of ecological fire frequencies (as will be discussed in the following subsection). The Forest Service has also been working on integrating remote sensing data and biophysical data in order to estimate historical fire frequencies.[15]

2.1.2 Area Burned in Prescribed Fire

Table 6 summarizes options for estimating the area burned in prescribed fires. Peterson and Ward estimated state-level emissions for prescribed burning in 1989. Prescribed fire emissions were also estimated in the FEP for 10 western states. (See the following section on *Previoous Inventories*.) These estimates can provide a starting point for emissions inventories in some states where prescribed fire data are not available.

Many states maintain databases of prescribed fires on state and private lands. For instance, California has developed the Prescribed Fire Incident Reporting System (PFIRS), which tracks prescribed burns by federal, state, and local agencies. In 1998, the DOI expanded its fire incident database to cover prescribed fire in addition to wildfire. As noted above, there is a need to discriminate between the acreage “treated” by prescribed fire and the acreage burned. In addition, there is a need to discriminate between the planned size of a prescribed burn and the actual area burned. Therefore, the acreage reported in fire databases should be assessed by land manager where possible. Databases should be analyzed by land area classification, ownership category, and reason for burning.

The satellite databases discussed in the previous section on wildfires can also be used to provide data on the area burned in prescribed fires. However, the same caveat applies concerning the ability of satellites to see through the canopy to the forest floor, where most burning occurs in a prescribed fire. Improved accuracy can be obtained from aerial surveys and ground surveys.

2.1.3 Type of Vegetation

Table 7 summarizes options for estimating the vegetative cover on the burned land, and lists advantages and disadvantages for each option. The least labor intensive method would be to use regional defaults for vegetative cover. Another option would involve drawing on information developed in previous inventories. This approach is used in the NEI for the Grand Canyon states (see following section).

A number of data bases are available which identify the vegetative cover using remote sensing data. The Forest Service has recently developed coarse-scale spatial data on current vegetative cover for the contiguous United States.[16, 17] The CAMFER and NIFC fire mapping projects for California and North America will also link observed fires to land cover databases using GIS. It must be noted that the satellite land cover databases focus mainly on the forest canopy, while most of the burned material is on the forest floor. In addition, any inaccuracies in fire location will propagate to the selection of vegetative cover when fire locations are matched to satellite databases. Therefore, accuracy can be improved by supplementing use of satellite with analysis by land managers. Improved accuracy can also be obtained from ground surveys and aerial surveys.

2.2 Previous Inventories

For their 1989 inventory, Peterson and Ward surveyed federal agencies, local air quality managers, local forestry organizations, and private forestry agencies to obtain estimates of the acreage treated by prescribed fire. This effort ultimately produced an inventory of prescribed fire emissions at the state level.[2, 3]

The FEP included another survey of land managers, which greatly expanded on the Peterson and Ward survey for the western states.[4] This survey used a much finer spatial resolution than the 1989 inventory. First, a 50x50 km grid was overlaid onto the GCVTC domain. Within each grid cell, the land was further subdivided by land ownership, vegetative cover, and state (for those grid cells falling on state boundaries). In addition to information on prescribed fire, land managers were then asked to characterize ecological fire frequencies for each parcel. This survey is summarized in Table 8. Prescribed fire activity was estimated for 1990, 1995, 2015, and 2040 in ten western states: Arizona, California, Colorado, Idaho, Nevada, Oregon, New Mexico, Utah, Washington, and Wyoming.

The GCVTC also produced detailed inventories for wildfire over the period from 1986 through 1993 in the above states and Montana. The acreage burned in wildfire was determined from databases maintained by federal and state land management agencies. The FMI/WESTAR project computed probabilities of wildfire based on an average of historical fire data from 1986 through 1996. These calculations are summarized in Table 9.[6]

Table 7. Options for Determining the Vegetative Cover in Wildland Fires

	➡ ➡ **Increasing level of detail and accuracy** ➡ ➡				
Option	Regional defaults	Estimates from existing inventories	Satellite data	Survey land managers	Ground-truthing with land surveys, aerial surveys, etc.
Advantages	Least labor intensive	Least resource intensive	Data are available for climax vegetation at resolutions to 1 km	More accurate	Most accurate
Disadvantages	Least accurate	Accuracy and detail is limited by previous inventories Vegetative cover may change from previous inventories	Categories may not match fuel classifications Satellite land cover data do not focus on the understory, where most fuel lies Vegetation at the reported fire location may not be representative of the bulk of the fire	More resource intensive	Resource intensive

Table 8. Summary of FEP Surveys to Estimate the Area Burned in Prescribed Fires

Initial classification of lands by location, ownership, and vegetation cover as shown below.			
Land classification and information source	Available categories		
Geographical location	50x50 km grids		
Ownership	USFS, BLM, FWS, NPS, BIA, other Federal, State/private/other		
Vegetation cover types (from AVHRR* data)	Agriculture Alpine tundra Annual grass Aspen/hardwood Barren Chaparral	Cottonwood/willow/ riparian Desert shrub Douglas-fir Lodgepole pine Mixed conifer Oakbrush	Spruce/fir Perennial grass Pinyon/juniper Ponderosa pine Sage Water
Field Query 1: Land allocation and extent of mechanical treatment. Land managers surveyed for each land area classification (LAC) - specified by grid cell, owner, and vegetation type and reason for burning			
Land allocation	Congressionally reserved, Administratively withdrawn, riparian reserves, "matrix" (denoting mixed activities such as logging, grazing, etc.), and undefined)		
Mechanical treatment	0 - not available for mechanical treatment 1 - 1-50% available 2 - 50-100% available		
Field Query 2: Land managers asked to characterize ecological fire frequency.			
Frequency	High, medium, and low estimates were given in years		
Seasonality	Percent of land (within each category and grid cell) burned in each season		
Intensity	Ground fire or stand replacement		
Field Query 3: Managers estimated fuel loading for each type of vegetative cover, and each land ownership and allocation category.			
"Natural" systems	High loading - areas subject to prolonged fire exclusion, or where a natural disturbance such as insects or wind had increased the fuel loading Medium loading Low loading - areas recently burned, either in wildfires or prescribed fires		
Activity-generated fuels	High, medium, or low fuel loading, as estimated by the cognizant land manager		
Field Query 4: Current and projected amounts of prescribed fire and management treatment			
Prescribed fire treatment types	Prescribed fire initial entry (PF_1) Prescribed fire maintenance (PF_M) Prescribed natural fire (PNF) Prescribed fire broadcast (PF_B) Prescribed fire piles (PF_P) Mechanical treatment		
End result:	characterization of prescribed fire activity and ecological wildfire frequencies, specific to each 50x50km grid square, and to each combination of land ownership, land allocation, and vegetation cover type within each grid square.		

* AVHRR = advanced very high resolution radiometry.

Table 9. Summary of Methods Used in the FMI/WESTAR Emissions Inventory to Estimate the Area Burned in Wildfire

1)	Used data on fire locations and dates from USFS, DOI and States for 1986 through 1996	
2)	Categorized fires by size and season	
	Size	0.25-15 acres ("10-acre" fire)[a]
		16-75 (50 acre)
		76-330 (200 acre)
		331-1750 (1000 acre)
		1750-12,500 (10,000 acre)
		12,501-37,500 (25,000 acre)
		>37,501 (50,000) acre
	Season	Spring (March thru May)
		Fall (September thru November
3)	Computed the probability of a small fire ("10-acre" fire)	
	By vegetation type and climactic region (4^{th} level Hydrological Unit Code [HUC])	
4)	Computed the probability of a 10-acre fire spreading to the 50-acre category, 50-acre fire spreading to the 200-acre category, and so on.	
	By "wildfire zone" (grouping of 4^{th} code HUC zones into larger climactic regions)	

[a]Fires are grouped into size ranges, in acres, and each size range is designated by a round number within the range. Hence, fires in the range of 0.25-15 acres are designated as "10-acre" fires.

EPA's NEI uses the GCVTC estimates of wildfire emissions for the western states during the period 1986 through 1993. For the western states in other years, emissions in the NEI were computed by applying adjustment factors based on the change in total acreage burned. These factors were developed from U.S. Department of Agriculture statistics and applied at the state level. Acreage burned in states not covered by the GCVTC was obtained from DOI and Forest Service reports.[18, 19, 20, 21] It should be noted that the Fire Emissions Joint Forum of the WRAP found gross errors in these databases for burning in 1996. The NEI uses Peterson and Ward's 1989 estimates for prescribed fire emissions and assumes these emissions are constant for other years.

2.3 Questions and Issues for Future Inventories

A White Paper on SIP inventory development by Sandberg and Peterson envisions a tiered approach with varying levels of precision, depending on the situation in the local area.[22] The NEI database, with its periodic updates of state data, may provide a workable framework for storing regional and national fire inventories. EPA maintains a national inventory at the county level, using default activity and emission factor data where necessary. States can provide more detailed updates for various categories of emissions.

As noted in Section 1, improved fire emissions data are needed for benchmark inventories (such as 1999 and 1996), for updates that would deal with interim years, and for future year projections (such as 2015 and 2040). The following is a summary of issues related to the estimation of acreage burned and land cover type for each of these inventory types.

General

- What additional guidance is needed, beyond the Sandberg and Peterson SIP inventory paper[22] for the development of state and local fire emissions inventories?

- What level of accuracy is needed?

- What data should be collected in the future?

- How should inventories incorporate land area classification, ownership category, and reason for burning?

- How should inventories incorporate natural burning vs. anthropogenic burning?

For benchmark inventories:

- How will the benchmark inventories be incorporated into the NEI or other regional inventories?

- Are entirely new inventories needed for 1996 and 1999, or can parts of the GCVTC, FEP, or FMI/WESTAR databases be used as foundations for the new inventories?

- Could a new 1996 or 1999 regional inventory incorporate a size cutoff, focusing on fires greater than the cutoff (1,000 acres or 10,000 acres, for instance)? If a size cutoff is used, should smaller fires be neglected or projected from earlier inventories (GCVTC, or the NEI database in the eastern U.S.)? (Note that there would be a mechanism for incorporating a more detailed local inventory into the broader regional database.) What would be an acceptable cutoff?

- The NEI point source emissions database contains fields for location (latitude and longitude) and seasonal distribution of emissions. Would these data be adequate for regional modeling, or would additional data be needed: for instance the area covered by the fire, and more information on temporal resolution (monthly, weekly, diurnal)? Could state-level or national "defaults" be used to provide this additional temporal detail?

For interim updates:

- Could interim year inventories be projected using a methodology similar to the NEI (based on state-level fire activity)?

For projection year inventories:

- Should future projections of wildfire be based on historical averages of actual incidents, or ecological fire frequencies?

- Should future projections of prescribed fires be based on historical averages or land managers plans for fires?

3. Fuel Loadings and Characteristics

Fuel materials typically include downed trees, fallen branches, decayed matter on the forest floor (duff), and small trees and shrubs. Tree crowns (branchwood and foliage) can also be burned in wildfires and prescribed fires. The fuel consumption in a fire will depend not only on the total pre-burn fuel loading, but also on the relative amounts of the different fuel types, and on the fuel condition. In prescribed fire, fuel loading and characteristics will be strongly affected by the type of burn (pile fire, windrows, understory burning, concentration burning) and by preburn harvesting. Therefore, inventories should differentiate among different types of burn.

3.1 Available Methods and Tools

Table 10 summarizes the methods available to estimate fuel loadings and characteristics, and lists advantages and disadvantages associated with each method. The most accurate method is to measure the fuel loading. The Forest Service has developed guidelines for measuring the amount of fuel materials.[23, 24, 25] The line intersect method has been used to develop information on fuel loading and characteristics in advance of a prescribed burn. In this method, a surveyor walks a line through the forest, measuring each downed log that is intersected, and gathering information on other debris and fuel material on the forest floor. Piles are measured, and samples of brush may be clipped and weighed. Unfortunately, these methods are very resource intensive for a regional scale inventory. In addition, they must be used before the fire occurs.

The Fire and Environmental Research Applications Group (FERA), in the Forest Services' Pacific Northwest region, has spearheaded development of a collection of photo-series documents to assist in characterizing fuel loads for various types of forests and grasslands. For each forest type, a series of stereo photos has been compiled to represent the range of fuel conditions. A detailed characterization of fuel materials is provided for each stereo photograph. Thus, a land manager can compare a given forest, or other ecosystem to a series of photographs of a similar ecosystem. Once the best match is found, fuel characteristics can be estimated based on the data provided with the selected photograph. Table 11 lists photo series' that are currently available. Photo series reports covering additional forest types were generated in the 1980s, however, the availability of these reports is limited. The Fuel Management Analyst program, developed by Fire Program Solutions, LLC, provides electronic access to the photo series books.[26] Additional photo series reports for the Southeast, the Rockies, and the Southwest are scheduled to become available later this year.

FERA is also developing a Fuel Characteristic Class (FCC) system, which could be used in tandem with the photo series system to determine fuel loadings and other parameters necessary to estimate emissions. As the system is envisioned, an FCC code for a given forest or other ecosystem would be determined based on photo series interpretations or other available information. The FCC system would then provide a linkage to fuel loadings and other parameters necessary to run fire emission models. Preliminary versions of the FCC have been used by FERA in the Pacific Northwest, and also in the GCVTC Fire Emissions Project. A national FCC system is expected to be completed in 2003.

Table 10. Options for Determining Pre-burn Fuel Loading

	→ → → → **Increasing level of detail and accuracy** → → → →					
Option	General estimate or regional defaults	Land manager determination of NFDRS fuel classes	Land manager determination of fuel type, with emission model defaults	Fuel characteristics classification system	Photo-series correlation (not applicable for wildfires)	Transect measurements (not applicable for wildfires)
Advantages	Least resource requirements	Classifications are already available in many cases	Streamlines modeling efforts	Good accuracy is expected	Good accuracy is expected	Most accurate
Disadvantages	Poor accuracy Does not account for emission mitigation measures for prescribed fire	Poor accuracy Does not account for emission mitigation measures for prescribed fire	Use of defaults limits accuracy Does not account for emission mitigation measures for prescribed fire	Still under development Does not account for emission mitigation measures for prescribed fire	Time consuming Training may be needed	Very resource intensive for a regional inventory

Fuel loadings can also be estimated using average values for various types of vegetative cover. Distributions of vegetation cover types have been mapped with a high degree of spatial resolution in various data bases.[15] The National Fire Danger Rating System (NFDRS) has also been used as a tool for estimating fuel loadings.[27] This system groups forests and other ecosystems into 20 broad classes according to the potential danger of wildfire. The Forest Service has produced a map of NFDRS categories with a resolution of 1-km using satellite data and surface observations for the contiguous 48 states.[28] The NFDRS classification system is based on typical fuel loadings and climactic conditions, but it does not provide the level of detail necessary to fully evaluate emission potential. The FCC is expected to be superior to the NFDRS in this respect. In the short term, however, NFDRS classifications are available for a large number of fires.

Table 11. Summary of Photo Series Available for Evaluating Fuel Loadings

Region	Vegetation Covered
Coastal Oregon forests[29]	Second growth Douglas-fir – western hemlock type Western hemlock – Sitka spruce type Red alder type
Willamette National Forest[30]	Douglas-fir – hemlock type
Interior Pacific Northwest[31]	Mixed conifer with mortality Western juniper Sagebrush Grassland
Pacific Coast[32]	Giant Sequoia groves
West (general)	Aspen[33]
Alaska[34]	Black spruce White spruce
East Texas[35]	Grass, clearcut, seed tree, loblolly pine, shortleaf pine, loblolly/shortleaf pine, slash pine, longleaf pine, hardwood cover
Black Hills[36]	Ponderosa pine Spruce
Central and Lake States[37]	Midwest red and white pine Northern tallgrass prairie Mixed oak
Northeast[38]	Northern hardwood Oak-hickory

The Forest Service's National Fire Emission Laboratory is working on methods to estimate fuel loadings from satellite data and other remote sensing data.[15] A major drawback of this approach is that remote sensing techniques "see" more of the forest canopy than the forest floor. As discussed above, most of the fuel for a fire is on the forest floor. Researchers are working on ways to correlate remote sensing data with conditions on the floor. However, remote sensing techniques are not expected to provide reliable information on fuel loadings for several years.[39]

A number of models have been developed to estimate fuel consumption in prescribed fire. The fuel consumption models generally contain default values of pre-burn fuel loadings for various types of vegetation. Table 12 lists vegetation categories included in the First Order Fire Effects Model (FOFEM). (FOFEM and other fuel consumption models will be discussed further in Section 4). For each of the categories listed in Table 12, FOFEM includes default loadings for litter, downed woody debris, duff, herbaceous undergrowth, shrubs, and regenerating trees. Table 13 illustrates the level of detail provided in the FOFEM default fuel models.

3.2 Previous Inventories

In the 1989 prescribed fire inventory by Peterson and Ward, land managers classified the acreage burned in each state by NFDRS category. Expert judgement was then used to estimate consumption for various fuel types.[2, 3]

The FEP survey of local land managers included an assessment of fuel loadings and characteristics. As discussed earlier, this survey was carried out on a 50x50 km grid, and also differentiated among different land ownership and land allocation classifications (see Table 8). For each type of vegetation cover, the cognizant land manager was asked to classify the fuel loading as high, medium, or low. The “high” fuel loading classification was designed to represent areas that had been subject to prolonged fire exclusion, or to a natural disturbance such as insect infestations or wind damage. The “low” classification was designed to represent areas that had recently been burned, either in a wildfire or a prescribed fire. The survey also differentiated between “natural” fuel loadings and “activity-generated” fuel loadings, which result from logging or mechanical thinning. Activity-generated fuels were also classified into high, medium, and low fuel loading categories.

With its survey covering 10 states at a resolution of 50 km, the FEP provides a unique source of information on fuel loadings. The bottom-up survey approach is superior to a top-down estimate. The survey results also provide a body of data that could be used to estimate fuel loadings for future fires based on vegetative cover type, NFDRS classification or FCC code (once the FCC classification system is available). However, states would have to check for data gaps and inconsistencies. In addition, it must be noted that manager knowledge of existing fuel loadings was characterized as “weak” in comparison with other aspects of the survey. However, the survey results still reflect the best currently available data for a broad regional inventory.

Table 12. Vegetation Categories Covered in FOFEM

Vegetation type	Classification [a]	Vegetation type	Classification [a]
Interior ponderosa pine	SAF 237	Red pine	SAF 15
Jeffrey pine	SAF 247	Eastern white pine	SAF 21
Interior Douglas-fir	SAF 210	Black spruce	SAF 204
Western white pine	SAF 215	White spruce	SAF 201
Douglas-fir-tan-oak-Pacific madrone	SAF 234	Douglas-fir-western hemlock	SAF 230
Blue spruce	SAF 216	Shortleaf pine	SAF 75
Engelmann spruce-subalpine fir	SAF 206	Virginia pine	SAF 79
Grand fir	SAF 213	Pond pine	SAF 98
Sierra Nevada mixed conifer	SAF 243	Black oak	SAF 110
Lodgepole pine	SAF 218	Oak-pine	FRES 14
Whitebark pine	SAF 208	Longleaf pine	SAF 70
Aspen	SAF 217, 16	Slash pine	SAF 84
Jack pine	SAF 1	Loblolly pine, Coastal	SAF 81
		Loblolly pine, Piedmont	SAF 81

[a] Society of American Foresters (SAF) cover types, and Forest and Range Ecosystem (FRES) categories.

Table 13. Sample Default Fuel Loading Data from FOFEM

Fuel type	Loading defaults (tons/acre) Sparse	Loading defaults (tons/acre) Abundant	Duff depth (inches)
Interior ponderosa pine			
Litter	1.4		
Downed woody debris			
0-1 inch diameter	0.7		
1-3 inches	0.8		
≥ 3 inches	5		
Duff	5		0.6
Herbaceous ground cover	0.1	0.3	
Shrubs	0.0	0.5	
Tree regeneration	0.0	0.3	

3.3 Questions and Issues for Future Inventories

The following is a summary of issues related to the estimation of initial fuel loadings for fire emission inventories.

- Do inventories provide adequate information for the level of modeling and impact analysis that are planned?
- What level of accuracy is needed?
- How should inventories provide for determining success with alternatives and trade-offs (prescribed fire versus wildfire, different types of prescribed fire)?
- Given the current state of flux with the FCC system, can the GCVTC fuel loading data (from 1993 or so) be used until the FCC is completed?
- How often does a fuel loading survey such as the GCVTC survey need to be repeated?
- How should future fuel loadings be adjusted to reflect previous wild and prescribed fires?

4. Fuel Consumption

The amount of fuel that is actually consumed in a fire depends on the type of fuel, its depth on the forest floor, its moisture level, and other factors, such as humidity, wind speed, and fire intensity. Within a particular fire, fuel consumption will also vary for different types of fuel.

4.1 Available Methods and Tools

Table 14 summarizes methods available to estimate fuel consumption, and lists advantages and disadvantages associated with each method. The options differ somewhat for prescribed and wildfires. In the case of wildfires the EPA's Compilation of Emission Factors (AP-42) provides default regional estimates of fuel consumption per acre.[40]

Two main models have been developed to predict fuel consumption. The most recent versions of these models are:

- First Order Fire Effects Model (FOFEM), Version 4.0[41]
- Consume, Version 2.1[42]

Both of these models are readily available through the internet. A number of other fire models incorporate fuel consumption algorithms from Consume. These include SMSINFO;[43] the Fuel Analysis, Smoke Tracking, and Report Access Computer System (FASTRACS),[44] the Automatic Calculation of Slash Tonnage (ACOST) model; and the Pile Tonnage Calculation Worksheet (PCOST).[45]

FOFEM and Consume both models use empirical data and formulas to predict fuel consumption. Detailed inputs are needed on climactic conditions and the quantity and nature of the fuel, but both models make extensive use of defaults as needed. Table 15 summarizes the inputs used by the fuel consumption subsystem of FOFEM.[41] Inputs for Consume are similar, with additional details for activity-generated fuels. As Table 15 illustrates, the input requirements for fuel consumption models are quite diverse and extensive. Many of these inputs would be difficult to compile on a broad regional scale. However, the models include typical defaults for most parameters. These parameter defaults can be used in emission calculations when specific information is not available.

Both FOFEM and Consume perform best for downed woody fuels. Performance is also good for shrubs, but not as good for duff and crowns. A 1994 study of four prescribed burns in northeastern Oregon compared the measured fuel consumption with the fuel consumption predicted by Consume and FOFEM.[46] Both models perform better if data is available on fuel moisture and on the number of days since the last rain. This information can be obtained from field personnel, maps, and records.

Table 14. Options for Estimating Fuel Consumption

	➔ ➔ **Increasing level of detail** ➔ ➔			
	Prescribed fires			
Options	Regional defaults or vegetation-specific defaults (AP-42)	Fuel consumption models with default inputs		Models with input from land managers
Advantages	Least resource requirements	Low resource requirements		Most accurate
Disadvantages	Poor accuracy	Use of defaults limits accuracy		Resource intensive
	Wildfires			
Options	Regional defaults (AP-42)	Fuel consumption models with dry fuel assumption	Consumption models with crown consumption and other appropriate adjustments	Models with input from land managers and crown adjustment
Advantages	Least resource requirements	Low resource requirements	Moderate resource requirements	Best accuracy
Disadvantages	Poor accuracy	May underestimate impacts of crown consumption and other factors associated with wildfires	Will require new assumptions Some relevant studies are not yet available	Resource intensive

Table 15. Summary of Inputs Used by FOFEM to Compute Fuel Consumption[41]

Parameter	Options (model defaults are in ***bold italics***)
General	
Region	Interior West, Pacific West, Northeast or Southeast
Vegetation cover	Black Spruce, White Spruce, Paper Birch, Douglas Fir, Ponderosa Pine, Jeffrey Pine, Western White Pine, White Fir, Englemann spruce Subalpine Fir, Blue Spruce, Mountain Hemlock-Subalpine Fir
General fuel information	
Fuel category	***Natural***, piles, slash
Dead fuel adjustment factor	***Typical***, light, heavy
Moisture conditions	Very dry, ***dry***, moderate, wet
Fire intensity	Extreme, very high, ***high***, moderate, low
Will fire burn tree crowns?	***No***, yes
Tree crown biomass loading	***Typical***, sparse, abundant
Herbaceous density	***Typical***, sparse, abundant
Tree regeneration density	***Typical***, sparse, abundant
Season of burn	Spring, summer, fall, winter
Customized fuel information	
Southeast pine information	Plantation, Natural Age of plantation (years): ***5***
Fuel loadings for: litter wood (0-1" diameter, 1-3", >3") duff herbaceous shrub, tree regeneration crown foliage crown small branchwood	Values in ton/acre. Defaults are set by the model based on the above inputs.
Fuel moisture for: Duff Wood	NFDRS fuel moisture code, adjusted code, or numerical percentage. Model will also set defaults based on the above inputs.
Pacific Northwest information	Days since significant rain: ***20***

Both FOFEM and Consume were developed to model fuel consumption in prescribed burns. The models are currently being modified to address wildfires but are not as well tested for that application. Previous inventories have used the models with dry fuel condition assumptions to estimate wildfire consumption. Some other adjustments may be needed. One of the shortcomings of the fuel consumption models for handling wildfire is the potential underestimation of crown consumption in severe fires. The Forest Service has an ongoing project to assess crown fuel characteristics in conifer forests.[47] Improved crown consumption algorithms are expected to be incorporated into a new version of Consume (Consume 3.0).

4.2 Previous Inventories

In the Peterson and Ward 1989 prescribed fire inventory, fuel consumption was estimated based on expert judgement.[2,3] In the FEP, an expert panel estimated the fuel moisture content for each vegetative cover type and for each fuel loading category. Fuel moisture was classified as dry (15% moisture), normal (30%) or wet (40%). The Consume model was then used to estimate fuel consumption for each vegetation and fuel loading category. An average emission factor, reflecting a weighted average of flaming and smoldering, was assigned for each vegetation type. In the FMI/WESTAR inventory, the GCVTC vegetative categories were consolidated for the purpose of estimating fuel consumption and emissions.[6]

4.3 Questions and Issues for Future Inventories

The following are issues related to the estimation of fuel consumption for fire emission inventories:

- Should the choice of models for estimating fuel consumption be at the discretion of each state, or do EPA and the WRAP need to approve a particular slate of models? Have some of the models undergone more testing and peer review than others?

- Consume and FOFEM have been used in some instances for wildfires. Is this appropriate, or is a separate methodology needed?

5. Fire Emission Factors and Relationships

Emissions of a given pollutant from a given fire are determined by sampling the offgas from the fire and measuring the concentration of the target pollutant. Typically, the researcher measures the concentration of CO_2 and other carbon-containing gases at the same time, and then uses a carbon-balance calculation to determine the fuel consumption associated with the measured emissions. Emission factors from fire are typically expressed in terms of the mass of pollutant emitted per mass of fuel consumed. The following is a sample calculation of an emission factor:

$$EF = \frac{MW \times \Delta C_{pollutant} \times F_c \times (1000 \text{ g/kg})}{(\Delta C_{CO2} + \Delta C_{CO} + \Delta C_{CH4} + {}_{\Delta cother}) \times (12 \text{ g/mole-C})} \qquad (4)$$

where: EF = Emission factor (g/kg)

MW = Molecular weight of the target pollutant (g/mole)

ΔC = Concentration in fire offgas minus concentration in clean air (moles per cubic meter)

F_c = Mass fraction of carbon in the fuel (g-carbon/g-fuel)

"Other" refers to total non-methane hydrocarbons and particulate carbon, expressed in terms of moles of carbon

Emission factors are often related to the combustion efficiency, or to emissions of carbon monoxide, which are both indicators of the relative amount of combustion by smoldering. Emissions of particulate species are often related to total PM emissions or total $PM_{2.5}$ emissions.

The first two sections of this chapter summarize the available models for estimating emissions and the methods used in previous large scale inventories. Section 5.3 discusses the calculation of combustion efficiency, and the balance of the chapter discusses available emission factors and algorithms for specific pollutants. Separate sections are devoted to carbon monoxide (CO), total particulate ($PM_{2.5}$ and PM_{10}), particulate elemental carbon (EC) and particulate organic carbon (OC), nitrogen oxides (NO_X), ammonia (NH_3), volatile organic compounds (VOC), sulfur dioxide (SO_2), and hazardous air pollutants (HAPs). The final section of this chapter summarizes options available for estimating emission factors for the above pollutants.

5.1 Available Models and Methods

In addition to predicting the amount of fuel consumed in a fire, the FOFEM and Consume fuel consumption models (discussed in Sections 3 and 4) include subsystems to estimate emissions of some pollutants. Table 16 summarizes the pollutants and situations covered by these models. The models use empirical emissions data assembled by the Forest Service in laboratory and field tests.[48, 49, 50, 51, 52] The empirical emissions relationships differentiate between flaming and smoldering conditions, and between different forest types and fuel conditions. Both models were developed primarily to assess impacts of prescribed fire. They can also be applied to wildfires, but have not been extensively tested for that application.

Table 16. Summary of Models Available for Estimating Fire Emissions

Model	Situations covered	Pollutants
FOFEM 4.0[41]	Designed for prescribed fires, but can also be applied to wildfire	PM_{10}, $PM_{2.5}$, CO
Consume 2.1[42]	Designed for prescribed fires, but can also be applied to wildfire	PM_{10}, $PM_{2.5}$, CO, CO_2, CH_4, and NMHC

FOFEM 4.0 and Consume 2.1 were completed in 1997 and 2000, respectively. Both FASTRACS and SMSINFO use earlier versions of the Consume emissions algorithms. The EPA's current AP-42 emission factors for prescribed fire are also derived from earlier versions of the Forest Service emissions database used in FOFEM and Consume, however some inconsistencies have been noted between AP-42 and the Forest Service emission factors.[40]

Though based on similar underlying emission factor databases and fuel consumption databases, FOFEM and Consume take a somewhat different approach to estimating emissions. FOFEM estimates the fuel consumption and the combustion efficiency (CE), taking into account the forest type and fuel conditions. The model does not retain separate emission factors for different types of fuel, but instead reflects the fuel differences through the CE term. Consume 2.1 contains a detailed matrix of flaming and smoldering emission factors for different types of vegetation types. The relative weighting of flaming and smoldering is determined based on fuel conditions.

5.2 Previous Emissions Inventories

In their prescribed fire inventory, Peterson and Ward used empirical relationships to compute emissions of various criteria pollutants and toxic air pollutants. The relationships used for $PM_{2.5}$, PM_{10}, and CO are the same as those currently used in FOFEM. The FEP also used these same relationships. The empirical relationships used in these inventories will be discussed below in the sections devoted to individual pollutants.

5.3 Combustion Efficiency

Many pollutants emitted from fire are products of incomplete combustion, including carbon monoxide (CO), particulate matter, and hydrocarbons. Therefore, emissions from a fire depend not only on the fuel consumption, but also on the combustion efficiency. Combustion efficiency is defined as the fraction of carbon released from fuel combustion in the form of CO_2. CE is calculated based on the composition of the fire offgas as compared to the composition of clean air:

$$CE = \frac{\Delta C_{CO2}}{\Delta C_{CO2} + \Delta C_{CO} + \Delta C_{CH4} + \Delta C_{other}} \qquad (5)$$

where: CE = Combustion efficiency

ΔC = Concentration in fire offgas minus concentration in clean air (moles per cubic meter)

"Other" refers to total non-methane hydrocarbons and particulate carbon, expressed in terms of moles of carbon

CE is relatively high under flaming conditions and relatively low under smoldering conditions. The average CE of a fire gives an indication of the relative amounts of fuel consumed under smoldering and flaming combustion.

When total carbon emissions are not measured, the modified combustion efficiency (MCE) may be reported instead of the CE. The MCE is simply the ratio of the concentration of CO_2 emitted by the fire to the total of CO_2 and CO:

$$MCE = \frac{\Delta C_{CO2}}{\Delta C_{CO2} + \Delta C_{CO}} \quad (6)$$

where: CE = Combustion efficiency

ΔC = Concentration in fire offgas minus concentration in clean air (moles per cubic meter)

Ward and Hao developed the following empirical relationship between CE and MCE, with a correlation coefficient (R^2) or 0.96:[53]

$$MCE = 0.15 + 0.86 \times CE \quad (7)$$

The models listed in Section 5.1 take into account the differences between flaming and smoldering conditions in their emissions estimates. Tables 17 gives the CE values used to generate emission factors in the FOFEM. These are based on a large number of primarily ground based measurements. Table 18 summarizes combustion efficiencies measured in airborne tests. As the table shows, CE was similar for prescribed fires and wildfires. Efficiencies may be somewhat higher for chaparral (CE = 0.93 to 0.95) than for forest fuels (CE = 0.91).

5.4 Carbon Monoxide

CO is very important in the development of emissions inventories for many pollutants. Because it is an indicator of smoldering combustion, its emission factor is often used to estimate emission factors for many other products of incomplete combustion. Researchers at the U.S. Forest Service developed the following empirical relationship between CO emissions and combustion efficiency based on extensive field and laboratory testing for a wide array of forest fuels:[54]

$$EF_{CO} = 961 - 984 \times CE \quad (8)$$

where: EF = Emission factor (kg/Mg fuel consumed)

CE = Combustion efficiency

The uncertainty of this correlation was estimated at $\pm$10%.

This algorithm was used in both the Peterson and Ward emissions inventory and the FEP emissions inventory.[2, 4] It is also currently used in FOFEM, and has been used to generate the forest-type emission factors used in Consume.[41, 42] Table 19 shows the average emission factors produced by the above algorithm in FOFEM for different types of fuel and levels of fuel moisture. Table 20 summarizes the average emission factors used in Consume 2.1 for different fire types and classes of vegetation. Because of the large number of measurements used by the Forest Service in developing this correlation and the quality of the correlation, we have not made any further review of CO emissions data.

5.5 Total Fine Particulate

Particulate emissions from fire have been studied extensively, resulting in a large body of empirical data. In 1988, Ward, Hardy, and Sandberg of the Forest Service calculated $PM_{2.5}$ and PM_{10} emission factors as a function of fuel type and phase of combustion (flaming versus smoldering).[55] These factors were used in EPA's AP-42 Compilation of Emission Factors.[40] However, since the last update of the AP-42 section for fire, the Forest Service fuel-specific emission factors have been improved and updated. These updated fuel-specific factors have been used in the FOFEM and Consume models.

Table 17. Combustion Efficiencies Used in FOFEM for Different Fuels and Fuel Moisture Levels[41]

	CE for pure flaming and smoldering		Amount of smoldering (%) [a]			Overall CE		
Fuel component	Flaming	Smolder-dering	Wet	Moder-ate	Dry	Wet	Moder-ate	Dry
Litter [c]	0.95	na	0	0	0	0.95	0.95	0.95
Wood 1-3 inches	0.92	na	0	0	0	0.92	0.92	0.92
Wood > 3 inches	0.92	0.76	50	30	20	0.84	0.87	0.89
Shrubs [d]	0.85	na	0	0	0	0.85	0.85	0.85
Duff	0.90	0.76	50	60	60	0.83	0.82	0.82
Canopy fuels	0.85	na	0	0	0	0.85	0.85	0.85

[a] Ratio of the amount of fuel consumed in smoldering combustion to the total amount of fuel consumed. The balance is flaming combustion.
[b] Based on general fuel moisture categories used in FOFEM. The "wet" category reflects moisture contents of 40% for wood greater than 3 inches and 200% for duff (based on dry mass). "Moderate" assumes wood moisture of 25% and duff moisture of 120%, and "dry" assumes 15% wood moisture and 75% duff moisture.
[c] Wood < 1 inch diameter
[d] Includes herbaceous materials and tree regeneration

Table 18. Combustion Efficiencies from Airborne Measurements

Description	Date	Combustion efficiency (CE)	Modified combustion efficiency (MCE)
Prescribed			
Hemlock (BC)	Sept 25, 1989 (a)	0.950 *	0.958
Pine (MT)	Oct 8, 1987 (a)	0.921 *	0.933
Pine (Ont)	Aug 28, 1987 (b)	0.915 *	0.928
Birch (Ont)	Aug 10, 1989 (a)	0.897 *	0.912
	Aug 12, 1989 (a)	0.950 *	0.958
Pine (Ont)	Aug 12, 1988 (b)	0.819 *	0.846
	Aug 22, 1988 (a)	0.914 *	0.927
Pine (NC)	Apr 14, 1997 (c)	0.917	0.925
	Apr 26, 1997 (c)	0.907	0.927
Chaparral (CA)	Dec 3, 1986 (b)	0.965 *	0.970
	Dec 12, 1986 (b)	0.923 *	0.935
	June 22, 1987 (b)	0.922 *	0.933
Wild			
Grasses and shrubs (AK)	June 13, 1997 (d)	0.908	0.925
Black spruce (AK)	June 21-24, 1997 (d)	0.902	0.916
	June 22, 1997 (d)	0.920	0.929
	June 24,27, 1997 (d)	0.905	0.917
	June 27-28, 1990 (e)	0.895	0.911
	June 27-28, 1990 (a)	0.944 *	0.953
Fir (OR)	Sept 17-19 (b)	0.907 *	0.921
Conifer (ID)	Sept 27-28, 1994 (f)	0.925 *	0.936
Pine (OR)	Sept 2, 1987 (b)	0.891 *	0.907
Averages (with standard deviations)			
All measurements		0.908 ± 0.029	0.927 ± 0.024
Prescribed		0.917 ± 0.035	0.929 ± 0.030
Wild		0.911 ± 0.016	0.924 ± 0.013
Forest fuels		0.911 ± 0.029	0.924 ± 0.025
Grasses and chaparral		0.929 ± 0.021	0.941 ± 0.017

* Calculated from MCE using equation 7.

Sources:

(a) Laursen, et al (1992)[56]
(b) Hegg, et al (1990)[57]
(c) Yokelson et al (1999)[58]
(d) Goode, et al (2000)[59]
(e) Nance et al (1993)[60]
(f) Babbitt, et al (1994)[61]

Table 19. CO Emission Factors Used in FOFEM for Different Fuels and Fuel Moisture Levels[41]

Fuel component	CO emission factors (kg/Mg fuel consumed)		
	Wet [a]	Moderate [a]	Dry [a]
Litter [b]	26.2	26.2	26.2
Wood 1-3 inches	55.7	55.7	55.7
Wood > 3 inches	134	103	87
Shrubs [c]	125	125	125
Duff	144	158	158
Canopy fuels	125	125	125

[a] Fuel moisture categories are defined in Table 17.
[b] Wood < 1 inch diameter
[c] Includes herbaceous materials and tree regeneration

Table 20. CO Emission Factors Used in Consume for Different Fire Types[42]

Fire type	Emission factors (kg/Mg)		
	Flaming	Smoldering	Average
Broadcast burned slash			
Douglas fir / hemlock	72	232	156
Hardwoods	46	183	128
Ponderosa / lodgepole pine	45	142	89
Mixed conifer	27	136	101
Juniper	41	125	82
Pile-and-burn slash			
Tractor-piled	22	116	77
Crane-piled	51	116	93
Average piles			85
Broadcast-burned brush			
Sagebrush	78	106	103
Chaparral	60	99	77

Ward and Hardy (1991) also developed the following general correlations between $PM_{2.5}$ and PM_{10} emissions and combustion efficiency.[54]

$$EF_{PM\text{-}2.5} = 67.4 - 66.8 \times CE \tag{9}$$

$$EF_{PM\text{-}10} = 1.18 \times EF_{PM\text{-}2.5} \tag{10}$$

where: EF = Emission factor (kg/Mg fuel consumed)
CE = Combustion efficiency

These relationships were used in the Ward and Peterson prescribed fire inventory and the FEP emissions inventory. They are also used directly in FOFEM 4.0, and were used to develop the average emission factors for various forest types in Consume 2.1. Table 21 shows the average emission factors produced by the above algorithm in FOFEM, and Table 22 summarizes the average emission factors used in Consume 2.1 for different fire types and classes of vegetation.

Ward, Susott, and others (1992) developed empirical relationships for $PM_{2.5}$ based on ground-based and airborne measurements of prescribed fires in British Columbia. In 1994, Babbitt, Ward, and others developed an empirical equation for $PM_{2.5}$ emissions from wildfires in Idaho, Montana, and Oregon. Table 23 shows these empirical relationships, along with the original Ward and Hardy relationship.

Table 24 summarizes additional recent measurements of PM_{10}, $PM_{2.5}$, and $PM_{2.5}$ components. The measured emission factors are compared with emission factors that would have been predicted using the measured combustion efficiencies and empirical relationships from the GCVTC emissions inventory. (The comparisons in Table 24 are based on the original Ward and Hardy formula for $PM_{2.5}$.)

Table 21. $PM_{2.5}$ Emission Factors Used in FOFEM for Different Fuels and Fuel Moisture Levels[41]

	$PM_{2.5}$ emission factors (kg/Mg fuel consumed)		
Fuel component	Wet [a]	Normal [a]	Dry [a]
Litter [b]	3.95	3.95	3.95
Wood 1-3 inches	5.95	5.95	5.95
Wood > 3 inches	11.3	9.15	16.2
Shrubs [c]	10.7	10.7	10.7
Duff	12.0	12.9	12.9
Canopy fuels	10.7	10.7	10.7

[a] Fuel moisture categories are defined in Table 17.
[b] Wood < 1 inch diameter
[c] Includes herbaceous materials and tree regeneration

Table 22. $PM_{2.5}$ Emission Factors Used in Consume for Different Fire Types[42]

Fire type	$PM_{2.5}$ emission factors (kg/Mg)			PM_{10} emission factors (kg/Mg)		
	Flaming	Smoldering	Average	Flaming	Smoldering	Average
Broadcast burned slash						
Douglas fir / hemlock	7.5	13.1	10.9	8.4	13.8	11.6
Hardwoods	6.1	11.7	11.2	7.0	13.0	12.5
Ponderosa / lodgepole pine	5.0	17.1	11.0	5.8	18.4	12.5
Mixed conifer	4.8	11.8	9.4	5.9	12.7	10.3
Juniper	13.0	11.9	9.4	7.7	12.9	10.2
Pile-and-burn slash						
Tractor-piled	3.3	7.0	5.4	3.7	8.0	6.2
Crane-piled	5.9	15.5	11.7	6.8	16.6	12.8
Average piles			8.6			9.5
Broadcast-burned brush						
Sagebrush	14.6	13.2	13.4	15.9	14.8	15.0
Chaparral	6.8	10.8	8.7	8.3	12.4	10.1
Wildfires						
Average			13.5			15.0

Table 23. Comparison of Measured Empirical Relationships for $PM_{2.5}$ Emissions in the United States

Fire type and location	Empirical relationship for $PM_{2.5}$	Correlation coefficient (R^2)	Source
Prescribed fires, Pacific Northwest	67.4 - 66.8×CE		Ward and Hardy (1991) - Used in GCVTC and Peterson & Ward inventories
Wildfires, Montana, Idaho, and Oregon	62.6 - 61.4×CE [a]	0.72	Babbitt, *et al* (1994)[61]
Prescribed fires, British Columbia			
Ground level tests	89 - 91.1×CE	0.87	Ward *et al* (1992)[62]
Airborne tests	126 - 129×CE	0.72	

[a] Estimated based on a published relationship with *modified combustion efficiency*:
$EF_{2.5} = 73.4 - 72.2 \times MCE$

Table 24. Summary of $PM_{2.5}$ and PM_{10} Measurements and Comparison with Empirical Relationships

Location, date, and citation	Vegetation	Combustion efficiency	Pollutant	Measured emission factor (kg/Mg) [a]	Predicted emission factor (kg/Mg) [b]
Prescribed fire, Los Angeles basin, December 1996, Einfeld *et al* (1989)[63]	Chaparral (sage, sumac, chamise)	Smoldering	$PM_{2.5}$	10.9 ± 3.5	16.2
			PM_{10}	13.8 ± 2.3	19.2
			$EC_{2.5}$	1.1 ± 0.4	1.5
			$OC_{2.5}$	6.1 ± 0.7	8.6
Prescribed burns, California, Hardy *et al* (1996)[64]	Chaparral	Flaming - 0.913	$PM_{2.5}$	6.8 ± 0.6	6.0
		Smoldering - 0.855		10.8 ± 1.1	9.9
		Overall - 0.880		8.7 ± 0.6	8.2
		Flaming - 0.913	PM_{10}	8.30	6.0
		Smoldering - 0.855		12.4	9.9
		Overall - 0.880		10.0	8.2
Wind tunnel tests, California, 1992 - 1993, Jenkins, *et al* (1996)[65]	Almond tree prunings	0.954	$PM_{2.5}$	4.50	3.3
			PM_{10}	4.80	3.9
	Douglas fir slash	0.946	$PM_{2.5}$	4.30	3.8
			PM_{10}	4.80	4.5
	Ponderosa pine slash	0.947	$PM_{2.5}$	3.30	3.7
			PM_{10}	3.70	4.4
	Walnut tree prunings	0.934	PM_{10}	5.00	4.6
			$PM_{2.5}$	4.70	5.4
Controlled facility, Yokelson *et al* (1996)[58]	Broadcast	0.961 [c]	$PM_{2.5}$	5.93	2.8
	Sagebrush	0.964 [c]	$PM_{2.5}$	2.32	2.6
	Slash	0.973 [c]	$PM_{2.5}$	1.48	2.0
Wildfire, Alaska, (A121), June 1990, Nance *et al* (1993)[60]	Black Spruce	0.895	$PM_{3.5}$	21.5 ± 4.8	7.2

[a] Ranges, where given, represent standard deviation.
[b] Computed based on equation 9.
[c] Estimated from the modified combustion efficiency.

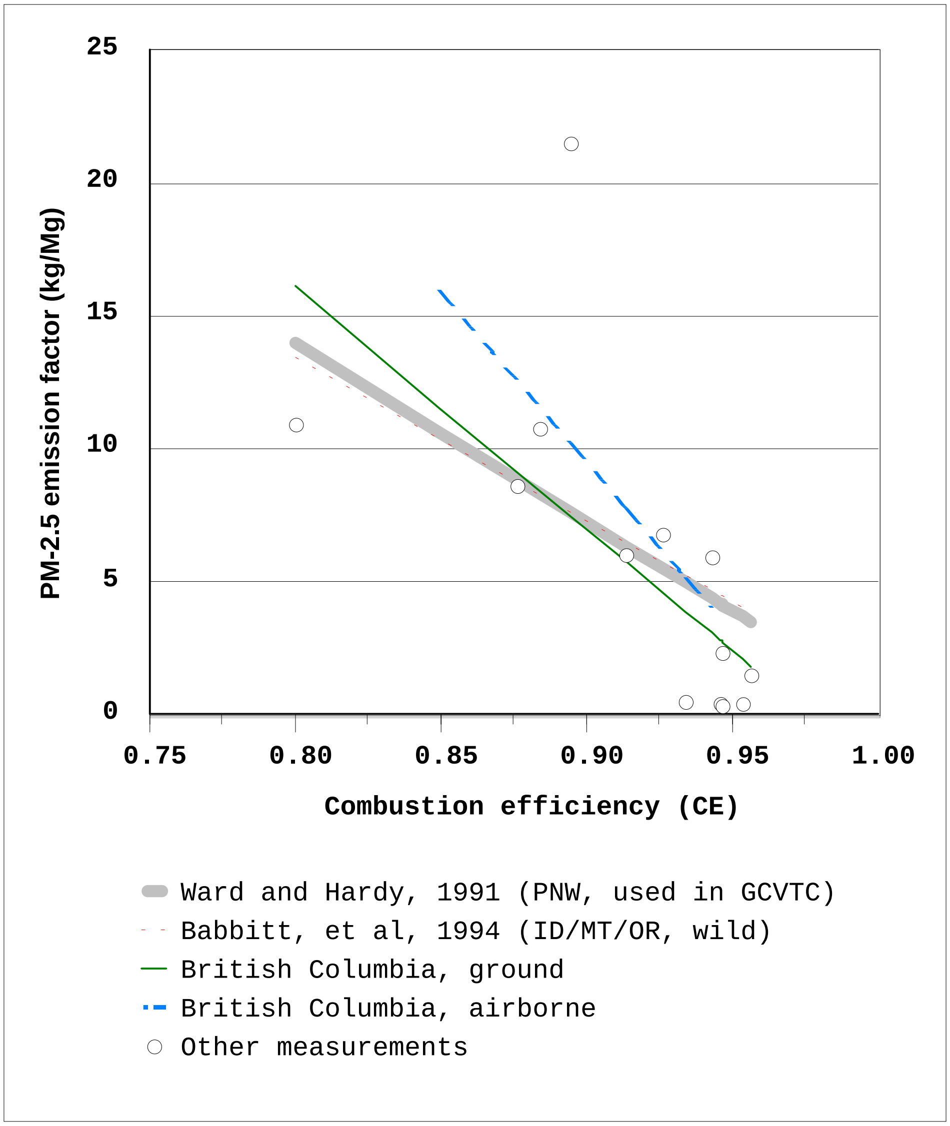

Figure 2. Comparison of empirical relationships and other recent measurements of $PM_{2.5}$ emission factors

Figure 2 illustrates the various empirical relationships for $PM_{2.5}$ as a function of combustion efficiency (CE). The figure also includes the additional $PM_{2.5}$ measurements from Table 24. Figure 2 shows that the relationship for $PM_{2.5}$ from wildfires in the Northwest is in good agreement with Ward and Hardy's original relationship. However, the correlations developed for British Columbia are statistically different from the original $PM_{2.5}$ equation. The authors suggest that this difference may be due to the inherent variability of emissions coupled with the narrow range of CE covered by the airborne measurements.

Table 24 and Figure 2 show that there is reasonable agreement between most of the additional measurements of $PM_{2.5}$ and the original Ward and Hardy empirical formula. However, the empirical relationship appears to underpredict emissions for the 1990 Alaska wildfire.[60] It should be noted that both Tables 23 and 24 are restricted to the United States and Canada, and to tests performed since the development of the FOFEM and Consume models. A good number of additional measurements have been made in Africa and South America, and a large volume of earlier data is also available.

5.6 Emission Factors for Particulate Elemental and Organic Carbon

A large fraction of the particulate matter emitted from combustion consists of elemental and organic carbon. These components have been used to analyze "fingerprints" of wildland fires and other combustion in ambient particulate samples. Table 25 summarizes available emissions measurements of EC and OC. The table also gives ratios of EC to total $PM_{2.5}$ and OC to total $PM_{2.5}$. Figure 3 illustrates the relationship between EC and total $PM_{2.5}$, and between OC and total $PM_{2.5}$.

As Table 25 shows, EC is similar for flaming and smoldering conditions, while OC increases considerably under smoldering conditions. In the case of OC, the ratio to total $PM_{2.5}$ is very similar for smoldering and flaming conditions. Thus, OC appears to correlate well with total $PM_{2.5}$ over the full range of combustion efficiencies. This is confirmed by the regression equation shown in Figure 3, with a correlation coefficient (R^2) of 0.97. This is less true for EC although the correlation coefficient is still quite high ($R^2 = 0.77$).

5.7 Emission Factors for Nitrogen Oxides

NO_X emissions are not calculated by any of the current fire models, nor are emission factors for NO_X included in the current edition of EPA's AP-42. However, NO_X has been measured in a number of studies, both in the field and in controlled facilities. These measurements are summarized in Table 26. In addition to the measured emission factor, the table gives the ratio of NO_X concentration to CO_2.

In general, NO_X emissions from combustion processes can be produced by two mechanisms: (1) oxidation of nitrogen compounds in the fuel, and (2) oxidation of nitrogen gas in the combustion air. However, very high temperatures (>1000 ºC) are required for significant oxidation of nitrogen gas.[66] Based on a large number of field and laboratory tests, Ward (1993) concluded that temperatures in the flames of prescribed fires do not typically reach levels that would result in significant oxidization of nitrogen in the air.[67] Therefore, NO_X emissions from fires should be strongly dependent on the nitrogen levels in fuel materials.

Lacaux *et al* (1996) confirmed the relationship between NO_X and fuel nitrogen for several fires in the African Savannah, calculating a correlation coefficient (R^2) of 0.9.[71] They also proposed an empirical formula relating the NO_X emission factor to fuel nitrogen content (see Table 26). We have used this relationship to predict NO_X emission factors for laboratory fires where fuel nitrogen concentrations were available. As shown in Table 26, Lacaux's empirical relationship also produces good agreement for these fires.

Table 25. Summary of Available Emissions Measurements for Particulate Elemental and Organic Carbon

Description		Emission factors (kg/Mg)			Ratios to $PM_{2.5}$ (weight %)	
		$PM_{2.5}$	Elemental carbon (EC)	Organic carbon (OC)	Elemental carbon (EC)	Organic carbon (OC)
Pacific Northwest (a)						
Chaparral	Flaming	20.0	1.84	9.60	9.2	48
	Smoldering	40.0	3.12	25.56	7.8	64
Conifer	Flaming	7.0	1.32	2.55	18.8	36
	Smoldering	14.0	0.48	7.27	3.4	52
Ponderosa pine	Flaming	6.0	0.65	3.31	10.9	55
	Smoldering	16.0	0.66	9.76	4.1	61
Hardwood	Flaming	6.0	0.50	3.62	8.3	60
	Smoldering	13.0	0.35	8.02	2.7	62
Slash - crane piled	Flaming	4.0	0.09	2.39	2.3	60
	Smoldering	4.0	0.04	2.42	1.1	60
Slash - tractor piles	Flaming	4.0	0.33	1.96	8.2	49
	Smoldering	4.0	0.12	2.12	2.9	53
Los Angeles (b)						
Chaparral (Lodi 1)	Flaming	7.7	0.58	3.49	7.5	45
Chaparral (Lodi 2)	Flaming	7.7	0.45	3.46	5.9	45
Chaparral (Lodi 3)	Flaming	5.5	0.81	2.83	14.7	51
	Smoldering	7.7	0.60	4.92	7.8	64
Brazil (c)						
Cerrado	Overall	4.0	0.13		3.3	
Forest	Overall	10.5	1.05		10.0	
Averages						
Flaming			0.73 ± 0.5	3.7 ± 2.2	9.5 ± 4.6	50 ± 7.2
Smoldering			0.77 ± 1.0	8.6 ± 7.4	4.3 ± 2.4	59 ± 4.6
Overall			0.73 ± 0.7	5.8 ± 5.7	7.2 ± 4.5	54 ± 7.7

Sources:

(a) Ward and Hardy (1988)[68]

(b) Ward and Hardy (1989)[69]

(c) Kaufman et al (1992)[70]

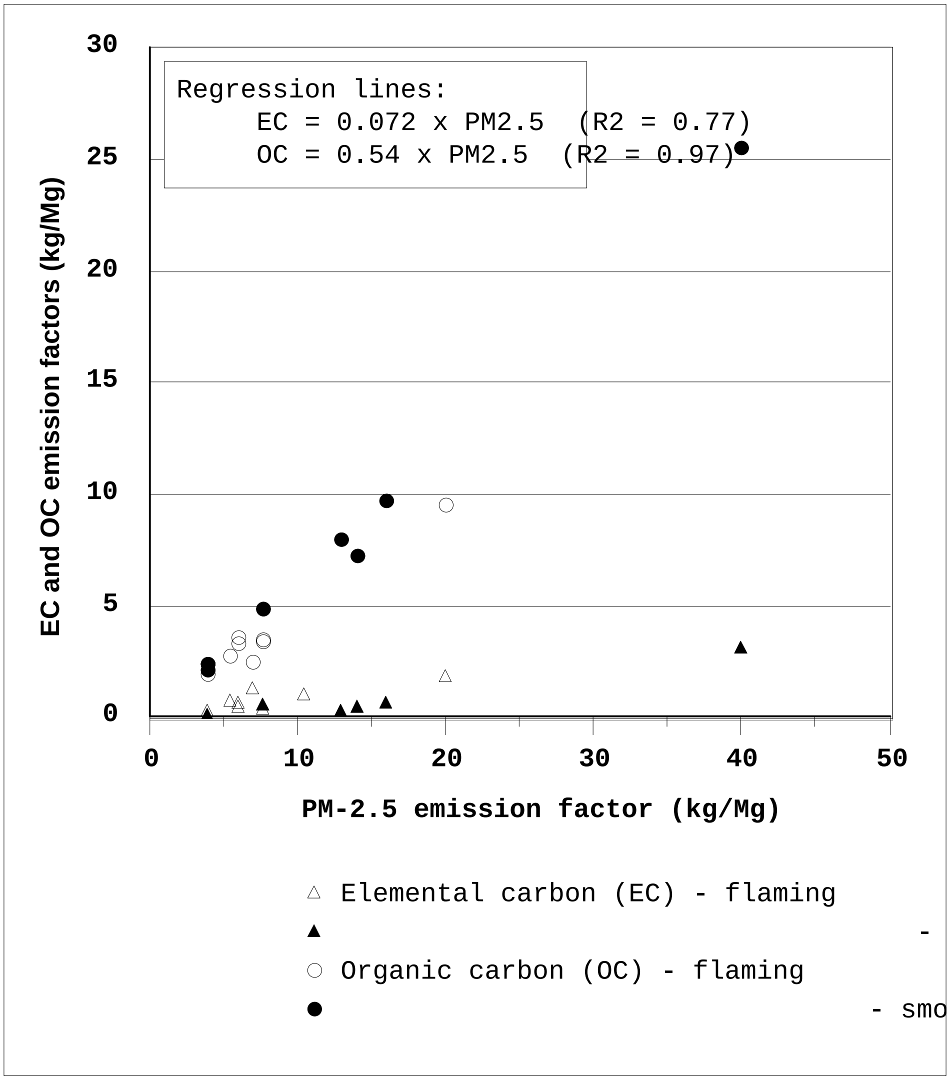

Figure 3. Relationships between particulate elemental and organic carbon and total $PM_{2.5}$

Various researchers have shown that NO_X emissions are associated with flaming conditions, while other nitrogen compounds such as NH_3 are produced in smoldering combustion.[71, 75] Figure 4 plots NO_X emission factors versus modified combustion efficiency, and confirms an increase in NO_X emissions for flaming conditions (higher MCE). However, the correlation coefficient with MCE is poor (R^2 = 0.11). In fact, both Table 26 and Figure 4 show a broad spread in NO_X emission factors.

Table 26 shows that emissions from grasses are somewhat higher than average emissions from forest fuels. This could be the result of higher nitrogen in foliage than in woody materials. Emissions are even higher for scrub brush fires, particularly in California. These values are about a factor of 3 higher than the emission factors for forests, and a factor of 2 higher than the factors for grasses. Laursen *et al* propose two possible causes for the increased emission factors. The first is deposition of NO_X and other nitrogen compounds on the chaparral foliage from air

Table 26. Summary of NO_X Emissions Measurements

Description and location		Modified combustion efficiency (MCE)	Ratio of NO_X to CO_2 (mole %)	Measured emission factor (kg/Mg)	Standard deviation or range	Predicted emission factor from Lacaux [a]
Forest - wildfire						
Alaska (B349), June 1997 (f)	Black spruce	0.929	0.14	2.5		
Alaska (B309), June 1997 (f)	Black spruce, shrub, bog	0.905	0.13	2.3		
Alaska (A121), June 1990 (a)	Black spruce	0.953	0.09	1.7	0.2	
Oregon (Grants Pass), Sept 1989 (b)	Douglas fir, True fir, hemlock	0.921	0.05	0.9	0.7	
Oregon (Roseburg), Sept. 1987 (b)	Pine, brush, Douglas fir	0.907	0.15	2.7	0.7	
Forest - prescribed fire						
Ontario (Charpleau), Aug. 1989 (a)	Paper birch and poplar	0.912	0.02	0.3	0.3	
Ont. (Hornepayne), Aug. 1989 (a)	Birch, poplar, mixed hardwoods	0.958	0.02	0.4	0.3	
Ontario (Battersby), Aug. 1988) (b)	Jack pine, white & black spruce	0.846	0.07	1.1	1.3	
Ontario (Peterlong), Aug. 1988 (a)	Jack pine, white & black spruce	0.927	0.17	2.9	2.5	
Ontario (Chapleau), Aug. 1987 (b)	Jack pine, aspen, Birch	0.928	0.20	3.5	2.3	
Montana (Troy), June 1987 (a)	Pine, Douglas fir, true fir	0.933	0.11	1.9	0.8	
Scrub - prescribed fire						
California (Lodi II), June 1987 (b)	Chaparral, chamise	0.933	0.20	3.5	0.8	
California (Lodi I), Dec. 1986 (b)	Chaparral, chamise	0.935	0.53	9.6	3.5	
CA (Ramona), Dec. 1986 (b)	Black sage, sumac, chamise	0.970	0.41	7.7	3.8	
Grasses						
Alaska, June 1997 (f)	Grasses, low shrubs	0.925	0.20	3.5		
Africa, 1991 - 1992 (c)	Savannah	0.934	0.32	4.4	1.9	
California wind tunnel, 1992 - 1993 (d)						
Almond tree prunings (0.49 % N)		0.969	0.15	4.1		4.2
Douglas fir slash (0.27 % N)		0.958	0.07	1.5		2.1
Ponderosa pine slash (0.30 % N)		0.957	0.09	1.4		2.4
Walnut tree prunings (0.60 % N)		0.948	0.25	5.3		5.2
Forest Service controlled facility						
Broadcast (e)	Flaming	0.989	0.23	3.9		
	Smoldering	0.874	0.06	0.9		
	Overall	0.961	0.19	3.1		
Slash (e)	Flaming	0.994	0.14	2.5		
	Smoldering	0.858	0.01	0.1		
	Overall	0.973	0.12	2.0		

Continued

Table 26. Summary of NO_X Emissions Measurements (continued)

Description and location		Modified combustion efficiency (MCE)	Ratio of NO_X to CO_2 (mole %)	Measured emission factor (kg/Mg)	Standard deviation or range	Predicted emission factor from Lacaux [a]
Forest Service controlled facility (continued)						
Crowns (e)	Overall	0.910	0.20	3.0		
Pine needles (e)	Flaming	0.990	0.26	5.1	4.6 - 5.5	
	Smoldering	0.829	0.03	0.4	0.28 - 0.47	
	Overall	0.958	0.22	4.1	3.9 - 4.4	
Ponderosa pine needles (0.39%N) (g)	Heading fire	0.972	0.10	3.0	0.7	3.2
	Backing fire	0.950	0.08	2.4	0.5	3.2
Simulated forest floor (e)	Overall	0.916	0.25	3.7	3.3 - 4.0	
Douglas fir litter (0.41% N) (g)	Overall	0.950	0.09	2.5	2.5	3.4
Sagebrush (e)	Flaming	0.980	0.33	5.6	5.2 - 5.9	
	Smoldering	0.871	0.20	3.0	2.3 - 3.7	
	Overall	0.965	0.31	5.2	5.0 - 5.3	
Grass (0.66% N) (g)	Overall	0.964	0.11	2.6	0.3	5.8
Averages						
Wildfires		0.923	0.11	2.0	0.7	
Prescribed forest facilities		0.917	0.10	1.7	1.3	
Controlled facilities - forest materials	Flaming	0.960	0.16	3.1	1.2	
	Smoldering	0.858	0.07	1.1	1.3	
	Overall	0.952	0.15	3.0	1.2	
All tests for forests		0.937	0.13	2.5	1.2	
Scrub and sagebrush		0.951	0.36	6.5	2.7	
Grasses		0.941	0.21	3.5	0.9	
All measurements		0.939	0.17	3.1	2.0	

[a] Lacaux et al (1996) propose an empirical model for NO_X emissions based on the concentration of nitrogen in the fuel:

NO_X (g/km) = 9.5 N(%) - 0.49 [R=0.9]

Sources:

(a) Laursen et al (1992)[56]
(b) Hegg et al (1990)[57]
(c) Lacaux et al (1996)[71]
(d) Jenkins et al (1996)[65]
(e) Yokelson et al (1996)[58]
(f) Goode et al (2000)[72]
(g) Goode et al (1999)[59]

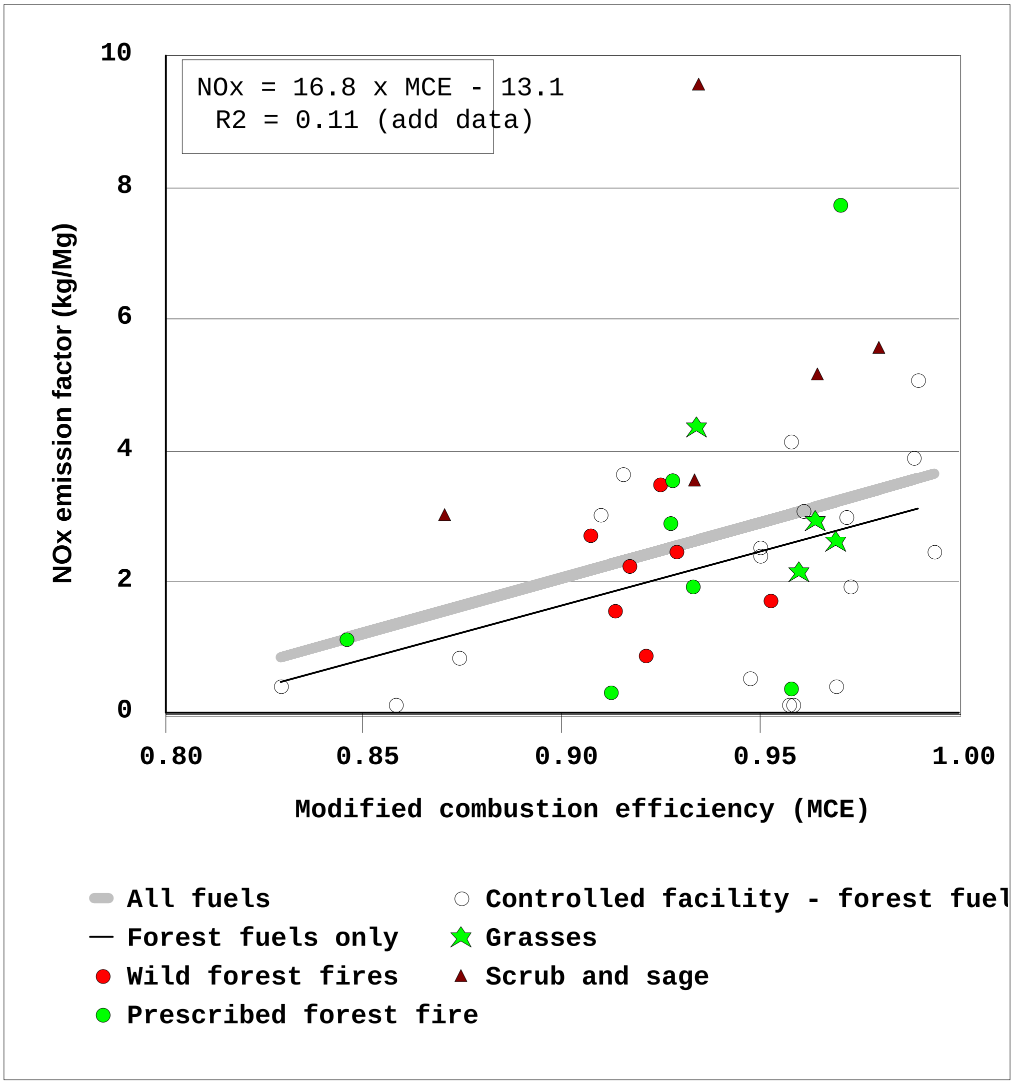

Figure 4. Relation of NO_X emission factor to modified combustion efficiency for different fuel types

pollution in the southern California basin. The second potential explanation is that the dominant chaparral consumed in the fires can produce large root nodules in which nitrogen fixation occurs.[56] It is also possible that fire temperatures were high enough to produce some oxidation of atmospheric nitrogen gas to NO_X.

5.8 Emission Factors for Ammonia

As noted in the previous section, ammonia (NH_3) emissions are associated with smoldering combustion.[71, 75] NH_3 emissions emanate from the degradation of nitrogen compounds in the fuel materials. Table 27 summarizes measurements of NH_3 emissions from fires in the U.S. and Canada. In addition to the measured emission factor, the table gives the ratio of NH_3 to CO.

Table 27. Summary of Ammonia Emissions Measurements

Description and location		Modified combustion efficiency (MCE)	Ratio of NH_3 to CO (mole-%)	Standard deviation or range	Measured emission factor (kg/Mg)	Standard deviation or range
Forest - wildfire						
NC, April 1997 (a)	Loblolly pine plantation		2.6			
AK (B349), June 1997 (b)	Black spruce	0.93	1.2		0.59	
AK (B309), June 1997 (b)	Black spruce, shrub, bog	0.92	1.2		0.70	
AK (B280), June 1997 (b)	Black spruce, shrub, bog	0.92	2.6		1.4	
AK (A121), June 1990 (c)	Black Spruce		1.3	0.5	0.64	0.31
AK (A121), June 1990 (d)	Black spruce	0.95	0.78		0.69	0.33
OR (Roseburg), Sept. 1987 (e)	Pine, brush, Douglas fir	0.91	3.1		2.0	0.9
OR (Silver), Sept. 1987 (e)	Douglas fir, True fir, hemlock	0.92	1.1		0.60	0.5
Forest - prescribed fire						
NC, April 1997 (a)	Pine, oak brush understory	0.93	1.1		0.56	
BC, Canada, Sept. 1989 (d)	Hemlock, deciduous, Douglas fir	0.96	0.58		0.45	0.3
Ont. Canada, Aug. 1989 (d)	Paper birch and poplar	0.91	0.00		0.00	
Ont. Canada, Aug. 1989 (d)	Birch, poplar, mixed hardwoods	0.96	0.00		0.00	
MT, Oct. 1989 (g)	Piled forest slash	0.86	1.2			
Ont., Canada, Aug. 1988 (d)	Jack pine, white & black spruce	0.93	0.72		0.94	0.55
MT, October 1987 (d)	Pine, Douglas fir, true fir	0.93	0.48		0.57	0.28
WA (h)	Pine, Douglas fir, true fir		0.07			
Ont. Canada, Aug. 1987 (e)	Jack pine, aspen, birch	0.93	0.20		0.10	0.07
Grasses and shrubs - wildfire						
AK (B320), June 1997 (b)	Grasses, low shrubs	0.93	1.5		0.77	
CA, August 1994 (i)	Brush (type 4)		4.2	1.1		
OR, August 1994 (i)	Grass, shrub, sage		4.3	1.6		
Grasses and shrubs - prescribed						
WY, October 1989 (g)	Sage	0.86	5.3			
FL, November 1987 (k)	Grass wetlands				0.27	0.35
CA (Lodi I), June 1987 (e)	Chaparral, chamise	0.93	0.20		0.09	0.04
CA (Lodi II), Dec. 1986 (e)	Chaparral, chamise	0.93	3.8		1.7	0.8

(continued)

Table 27. Summary of Ammonia Emissions Measurements (continued)

Description and location		Modified combustion efficiency (MCE)	Ratio of NH_3 to CO (mole-%)	Standard deviation or range	Measured emission factor (kg/Mg)	Standard deviation or range
Forest Service controlled facility						
Broadcast burning (l)	Flaming	0.99	1.4		0.10	
	Smoldering	0.87	2.3		1.80	
	Overall	0.96	2.3		0.57	
Crowns (l)		0.91	2.0		1.1	
Douglas fir litter (m)		0.95	0.48		0.28	0.14
Pine needles (l)	Flaming	0.99	0.60		0.04	0.02 - 0.07
	Smoldering	0.83	1.9		2.24	2.2 - 2.3
	Overall	0.96	1.7		0.49	0.48 - 0.50
Ponderosa pine needles (m)	Backing fire	0.95	0.73		0.20	0.04
	Heading fire	0.97	1.2		0.43	0.065
Simulated forest floor		0.92	2.6		1.36	1.24 - 1.47
Sage brush (m)	Flaming	0.98	1.0		0.12	0.12 - 0.12
	Smoldering	0.87	1.0		0.85	0.75 - 0.96
	Overall	0.96	1.0		0.23	0.19 - 0.28
Grass (m)	Flaming	0.97	0.10		0.03	0.21
	Smoldering	0.96	1.0		0.37	0.037
	Overall	0.96	0.75		0.31	0.025
Averages						
Forest fuels	Flaming	0.96			0.36	0.39
	Smoldering	0.86			1.63	1.48
	Overall	0.93	1.2	0.9	0.63	0.50
Grasses and sage	Flaming	0.97			0.078	0.063
	Smoldering	0.90			0.61	0.39
	Overall	0.93	2.6	2.0	0.56	0.60
All measurements			1.5	1.2	0.70	0.59

Sources:

(a) Yokelson et al (1999)[73]
(b) Goode et al (2000)[72]
(c) Nance et al (1993)[74]
(d) Laursen et al (1992)[56]
(e) Hegg et al (1990)[75]
(g) Griffith et al (1991)[75]
(h) Hegg et al (no date)[57]
(i) Worden et al (1994)[76]
(k) LeBel et al (1988)[77]
(l) Yokelson et al (1996)[75]
(m) Goode et al (1999)[59]

Laursen et al (1992) proposed an empirical equation for estimating NH_3 emissions based on the ratio of the concentrations CO to CO_2:[56]

$$EF_{NH3} = 5.85 \times \frac{EF_{CO}}{EF_{CO2}} + 0.08 \qquad (11)$$

where: EF = Emission factor (kg/Mg fuel consumed)

The correlation coefficient (R^2) for this equation (based on 9 data points) was 0.70. FEP researchers estimated NH_3 emissions at 1.4% of CO emissions, by weight.[4] The ammonia emission models developed by Laursen and the GCVTC can be expressed in terms of the MCE. We also performed a regression analysis of NH_3 versus MCE for the data in Table 27. The resulting three expressions for NH_3 based on MCE are as follows:[***]

Laursen (9 data points, R^2 = 0.70): $$EF_{NH3} = \frac{3.72}{MCE} - 3.64 \qquad (12)$$

GCVTC $$EF_{NH3} = 15.9 - 16 \times MCE \qquad (13)$$

Table 27 (32 data points, R^2 = 0.59) $$EF_{NH3} = 12.9 - 13.1 \times MCE \qquad (14)$$

Figure 5 graphs NH_3 as a function of MCE for the data given in Table 27. The figure also shows the above three relationships. Laursen's 1992 relationship gives lower emissions estimates than the regression based on Table 27. Estimates based on the GCVTC relationship are similar to the current regression results, but somewhat higher.

5.9 Volatile Organic Compounds

The Consume 2.1 model and AP-42 include emission factors for non-methane hydrocarbons (NMHC). The FEP used the following empirical relationships to compute NMHC based on Ward and Hardy (1991):[54]

$$EF_{NMHC} = 0.76 + (0.616 \times EF_{CH4}) \qquad \pm 25\% \qquad (15)$$

$$EF_{CH4} = 42.7 - (43.2 \times CE) \qquad \pm 20\% \qquad (16)$$

where: EF = Emission factor (kg/Mg fuel consumed)

For combustion sources, NMHC emissions are generally taken as equivalent to VOC emissions, which are used in gridded models for ozone and secondary particulate matter formation. However, NMHC emission factors for fire are derived from measurements made by

[***]Laursen's relationship was converted to MCE using equation 6 and the molecular weights of CO and CO_2. The above GCVTC equation was obtained by combining the emission expressions for NH_3 and CO, and using equation 7 to convert combustion efficiency (CE) to modified combustion efficiency (MCE).

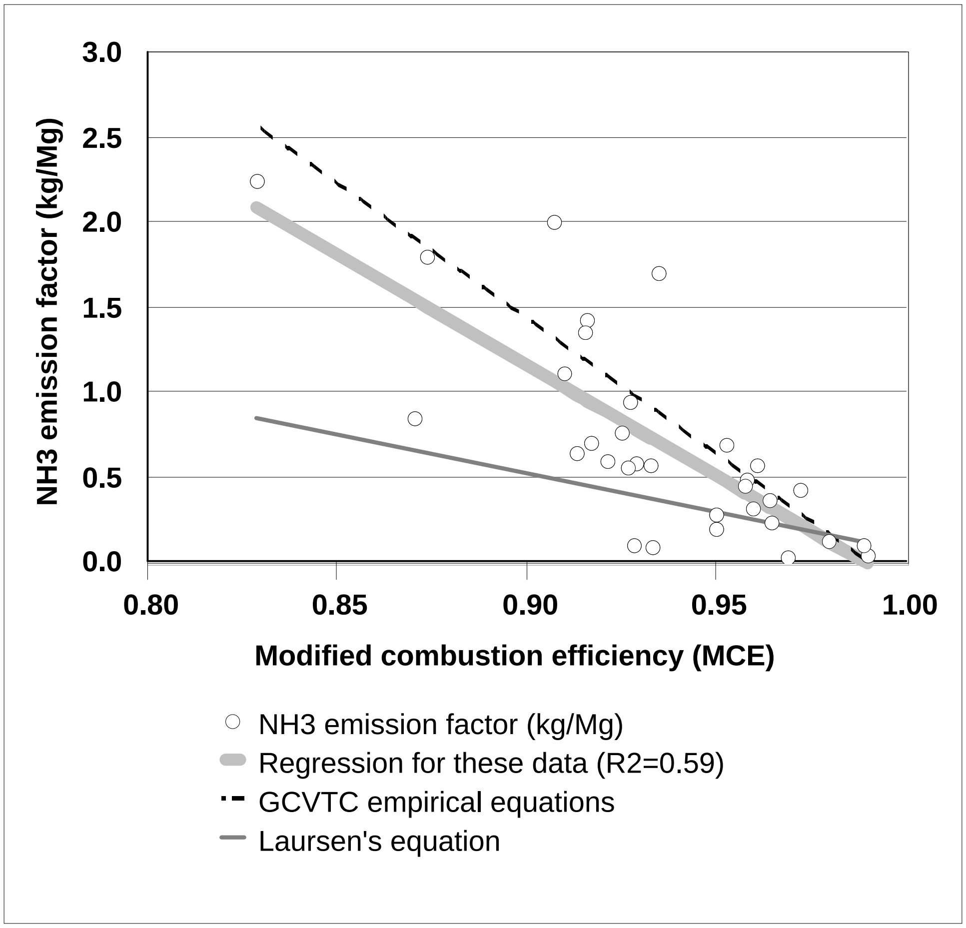

Figure 5. Relation of NH_3 emission factor to modified combustion efficiency

gas chromatography (GC) and flame ionization detection (FID).[51] The FID detection system has a reduced sensitivity to oxygenated compounds such as formaldehyde, other aldehydes, and carboxylic acids.[78] Therefore, emissions of these compounds may be underestimated in the overall NMHC emission factors. It should be noted that these oxygenated species are disproportionately important in the formation of secondary aerosols.[79]

Recent fire studies have used infrared spectroscopy to measure emissions of individual VOC. These measurements are summarized in Table 28. The table gives emission factors for each major organic species, as well as total organic compound emissions. The total emission factors are expressed in terms of the mass of carbon. For comparison, Table 28 also gives the emission factor that would be predicted from the earlier empirical equation for NMHC.

Figure 6 plots the test results from Table 28 against CO emissions (CO is used as an indicator of smoldering conditions). Again, the figure also shows the emission factor that would be predicted from the earlier empirical equation for NMHC. Figure 6 shows an association between VOC emissions and CO emissions, with VOC emissions increasing in proportion to CO.

Table 28. Recent Measurements of Speciated Volatile Organic Compounds

Fire type, location, date, vegetation type, and source		Modified combustion efficiency (MCE)	Measured emission factors (kg/Mg)									Total NMHC predicted from MCE (kg/Mg)
			Meth-anol	Formal-dehyde	Formic acid	Acetic acid	Ethane	Ethyl-ene	Acetyl-ene	C3&4 hydro-carbons	Total	
Wildfires, Alaska, June 1997 (a)												
B280, Black spruce, shrub, bog		0.92	1.44	2.25	1.04	3.38		2.42	0.29		10.8	3.24
B309, Black spruce, shrub, bog		0.92	1.57	1.81	1.21	2.26		1.79	0.20		8.8	3.24
B320, Grasses, low shrubs		0.93	1.45	2.38	1.57	2.95		3.28	0.88		12.5	2.93
B349, Black spruce		0.93	1.23	1.50	0.71	1.61		1.18	0.20		6.4	2.93
Prescribed fires, North Carolina, April 1997 (b)												
Mature pine, oak brush		0.93		2.18							2.2	3.08
Pine, oak brush		0.93	2.03	2.32	1.17	3.11			1.26		9.9	3.02
Controlled facility												
Broadcast (c)	Flaming	0.99	0.10	0.43		0.01	0.17	0.29	0.23		1.2	1.10
	Smoldering	0.87	0.96	0.87		1.31	1.82	1.36	0.40		6.7	4.66
	Overall	0.96	0.30	0.68		0.43	0.58	0.62	0.30		2.9	1.97
Pine needles (c)	Flaming	0.99	0.05	0.26		0.17	0.20	0.20	0.21		1.1	1.07
	Smoldering	0.83	1.59	1.26		8.76	6.06	3.07	1.13		21.9	6.05
	Overall	0.96	0.59	0.42		2.43	1.26	0.73	0.40		5.8	2.06
Sagebrush (c)	Flaming	0.98		0.47			0.08	0.36	0.37		1.3	1.38
	Smoldering	0.87		0.44			0.36	0.43	0.50		1.7	4.75
	Overall	0.97		0.44			0.12	0.38	0.36		1.3	1.84
Slash (c)	Flaming	0.99		0.13			0.03		0.18		0.3	0.95
	Smoldering	0.86		1.31			1.50		0.48		3.3	5.16
	Overall	0.97		0.35			0.23		0.22		0.8	1.60

(continued)

Table 28. Recent Measurements of Speciated Volatile Organic Compounds (continued)

Fire type, location, date, vegetation type, and source	Modified combustion efficiency (MCE)	Measured emission factors (kg/Mg): Meth-anol	Formal-dehyde	Formic acid	Acetic acid	Ethane	Ethyl-ene	Acetyl-ene	C3&4 hydro-carbons	Total	Total NMHC predicted from MCE (kg/Mg)
Controlled facility (continued)											
Crowns, Overall (c)	0.91	3.18	2.75	1.14	6.90	1.99	3.16	1.29		20.4	3.55
Simulated forest floor, Overall (c)	0.92	2.10	2.29		5.06	1.51	1.59	0.72		13.3	3.36
Grass, Overall (d)	0.96	0.49	0.70	0.08	1.18		0.41	0.08	0.21	3.2	1.90
Douglas Fir litter, Overall (d)	0.95	0.82		0.90	2.20		1.11			5.0	2.31
Ponderosa pine needles (d) Backing fire	0.95				0.55		1.28	0.15	0.17	2.2	2.31
Ponderosa pine needles (d) Heading fire	0.97	0.59			1.38		0.65	0.10		2.7	1.69
Averages (kg/Mg)											
Flaming										4.8 ± 4.0	
Smoldering										8.4 ± 8.0	
Overall										6.8 ± 5.3	
Ratio to CO emissions (weight-%)										8.5 ± 4.7	

Sources:

(a) Goode, et al (2000)[72]
(b) Yokelson et al (1999)[73]
(c) Yokelson, et al (1996)[58]
(d) Goode et al (1999)[59]

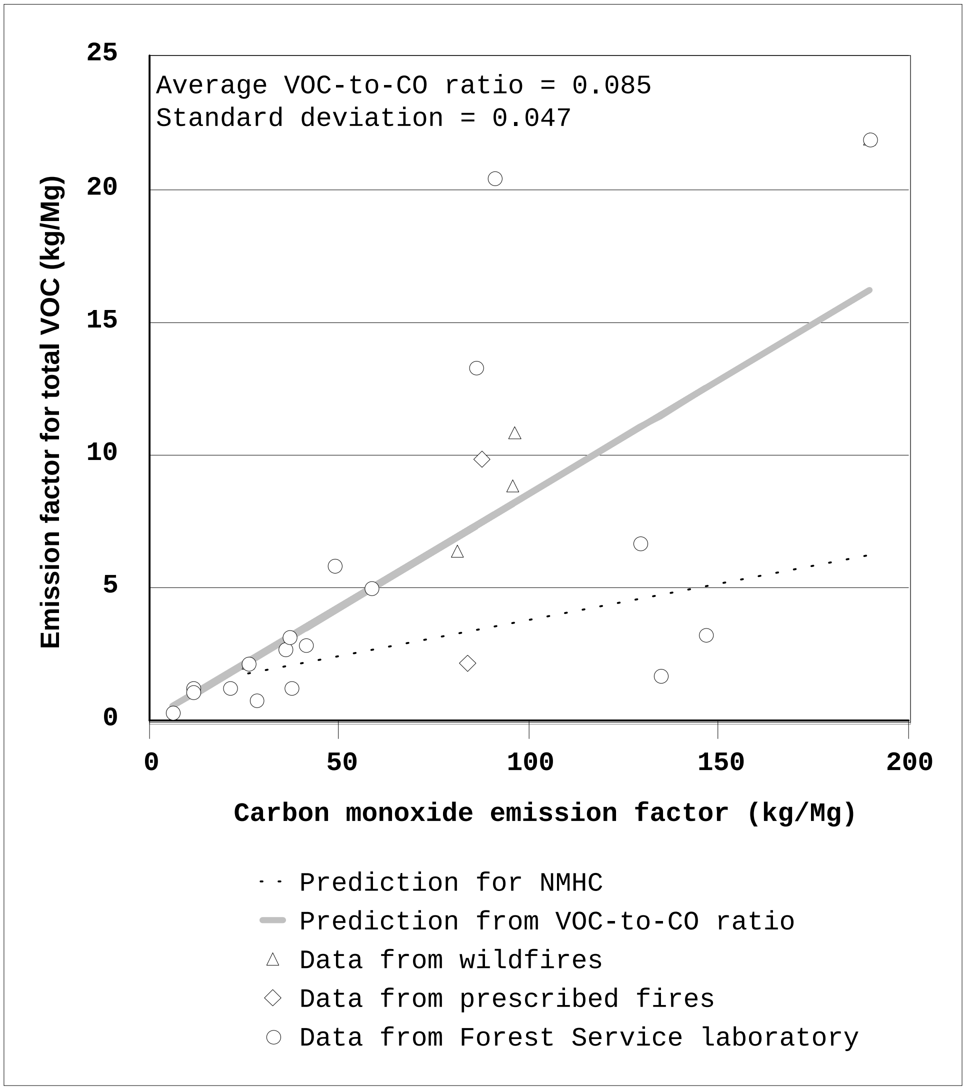

Figure 6. Relation of total VOC to carbon monoxide emissions and comparison to predicted NMHC

Total VOC emissions calculated from speciated tests are, on average, somewhat higher than NMHC emissions predicted from the earlier empirical relationship.

5.11 Emission Factors for Sulfur Dioxide

Sulfur compounds in fuel materials produce SO_2 emissions from wild and prescribed fires. These emissions are minor in comparison with other pollutants, and SO_2 emission factors are not included in fire models or in AP-42. Table 29 summarizes SO_2 data from controlled tests carried out by the Forest Service and the California Air Resources Board (CARB). For each test, the table gives the MCE, emission factor, and ratio of SO_2 to CO_2. For the CARB tests, SO_2 emissions are also expressed as a fraction of total sulfur in the fuel material.

Table 29. Summary of SO_2 Emissions Measurements

Fuel material	Fire type	Modified combustion efficiency (MCE)	Emission factor (kg/Mg)	Range or standard deviation	SO_2 as a fraction of fuel sulfur (%)	Ratio to CO_2 (mole-%)
Forest service controlled facility, Yokelson et al (1996) [58]						
Broadcast	Flaming	0.989	0.44			0.02
	Smoldering	0.874	0.06			0.00
	Overall	0.961	0.43			0.02
Crowns	Overall	0.910	1.4			0.07
Pine needles	Flaming	0.990	2.1	1.73 - 2.56		0.08
	Overall	0.958	1.4	0.99 - 1.73		0.05
Sagebrush	Flaming	0.980	1.8	1.66 - 1.99		0.08
	Overall	0.965	1.4	1.18 - 1.70		0.06
Simulated forest floor	Overall	0.916	2.1	1.66 - 2.61		0.10
Slash	Flaming	0.994	1.2			0.05
	Smoldering	0.858	3.2			0.16
	Overall	0.973	1.2			0.05
California wind tunnel, 1992 - 1993, Jenkins et al (1996) [65]						
Almond tree prunings	Overall	0.969	0.06		82.7	0.02
Douglas fir slash	Overall	0.958	0.05		99.6	0.02
Ponderosa pine slash	Overall	0.957	0.03		128	0.01
Walnut tree prunings	Overall	0.948	0.21		93.8	0.07
Average		0.949	1.04	1.10		0.05

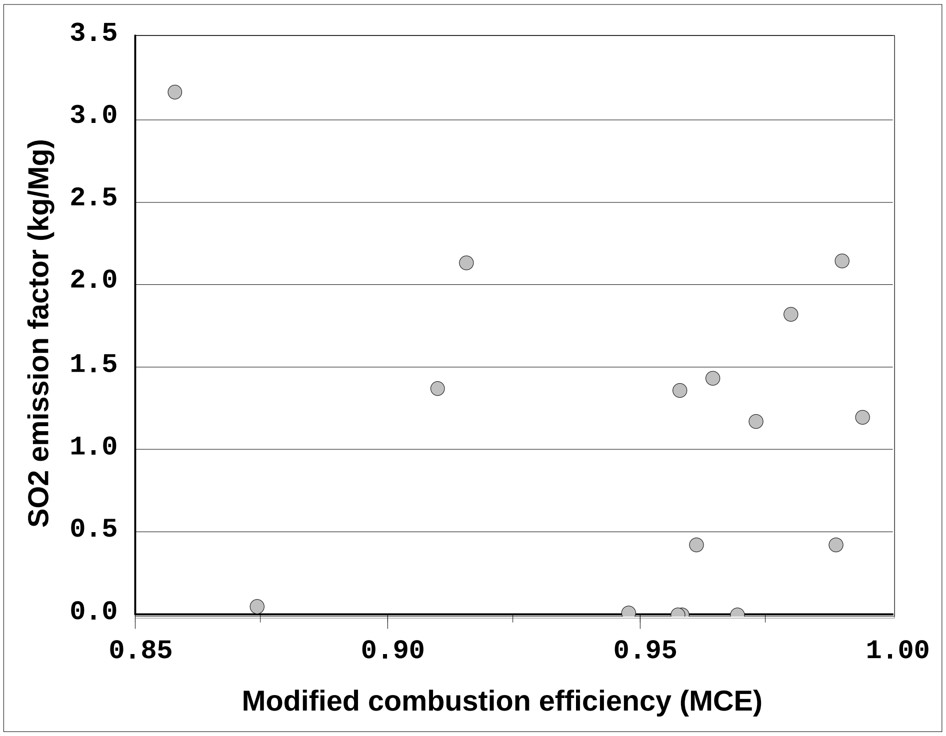

Figure 7. Relation of SO_2 emission factor to modified combustion efficiency

The California tests show that SO_2 emissions account for all of the sulfur in the fuel, within the uncertainty of the measurements. However, other studies have detected small amounts of other sulfur compounds such as carbonyl sulfide (COS).[80] As Table 29 shows, the average emission factor is about 1 kg-SO_2/Mg of fuel burned. The emission factor varies considerably (standard deviation of 0.93), probably because of variability in fuel sulfur content. Data on sulfur content is not generally available for actual wildfires or prescribed fires. As shown in Figure 7, SO_2 emissions are not correlated with modified combustion efficiency ($R^2 = 0.06$).

5.12 Hazardous Air Pollutants

As noted in Section 5.9, emission measurements are available for a number of individual organic species emitted from fires. These species include formaldehyde and methanol, which are hazardous air pollutants (HAPs) regulated under Title III of the Clean Air Act. Table 30 summarizes available data for oxygenated volatile organic HAPs: methanol, formaldehyde, and vinyl acetate. Table 31 summarizes data for benzo(a)pyrene and total polycyclic aromatic hydrocarbons (PAH). Table 32 summarizes data for volatile aromatic HAPs: benzene, toluene, xylenes, styrene, phenol, cresols, and naphthalene. Table 33 summarizes data for chlorinated HAPs: methyl chloride, methylene chloride, carbon tetrachloride, trichloroethane, and perchloroethane. Table 34 summarizes data for other HAPs: hexane, butadiene, acetonitrile, and acrylonitrile. Table 35 summarizes data for HAP metals: cadmium (Cd), chromium (Cr), manganese (Mn), nickel (Ni), and lead (Pb).

Table 30. Measured Emissions of Volatile Oxygenated HAPs

Fire type		Modified combustion efficiency (MCE)	Measured emission factors (kg/Mg): Methanol	Formal-dehyde	Vinyl acetate
Wildfires, Alaska, June 1997 (a)					
B280, Black spruce, shrub, bog		0.92	1.44	2.25	
B309, Black spruce, shrub, bog		0.92	1.57	1.81	
B320, Grasses, low shrubs		0.93	1.45	2.38	
B349, Black spruce		0.93	1.23	1.50	
Prescribed fires					
North Carolina Pine, oak brush (b)		0.93	2.03	2.25	
Wyoming, sage (c)		0.86	0.99		
Montana, piled forest slash (c)		0.84	8.17		
Controlled facilities					
Broadcast (d)	Flaming	0.99	0.10	0.43	
	Smoldering	0.87	0.96	0.87	
	Overall	0.96	0.30	0.68	
Pine needles (d)	Flaming	0.99	0.05	0.26	
	Smoldering	0.83	1.59	1.26	
	Overall	0.96	0.59	0.42	
Sagebrush (d)	Flaming	0.98		0.47	
	Smoldering	0.87		0.44	
	Overall	0.97		0.44	
Slash (d)	Flaming	0.99		0.13	
	Smoldering	0.86		1.31	
	Overall	0.97		0.35	
Crowns, Overall (d)		0.91	3.18	2.75	
Simulated forest floor, Overall (d)		0.92	2.10	2.29	
Grass, Overall (e)		0.96	0.49	0.70	
Douglas Fir litter, Overall (e)		0.95	0.82		
Ponderosa pine needles (e)		0.95	0.59		
Ponderosa pine (f)					
Wood	Flaming		0.75		0.05
	Smoldering		4.30		3.00
Needles	Smoldering		4.90		2.00
Bark	Self sustaining		1.00		0.50
	Smoldering		1.10		1.00
Litter	Self sustaining		0.60		0.50
	Smoldering		2.00		0.70
Duff			0.55		0.30
			0.69		0.15
Humus	Smoldering		0.09		
Average emission factors	Flaming		1.5 ± 1.8	1.4 ± 1.0	0.30 ± 0.20
	Smoldering		2.3 ± 1.9	0.97 ± 0.40	1.9 ± 1.2
	Overall		1.7 ± 1.8	1.5 ± 0.91	0.91 ± 0.98
Average ratios to CO (weight %)			0.99 ± 0.93	1.6 ± 1.0	na

Sources:
(a) Goode, et al (2000)[72]
(b) Yokelson et al (1999)[73]
(c) Griffith (1991)[75]
(d) Yokelson, et al (1996)[58]
(e) Goode et al (1999)[59]
(f) McKenzie et al (1995)[81]

Table 31. Measured Emissions of Benzo(a)pyrene and Total PAH

Description		Emission factors (g/Mg fuel)		Ratios to fine particulate matter (g/Mg $PM_{2.5}$)	
		BaP	PAH	BaP	PAH
Slashed pine litter, combustion chamber (a)					
Heading	Flaming	0.029	5.6	2.8	559
	Smoldering	0.10	27	1.2	327
Backing	Flaming	0.40	18	68	3,077
Logged units, Western Oregon (b)	Flaming	0.32		28	
	Smoldering	0.25		16	
Wind tunnel (c)					
Douglas fir slash	Flaming	0.035	14	2.1	307
Ponderosa pine slash	Flaming	0.050	6.5	4.2	273
	Smoldering	0.000	21	0.0	167
	Overall	0.039	9.7	3.2	248
Almond prunings	Flaming	0.028	6.8	1.6	157
Walnut prunings	Flaming	0.006	8.5	0	219
Average		0.13	13	14	699
Standard deviation		0.15	7.5	22	1,056

(a) McMahon and Tsoukalas (1978)[82]
(b) Ward and Hardy (1984)[83]
(c) Jenkins (1996)[65]

Table 32. Measured Emissions of Volatile Aromatic HAP

Fire type		Modified combustion efficiency (MCE)	Emission factor (g/kg)						
			Benzene	Toluene	Xylenes	Styrene	Phenol	Cresols	Naphthalene
Almond prunings, pile fire (a)		0.97	0.030	0.020	0.003	0.010	0.011	0.009	0.007
Douglas fir slash, pile fire (a)		0.96	0.20	0.16		0.14	0.093		0.014
Ponderosa pine slash, pile fire (a)		0.96	0.44	0.35	0.056	0.27	0.25	0.20	0.017
Walnut prunings, pile fire (a)		0.95	0.016	0.011		0.002		0.007	0.018
Grasses, wood, hay, pine needles (b)		0.93	0.34	0.24	0.12				
Ponderosa pine (c)									
Wood	Flaming						0.020	0.070	
	Smoldering	0.85					0.110	0.086	
Bark	Self sustaining						0.120	0.090	
	Smoldering						0.29	0.11	
Litter	Self sustaining						0.070	0.060	
	Smoldering						0.32	0.13	
Duff	Self sustaining						0.080	0.041	
	Smoldering						0.20	0.079	
Needles	Smoldering						0.35	0.099	
Humus	Smoldering						0.040		
Average emission factors									
Flaming							0.094	0.073	
Self sustaining							0.090	0.064	
Smoldering							0.24	0.10	
Overall			0.20±0.19	0.16±0.15	0.058±0.056	0.11±0.13	0.15±0.12	0.08±0.05	0.014±0.005
Average ratio to CO (weight %)			0.38±0.40	0.29±0.32	0.096±0.08	0.22±0.29	0.26±0.29	0.16±0.26	0.026±0.01

Sources:
(a) Jenkins, et al (1996)[65]
(b) Lobert, et al (1991)[84]
(c) McKenzie, et al (1995)[81]

Table 33. Measured Emissions of Chlorinated HAPs

Fire type	Modified combustion efficiency (MCE)	Emission factor (g/kg) Methyl chloride	Methylene chloride	Carbon tetra-chloride	Trichloro-ethane	Perchloro-ethane
Prescribed fire						
Pine and fir, Montana, October 1987 (a)	0.93	0.015				
Pine and spruce, Ontario, August 1988 (a)	0.93	0.021				
Birch and poplar, Ontario, August 1989 (a)	0.91	0.017				
Birch, poplar, and hardwood, Ontario, August 1989 (a)	0.96	0.013				
Wildfire						
Black spruce, Alaska, June 1990 (a)	0.95	0.043				
Savannah, Ivory Coast, February 1991 (b)		0.083	0.0073	0.0002	0.0009	0.00001
Controlled facility						
Grasses, wood, hay, straw, pine needles (c)	0.93	0.18				
Average	0.94	0.053±0.06	0.0073	0.0002	0.0009	0.00001

Sources:
(a) Laursen et al (1992)[56]
(b) Rudolph et al (1995)[85]
(g) Lobert, et al (1991)[84]

Table 34. Measured Emissions of Other Organic HAPs

Fire type	Combustion efficiency (CE)	Modified combustion efficiency (MCE)	Emission factor (g/kg) Hexane	Buta-diene	Aceto-nitrile	Acrylo-nitrile
Ponderosa pine slash, pile fire (a)	0.95	0.96	1.42			
Grasses, wood, hay, straw, pine needles (b)	0.91	0.93		0.13	0.223	0.029

Sources:
(a) Jenkins, et al (1996)[65]
(b) Lobert, et al (1991)[84]

Table 35. Measured Emission Ratios for HAP Metals

Description		Ratio to $PM_{2.5}$ (%) Cd	Cr	Mn	Ni	Pb	$PM_{2.5}$ emissions (kg/Mg)
Prescribed fires, Pacific NW (a)							
Chaparral	Flaming	0.055	0.000	0.010	0.002	0.425	20
	Smoldering	0.015	0.000	0.014	0.001	0.082	40
Conifer	Flaming		0.113	0.038	0.009	0.154	7
	Smoldering		0.024	0.020	0.010	0.078	14
Crane piled	Flaming	0.001	0.000	0.019	0.000	0.007	4
	Smoldering	0.040	0.001	0.018	0.000	0.003	4
Hardwood	Flaming	0.169	0.018	0.023	0.024	0.211	6
	Smoldering	0.066	0.003	0.011	0.003	0.031	13
Ponderosa pine	Flaming	0.045	0.003	0.016	0.005	0.068	6
	Smoldering	0.014	0.000	0.008	0.002	0.019	16
Tractor piled	Flaming	0.066	0.000	0.045	0.011	0.234	4
	Smoldering	0.015	0.000	0.005	0.027	0.010	4
Prescribed chaparral fires, Los Angeles (b)							
Lodi 1	Flaming			0.010	0.000	0.300	7.7
Lodi 2	Flaming			0.010	0.000	0.600	7.7
Lodi 3	Flaming			0.030	0.000	0.370	5.5
	Smoldering			0.010	0.000	0.080	7.7
Averages (with standard deviations)	Flaming	0.067 ±0.062	0.022 ±0.045	0.022 ±0.013	0.006 ±0.008	0.263 ±0.184	
	Smoldering	0.030 ±0.034	0.005 ±0.006	0.012 ±0.012	0.006 ±0.006	0.043 ±0.074	
	Overall	0.049 ±0.048	0.014 ±0.032	0.018 ±0.011	0.006 ±0.009	0.17 ±0.18	

(a) Ward and Hardy[68]
(b) Ward and Hardy[69]

5.13 Summary of Available Methods for Estimating Pollutant Emission Factors

Tables 36 and 37 outline the options and methods available to estimate emission factors, and summarize the advantages and disadvantages associated with each option. Table 36 addresses CO and $PM_{2.5}$. Table 37 addresses the remaining pollutants, which are often estimated from CO and $PM_{2.5}$.

Tables 38 and 39 and summarize emission factors for criteria and other pollutants. Table 38 lists CO, $PM_{2.5}$ and PM_{10} emission factors for specific fuel types and fire configurations. These factors are taken from the Consume emission model.[42] Table 39 lists general emission factors and empirical relationships for criteria and other pollutants. As many options as possible are provided for emission factors, for instance separate emission factors for flaming and smoldering, as well as combined fire-average factors.

Table 36. Options for Estimating CO and $PM_{2.5}$ Emission Factors

	➡ ➡ Increasing level of detail ➡ ➡				
Options					
CO	Regional defaults (AP-42)	Separate emission factors for flaming and smoldering	Fuel consumption models (FOFEM, Consume, etc.) with default inputs	Fuel consumption models with input from land managers	Emission factors for specific fuel type
$PM_{2.5}$	"	"	"	"	"
Advantages	Least effort required	Improved accuracy	Improved accuracy with little additional effort	Improved accuracy	May improve accuracy if appropriate factors are available
Disadvantages	Least accuracy	Relative amounts of flaming and smoldering combustion must be known	Default inputs may not provide desired accuracy	Considerable effort required	Factors would be based on limited measurements, considerable effort required

Table 37. Options for Estimating Emission Factors for EC, OC, NO_X, NH_3, VOC, SO_2, and HAPs

	➨ ➨		Increasing level of detail		➨ ➨
Options					
EC	Overall average factor	Separate factors for flaming and smoldering	Relation to $PM_{2.5}$		
OC	"		Separate relation for flaming and smoldering		
NO_X and NH_3	"	Separate factors for flaming and smoldering, and for forests, grass, and scrub	Relation to MCE or CO	Relation to nitrogen in fuel, separate relations for flaming and smoldering	Emission factors for specific forest type
VOC	"	"	Relation to CO		Emission factors for specific forest type
SO_2	"				
Volatile HAPs	Average factor		Relation to CO		
Particulate HAPs	Relation to $PM_{2.5}$				
Advantages	Least information required	Improved accuracy	Improved accuracy with little additional effort	Better correlation	May improve accuracy if appropriate factors are available
Disadvantages	Least accuracy	Information required on breakdown between flaming and smoldering	Information required on CO, MCE, or CE and $PM_{2.5}$	Information required on fuel nitrogen	Factors would be based on limited measurements, considerable effort required

Table 38. Summary of Emission Factors for Specific Fuels and Configurations

Fuel and fire configuration	Emission factor (g/kg)		
	Flaming	Smoldering	Fire average
CO			
Broadcast-burned slash			
Douglas fir / hemlock	72	232	156
Hardwoods	46	183	128
Ponderosa / lodgepole pine	45	143	89
Mixed conifer	27	137	101
Juniper	41	125	82
Pile-and-burn slash			
Tractor-piled	22	116	77
Crane-piled	51	116	93
Average piles			85
Broadcast-burned brush			
Sagebrush	78	106	103
Chaparral	60	99	77
$PM_{2.5}$			
Broadcast-burned slash			
Douglas fir / hemlock	7.5	13.1	10.9
Hardwoods	6.1	11.7	11.2
Ponderosa / lodgepole pine	5.0	17.1	11.0
Mixed conifer	4.8	11.8	9.4
Juniper	7.0	11.9	9.4
Pile-and-burn slash			
Tractor-piled	3.3	7.0	5.4
Crane-piled	5.9	15.5	11.7
Average piles			8.6
Broadcast-burned brush			
Sagebrush	14.6	13.2	13.4
Chaparral	6.8	10.8	8.7
Wildfires - average			13.5
PM_{10}			
Broadcast-burned slash			
Douglas fir / hemlock	8.3	13.8	11.6
Hardwoods	7.0	13.0	12.5
Ponderosa / lodgepole pine	5.8	18.4	12.5
Mixed conifer	5.9	12.7	10.3
Juniper	7.7	12.9	10.2
Pile-and-burn slash			
Tractor-piled	3.7	8.0	6.2
Crane-piled	6.8	16.6	12.8
Average piles			9.5
Broadcast-burned brush			
Sagebrush	15.9	14.8	15.0
Chaparral	8.3	12.4	10.1
Wildfires - average			15.0

Source: Consume 2.1 emission model.[42]

Table 39. Summary of General Emission Factors and Empirical Relationships

	Average emission factors - with standard deviations (kg/Mg)							
	Flaming		Smoldering		Overall		Empirical relationships	Standard deviation or R^2
CO_2	1,650		1,393		1,521		1833 × CE	±5
CO	75		213		144		961 - (984 × CE)	±10
CH_4	3.8		9.9		6.8		42.7 - (43.2 × CE)	
$PM_{2.5}$	7.3		17		12		67.4 - (66.8 × CE)	
PM_{10}	8.6		20		14		1.18 × $PM_{2.5}$	
Elemental carbon	0.73	±0.50	0.77	±1.0	0.73	±0.70	0.072 × $PM_{2.5}$	±63
Organic carbon	3.7	±2.2	8.6	±7.4	5.8	±5.7	0.54 × $PM_{2.5}$	±14
NO_x								
Forest fuels	3.1	±1.2	1.1	±1.3	2.5	±0.12		
Grasses					3.5	±0.90		
Scrub and sage			3.0		6.5	±2.7		
Overall					3.1	±2.0	(16.8 × MCE) - 13.1 9.5 N(%) - 0.49	R^2 = 0.11 R^2 = 0.9
Ammonia								
Forest fuels	0.36	±0.39	1.6	±0.7	0.63	±0.50	0.0073 × CO	±75
Grasses and scrub	0.078	±0.063	0.61	±0.34	0.56	±0.60	0.016 × CO	±77
VOC	4.8	±4.0	8.4	±8.0	6.8	±5.3	0.085 × CO	±55
SO_2					0.83	±0.76		

(Continued)

Table 39. Summary of Emission Factors and Empirical Relationships (continued)

	Average emission factors - with standard deviations (kg/Mg)				Standard deviation
	Flaming	Smoldering	Overall	Empirical relationships	or R^2
HAPs					
Methanol	1.5 ±1.8	2.3 ±1.9	1.7 ±1.8	0.0099 × CO	±94
Formaldehyde	1.4 ±1.0	0.97 ±0.4	1.5 ±0.9	0.016 × CO	±63
Vinyl acetate	0.30 ±0.20	1.9 ±1.2	0.91 ±0.98		
Benzo(a)pyrene			0.00013 ±0.00015		
Total PAH (excluding naphthalene)			0.01 ±0.075		
Benzene			0.20 ±0.19	0.0038 × CO	±105
Toluene			0.16 ±0.15	0.0029 × CO	±110
Xylenes			0.058 ±0.056	0.00096 × CO	±83
Styrene			0.11 ±0.13	0.0022 × CO	±132
Phenol			0.15 ±0.12	0.0026 × CO	±112
Cresols			0.08 ±0.05	0.0016 × CO	±163
Naphthalene			0.014 ±0.005	0.00026 × CO	±38
Methyl chloride			0.053 ±0.060		
Methylene chloride			0.0073		
Carbon tetrachloride			0.0002		
Trichloroethane			0.0009		
Perchloroethane			0.00001		
Hexane			1.4		
Butadiene			0.13		
Acetonitrile			0.22		
Acrylonitrile			0.029		
Cd				0.00049 × $PM_{2.5}$	±100
Cr				0.00014 × $PM_{2.5}$	±229
Mn				0.00018 × $PM_{2.5}$	±61
Ni				0.00006 × $PM_{2.5}$	±150
Pb				0.0017 × $PM_{2.5}$	±106

6. Temporal Resolution and Other Dispersion Model Inputs

Emissions inventories for wildland fire are needed for dispersion modeling efforts to predict the ambient impacts of fire and other emission sources. These models generally fall into two categories: Gaussian models used to predict local impacts, generally for short time frames; and gridded atmospheric simulation models used to predict regional or national scale ambient impacts. These models require information on the temporal distribution of emissions, on the specific location of emissions, and on the height and buoyancy of emissions. Detailed Gaussian modeling of an actual fire requires hourly emissions estimates to match hourly meteorological data. Gridded models generally use seasonal allocation factors, combined with hourly allocation factors for typical days in each season. These allocation factors can be applied at the national, state, or county level. Gridded models can also use day-specific emissions estimates and day-specific hourly factors to simulate specific episodes.

6.1 Available Databases and Tools

Table 40 summarizes options for determining the temporal distribution of emissions, and lists advantages and disadvantages associated with each option. Detailed fire incident databases maintained by the Forest Service, the DOI, and many states (discussed in Chapter 2) provide a starting point for calculating seasonal allocation factors at various levels of geographic detail. These databases can also be used to produce emissions estimates for specific fires, however they do not provide enough detail to estimate daily or hourly emissions.

Daily and hourly emissions can be estimated using the Emissions Production Model (EPM-2) developed by the Forest Service.[86] EPM-2 incorporates algorithms from the FOFEM and Consume emission models, as well as the Briggs plume rise algorithm. EPM-2 simulations can be used to develop hourly allocation factors for gridded models and hourly emissions estimates for Gaussian models. EPM-2 also estimates the heat release rate and resulting buoyancy of fire emissions, and can be linked to a number of Gaussian dispersion models. The PLUMP is another model that can be used to estimate plume rise for fire emissions.[87]

Source apportionment techniques can also be used to estimate the ambient impact of fire emissions, either independently or in conjunction with atmospheric dispersion modeling. These techniques involve detailed chemical analysis of ambient particulate matter to identify components that are characteristic of fire emissions, such as particulate elemental and organic carbon. Radiocarbon dating can also be used to estimate the breakdown of this carbon between fossil fuel sources (coal, oil, and natural gas) and wood combustion.

6.2 Previous Inventories

The FEP estimated seasonal fire emissions based on a survey of land managers.[4] EPA's NEI is often used in gridded modeling studies, which use national average seasonal and hourly allocation factors. These factors have not been updated to reflect the information available in large scale fire incident databases.

Table 40. Options for Determining the Temporal Distribution of Fire Emissions

	➙ ➙ Increasing level of detail ➙ ➙			
Option	Default seasonal and/or hourly profiles	Allocation using actual seasonal fire frequencies	Fire-specific emission calculations	Fire-specific hourly modeling with the Emission Production Model (EPM)
Advantages	Lowest level of effort	Better detail for predicting ambient impacts and model validation efforts	Better detail for short term or local modeling. Allows determination of the effectiveness of alternative burning strategies in reducing emissions or impacts	Most detail for local modeling Level of effort is manageable for small scale studies such as a single large fire
Disadvantages	Lowest level of detail	Considerable data manipulation required to incorporate details for specific regions and target years	More effort required	Considerable effort and data manipulation would be required for a large scale inventory

7. Structure of the Fire Emissions Inventory

Emissions inventories for wild and prescribed fire must feed into national, regional, and state-level emissions inventories that are developed for other manmade and natural emission source categories. The resulting comprehensive emissions inventories are used in modeling studies and other assessments of NAAQS attainment, regional haze, and other air pollution problems. The methodologies used for other emission source categories provide useful examples that could be used in fire inventories.

7.1 Point and Area Source Inventories

Emissions inventories are typically divided into point, area and mobile source components. Point sources are included in the inventory as discrete emission points. Area and mobile source categories represent aggregates of emission sources that are too small and too numerous to be included individually in the point source inventory. Mobile source inventories cover highway vehicles and off-road vehicles and engines. Area source inventories estimate total emissions at the county level for various consumer, commercial, and industrial activities. For the national inventory, the threshold for facilities to be included in the point source inventory instead of the area source inventory has historically been 100 tons of emissions per year for any criteria pollutant. Lower cutoffs are used for state and local criteria pollutant inventories and for hazardous air pollutants (HAPs).

Fire inventories could also be divided into more detailed and less detailed components. In this framework, detailed and rigorous emissions estimates could be developed for large fires and fires near urban areas or Class I areas. (By analogy, criteria pollutant inventories typically are more detailed for urban areas and for larger sources.) Smaller fires could be aggregated to county or grid level estimates. Subcategories could also be used for various land ownership and administrative classifications.

7.2 Top-down and Bottom-up Approaches

For large scale emissions inventories, the EPA has recently been using a combination of top-down and bottom-up approaches, as illustrated in Figure 8. Initially, the EPA develops county-level area source emissions estimates on a national scale using generalized methodologies and information. This “default” inventory is suitable for some large-scale regional analyses and screening analyses. EPA also provides general guidance for states and local agencies to develop area sources emissions estimates through the Emissions Inventory Improvement Program (EIIP). In order to analyze local air pollution problems, states and local agencies may develop smaller scale inventories that are more rigorous and detailed than the national default inventory. Periodically, these more accurate inventories are incorporated into the default inventory, and the national inventory is improved.

Again, a similar approach can be used for fire inventories, where a national default inventory could be developed for large scale and screening analyses. States, local agencies, and tribes could then provide improved inventories which would be substituted into the national inventory for specific geographic areas or time periods.

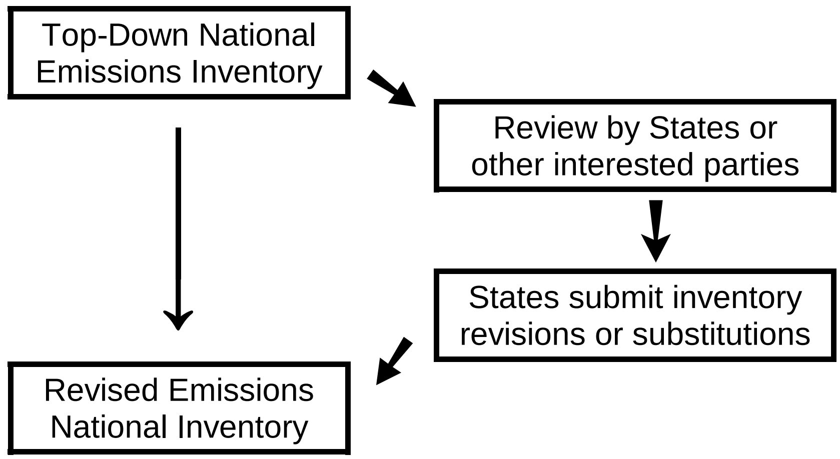

Figure 8. Incorporation of detailed local information into a default top-down emissions inventory

7.3 Appropriate Levels of Precision for Fire Inventories

7.3.1 Typical Precision of Air Quality Model Inputs

Emissions inventories for fire may be used in both plume models (or Gaussian models) and grid-based models (Eulerian models). Plume modeling generally requires detailed information on the emissions source, including an exact location, information on the surrounding terrain, and hourly emissions estimates. The plume modeling approach is primarily used for local modeling of large emission sources that are found in the point sources inventory.

Most modeling studies of regional haze will use grid-based models. Emissions inputs for regional grid models typically are allocated to grid cells measuring 50 to 60 kilometers on a side. Smaller grid resolutions (down to 2 km) are used for more detailed local modeling studies. Grid-based models generally use a 1-hour temporal resolution. However, the majority of emissions inputs are expressed in terms of hour-by-hour emission rates over the course of a set of "typical" or episode specific days. This temporal resolution is designed to reflect the difference in emissions that occurs for most categories of emissions on weekdays versus weekends and in the different seasons. For large emission sources (e.g., utility boilers), episode-specific emissions estimates may be developed which would reflect actual activity patterns or impacts of actual meteorological conditions on emissions.

The standard approach of allocating emissions to a set of typical day-types (spring weekday, summer weekday, etc.) is not well suited to fire emissions. This approach requires a routine which is not present in the case of fire. That is, wildfires or prescribed fires in a particular grid or county cannot be represented as seasonal averages. Wildfire typically have a duration of a week to a month, but emissions may vary by several orders of magnitude during the course of a particular fire. Prescribed fires may be as short as a day.

7.3.2 Previous Recommendations on Fire Inventory Requirements

Sandberg and Peterson prepared a White Paper in 1997 outlining recommendations for estimating fire emissions in SIP emissions inventories.[22] The White Paper defines three levels of inventory precision:

- Default level - based only on information that is currently available
- Level I - a basic level that would be considered a national model for SIP development
- Level II - a detailed level, where more precise analysis is needed

Table 41 summarizes the levels of precision recommended in the White Paper for Level I and II inventories.

Table 41. Overview of the Levels of Inventory Precision Suggested in the White Paper on SIP Emissions Inventory Development for Wildland Fire

Parameter	Suggested minimum precision (Level I)	Options for increasing precision (Level II)
Size cutoff	Prescribed fire: 100 tons of biomass consumed Wildfire: 10 acres or 100 tons of biomass consumed	de minimus may vary by state or other administrative division
Time period	year	season, month, day
Location	administrative area	county, latitude and longitude, watershed
Area burned	acreage	stratify by fuelbed description
Fuelbed description	grass, brush, forest floor, forest crowns or slash	Prescribed fire: vegetative type, fuel profile, fuel profile by loading category (high, medium, or low), inventoried fuel loadings Wildfire: acreage burned by date, fuelbed, fire intensity (severe, moderate, or low), etc.
Fuel consumed (percent or mass/acre)	expert estimate	site specific information for driving predictive algorithms
Emission factor	burn average (based on tabular value)	site specific information to allow consumption to be apportioned into flaming and smoldering phases

Source: Sandberg and Peterson[22]

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Appendix A.
Methods for Mitigating Emissions *

There are two general types of control options for air pollutant emissions from prescribed burns: those that reduce the total amount of emissions, and those that reduce the impact of emissions on smoke-sensitive areas (also known as smoke management techniques).

A.1 Emission Reductions Techniques

There are four major factors that influence the amount of emissions produced: area burned, fuel loading, fuel consumption, and combustion efficiency. It is helpful to group emission reduction techniques by the method by which they reduce emissions.

A.1.1 Reducing the Area Burned

Reducing the area burned is one way to reduce emissions from burning, if the technique used reduces burning in the long term. (Caution must be taken so that reducing the area burned does not actually result in delaying the release of emissions either through prescribed burning at a later date or as a result of wildfire.) Alternatives to fire are least applicable when fire is needed for ecosystem or habitat management, or forest health enhancement. In some areas and for some vegetation types, where fire is used to eliminate an undesirable species or dispose of biomass waste, alternative methods can be used to accomplish effects similar to what burning would accomplish. Examples of specific techniques include:[1]

- *Mechanical treatments and reduced fuel loading:* These treatments may include whole tree harvesting and/or yarding of unmerchantable (YUM), harvesting the small and defective wood to tighter specifications, firewood sales, encouraging the production of pulp, paper, and specialty forest products, and the use of grazing or browsing animals. The removal of fuels may result in sufficient treatment so that burning is not needed. However, mechanical treatments may interfere with land management objectives if they cause undue soil disturbance or compaction, stimulate alien plant invasion, impair water quality, or remove material needed for nutrient cycling or small animal habitat. A difficulty with mechanical treatments is that most require good road access which may not be available.

- *Chemical treatments:* These treatments may produce effects similar to fire when the objective is to reduce or remove live vegetation and/or species from a site. Certain chemical treatments have their own set of ecological and public-relations problems.

- *Concentration burning* is the burning a subset of a larger area.

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* This appendix is taken mainly from a paper by Peterson and Leenhouts (1997).[1]

- *Burning fees* can be charged per acre burned or per ton emitted to discourage burning on private or public lands.

A.1.2 Reducing Fuel Loading

Reducing fuel loading prior to burning results in less fuel being available to burn and therefore less emissions. Reducing fuel loading is accomplished by physical removal of fuels prior to burning, or scheduling burning before new fuels appear.

- *Mechanical fuel removal:* This strategy is basically the same as mechanical treatments in the previous section, except that in this case, the treatments are followed by fire. With increased utilization, burning is done more safely and at lower cost because there are fewer large pieces to extinguish. This option also results in additional site preparation and less risk of escaped slash fires; nutrients are conserved, the organic layer is preserved, and the mineral soil remains unaltered. The effectiveness of this technique is marginal during very dry or very wet weather.[1, 2, 3, 4, 5]

- *More frequent burning:* Frequent, low-intensity fires can prevent unwanted vegetation from becoming established on the forest floor. If longer fire rotations are used, this vegetation has time to grow, resulting in extra fuel loading at the time of burning. This technique generally has positive effects on land management goals since it is likely to result in fire regimes that more closely mimic natural fire frequencies.[1] This option also releases plant nutrients and minimizes overstory damage.[5]

- *Burning when there is less fuel:* Burning can sometimes be scheduled for times of year before new fuels appear. Brushy cover loose their leaves in the fall and increase the amount of litter in the fuel bed. Burning before the fall can reduce the amount of fuel available in certain cover types. Burning before greenup in brushy and/or herbaceous fuelbed cover types also results in less fuel being available for burning.[1, 4]

A.1.3 Reducing Fuel Consumption

Emission reductions can be achieved when significant amounts of fuel are at or above the moisture of extinction, and therefore unavailable for combustion. However, this strategy may leave large amounts of fuel in the treated area to be burned in the future. Long-term emission reductions are achieved only if the fuels left behind can be expected to decompose or be otherwise sequestered at the time of subsequent burning. Reducing fuel consumption reduces fireline intensity, crown and foliage scorch, and cambium injury, thus reducing flora and fauna mortality.[1]

- *Burning when there is a high fuel-moisture content:* Usually litter and duff burns inefficiently; if it is moist, the amount that is consumed can be reduced. The necessary conditions usually occur in the Spring where snow has covered the ground all winter, or within a few days of a soaking rain. Large-diameter fuel consumption and smoldering can also be reduced if it is burned when it has a high fuel moisture content. This method can be effective with both natural and activity fuels. Burning logging sites within 3 or 4 months after the timber harvest before the large fuels cure can also reduce emissions. One drawback to this option is that the Spring-like conditions required usually occur on a limited number of days each year. It also must be noted that although clean piles burn more efficiently, dirty piles can create more problems with smoldering.[1, 2, 4, 4, 5, 6]

- *Mass ignition:* Mass ignition occurs though a combination of dry fine fuel and very rapid ignition, such as through the use of a helitorch. When done correctly, mass ignition creates a very strong column of convection current which draws much of the heat away from the fuelbed, preventing drying and preheating of larger, moister fuels. The fire dies out shortly after the fine fuels fully consume and there is little smoldering or consumption of the larger fuels and duff, reducing the amount of fuel consumed. The conditions needed are only possible in open areas with broadcast activity fuels (generally clearcuts). In addition to reducing emissions, mass ignition also reduces the risk of slash-fire escapes.[1, 2, 4, 5]

- *Rapid mop-up:* Rapidly extinguishing a fire can reduce fuel consumption and smoldering emissions somewhat, although this option is not particularly effective and can be costly. Rapid mop-up primarily effects smoldering consumption of large-woody fuels and duff. This option can reduce the risk of slash-fire escapes.[1, 2, 4]

A.1.4 Increasing Combustion Efficiency

Combustion efficiency can be increased by shifting the majority of the consumption away from the smoldering phase and into the more efficient flaming phase. Increasing combustion efficiency can reduce emissions, except for NO_X and CO_2. It also results in an increased fireline intensity, which can cause an increase in microorganism mortality.[1]

- *Burning fuels in piles or windrows:* Fuels concentrated into piles or windrows generate greater heat and burn more efficiently. Concentrating fuels into piles and windrows generally requires the use of heavy equipment which can negatively impact soils and water quality. Piles and windrows also cause temperature extremes in the soils directly underneath and can result in areas of soil sterilization.[1]

- *Backing fires:* Backing fires cause more flaming combustion, which burns more efficiently and causes less pollutant emissions than smoldering combustion. In the time that the backing fire passes, most available fuel is consumed, so the fire quickly dies out with very little smoldering combustion occurring. Backing fires in fine fuels also concentrate the heat near the root collars of weed species. This option requires moderate winds and very dry fine fuels.[1, 4, 5]

- *Rapid mop-up:* Rapidly extinguishing a fire results in some minor reductions in smoldering consumption.[1] See description above.

- *Mass ignition with a shortened fire duration:* With mass ignition the fire dies out shortly with little smoldering or consumption of the larger fuels or duff.[1] See description above.

A.2 Smoke Management Techniques

The purpose of smoke management techniques is to minimize the impacts of smoke on urban and residential areas, heavily-used recreation areas, Class I areas, and other sensitive areas. Smoke management techniques do not reduce the amount of emissions created.

- *Meteorological scheduling* involves scheduling burns for periods of good atmospheric dispersion, when prevailing winds will blow the smoke away from sensitive areas;

- *Pre-ignition modeling* predicts downwind particulate concentrations (although the accuracy of these estimates may be low, it may be appropriate to require such modeling if there is a lack of trained smoke management meteorologists at the state or local level) which can be used to inform burn decisions; and

- *Active-phase smoke monitoring* allows burn managers to discontinue ignition and/or extinguish the fire if the winds change, or if the smoke begins to behave in an unexpected way, or if particulate concentrations in sensitive areas build to unacceptable levels.

- *Choosing conditions that encourage cloud scavenging:* With the right atmospheric conditions, a portion of smoke particles can be removed from the atmosphere through cloud processing of smoke, where the smoke particles are incorporated into cloud droplets. This process is also known as nucleation scavenging. There is evidence that approximately 50% of emissions can be removed if the fire is capped by, or the smoke introduced into, a modest-sized cumulus cloud. To enhance this process, the moisture content of the atmosphere must be adequate, the winds must be correct, and there must be enough energy provided by the fire itself. Because this option requires heat from the fire, it can be an alternative to using emission reduction techniques that rely heavily on reducing biomass consumption. Fire prescriptions which call for burning into coastal stratus or strato-cumulus overcast conditions, or into slow moving storms, could also result in improved removal efficiencies.[7]

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