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Emissions from Forest Burning in the Southeastern United States: Application of a Model Determining Spatial and Temporal Fire Variation

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Significant quantities of forest land burn in the southeastern United States as a result of wildfire and fire prescribed for a variety of land-management objectives. Hence, the types of fires range from generally high-intensity wildfires and site-preparation fires to low-intensity, prescribed fires in the forest understory. Due to their role as oxidants, greenhouse gases, and primary pollutants, interest is considerable in the quantity of particulates and gases emitted in these fires; however, reliable estimates of emissions are difficult to arrive at because quantities vary in response to type and quantity of fuel, moisture content, and characteristics of fire. For example, Laursen et al. (1992) found substantial variation in emissions factors for NO_x (0.30-14.5), CH_4 (1.0–8.9), nonmethane organic compounds (NMOC) (0.71-2.67), and N_2O (0.032-1.3) among a variety of ecosystems and fire characteristics. Their approach to predicting global-scale emissions from burning was to use average emissions from a variety of fires in western North America coupled with global estimates of hectares burned. At global scales, the effect of averaging across a wide range of emissions rates is minimized because these rates encompass the spectrum of fire-emissions combinations. Peterson and Ward (1994) developed annual estimates of emissions from prescribed fires in 1989 for Environmental Protection Agency (EPA) regions in the United States. They used fuel- and fire-specific emissions factors from fires in western states, fuel type specific loadings, and fire-objective-driven consumption estimates. At smaller scales, such as the southeastern region studied here, we hypothesized that more refined estimates of emissions-fire combinations for the southeast, and accounting for climatic effects on consumption, would improve estimates of emissions and better define source areas.

Our objective was to develop a southeastern U.S. region (N. Carolina, S. Carolina, Georgia, Virginia, Alabama, Tennessee, and Florida) scale model that will estimate emissions (particulates, CO_2, CO, NO_x, N_2O, THC, CH_4, and NMOC) from forest burning. Our approach was to develop a regional forest-burning emissions model (FBEM) responsive to variation in fuels and fire characteristics (figure 68.1).

Description of Model

The model was programmed in QBASIC on a personal computer. QBASIC was chosen because it is readily available, inexpensive, and easy to use. Data required to run the model are input from a separate file. This file includes state and province codes, four climatic variables (total monthly rainfall, average monthly temperature, average monthly relative humidity (%), and average monthly wind speed), hectares burned (by wildfire, slash fire, and understory fire), and pine vs. hardwood distribution. The climate data are used to estimate fuel moisture in a submodel within FBEM (see fuel-moisture section below). Parameters for emissions factors (g emissions/kg fuel consumed; by fire and fuel type) and fuel loading (kg ha^{-1}; by fire and fuel type) are constant and written directly in the model code; however, they can easily be changed when more site or region specific parameters are available. The model predicts emissions of particulates, carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NO_x), nonmethane organic carbons (NMOC), total hydrocarbons (THC), nitrous oxide (N2O), and methane (CH4). Emissions reflect interest in particulate matter (PM), oxidant precursor and radiatively important gases, and availability of emissions factors. The current version of the model has a monthly temporal resolution and a spatial resolution of province (i.e., coastal plain, piedmont, mountain, and Cumberland Plateau) by state (figure 68.2). This provincial breakdown corresponds to spatial patterns of burning types. For instance, in states with significant amounts of managed forest, most prescribed burning in pine occurs on the coastal plain, but hardwood wildfire is more common in the piedmont and mountain provinces.

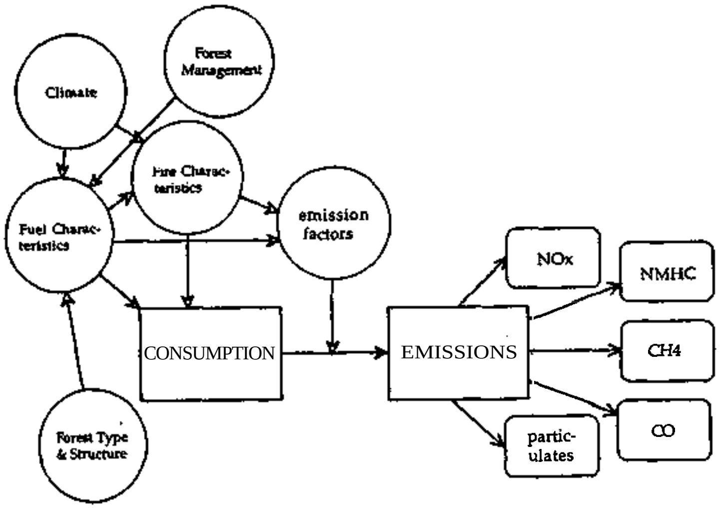

Figure 68.1 Conceptual diagram of modeling components and linkages in FBEM. For simplicity, only a subset of emissions is shown.

Development of Database

A large component in the research involved assembling, summarizing, and synthesizing data required to develop the linkages between model components, shown in figure 68.1. Data were acquired from a variety of sources, including computerized literature searches and personal contact with state and federal agencies. For example, we retrieved and extracted data from more than 200 publications on emissions, fuel loading, and fuel consumption for forest burning in North America. In addition, we established contacts with all state agencies responsible for recording fire information on state and federal lands. As with any large-scale modeling effort, the quantity and specificity of data varied considerably among components. This variability strongly influenced both the spatial and temporal resolution of FBEM.

The model was applied to climate and burn databases for calendar year 1982. We chose 1982 because error-free regional climatic data were readily available and we assumed that burn databases from the 1980s would be readily accessible (i.e., in computerized form) from the individual states.

Climate

Monthly climate data (precipitation, air temperature, relative humidity, wind speed) for each county and state were obtained from the Forest Health Atlas (Marx 1988). These data were originally first-order station data acquired from the National Climatic Data Center (NCDC), which were subsequently checked for accuracy. Typically, the NCDC data had error rates of between 5 and 40% (Marx 1988) and so a large portion of the data was removed prior to usage. For use in FBEM, climate data were averaged by province within each state.

Forest Type

We used information from the USDA Forest Service Forest Inventory and Analysis (FIA) plots (Beltz et al. 1992) to determine the relative distribution of pine versus hardwood forest types. FIA data provided volume estimates for major species groups for the eastern United States. We summed those data by hardwood and pine for each county, and determined the percent age distribution for each. Using this approach, we could not distinguish the percentage of land area that was in pure pine stands, pure hardwood stands, and pine/hardwood mixtures. County data were averaged by province to provide a province-level estimate for each state.

Fuel Load

Values from the literature were used to estimate fuel loads of understory, slash, and wildfires. Typical fuel loads of 10 000, 3000, and 1000 kg ha^{-1} for wildfire, slash, and understory fire types, respectively, were used in the FBEM model. Where available, more specific fuel-load estimates can be readily input into FBEM.

Fuel Moisture

We used a simple fine-fuel moisture content (FFMC) model (Rothermel et al. 1986 [Appendix A], Simard and Main 1982) to determine climatic effects on fuel moisture. FFMC is a daily model, with temperature, wind speed, precipitation, and relative humidity as driving variables. The temporal resolution of FBEM was monthly, and so we calibrated the daily FFMC

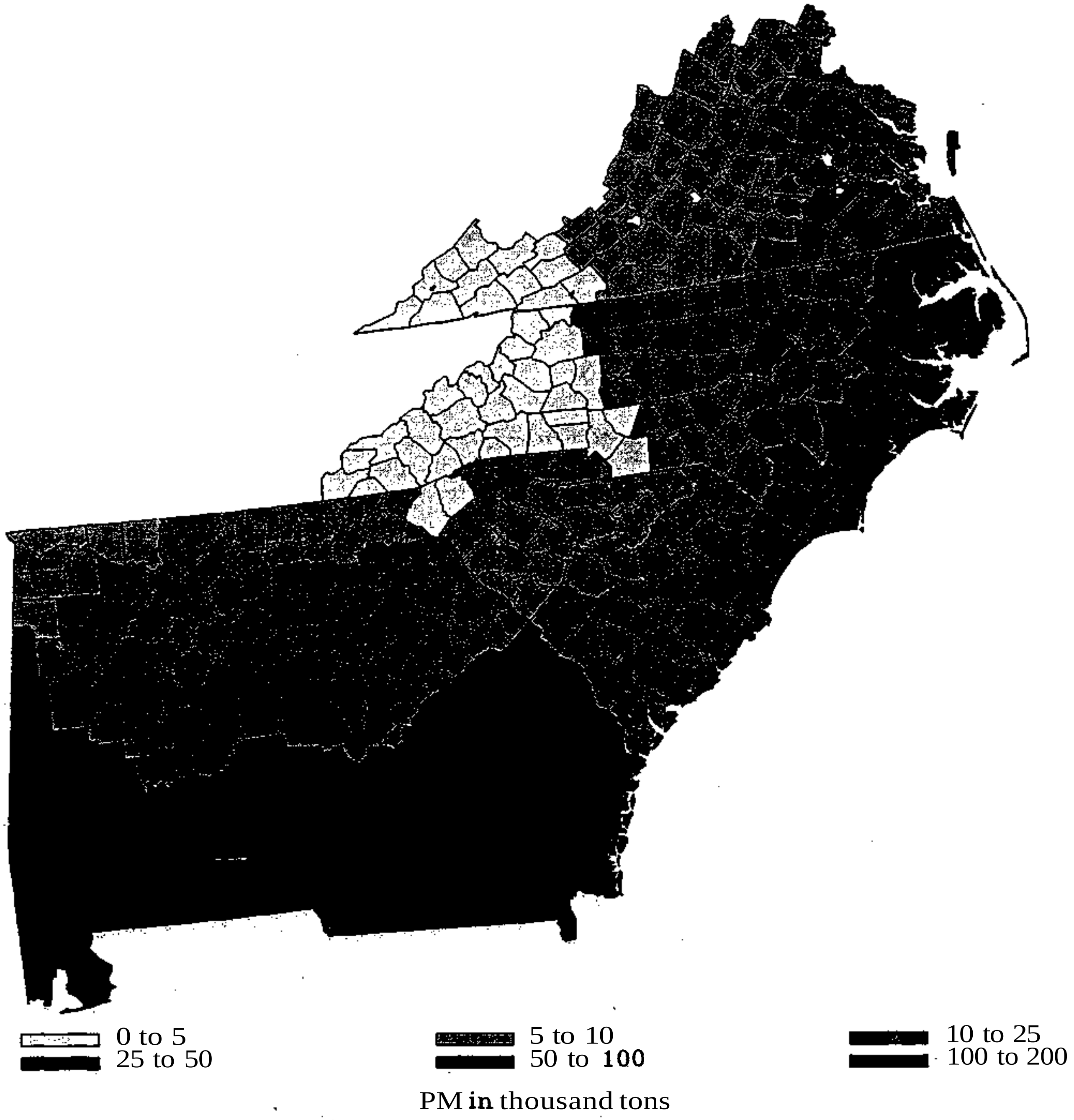

Figure 68.2 PM emissions (Gg) by state and province. Data for Georgia were derived by assuming equal emissions to Alabama.

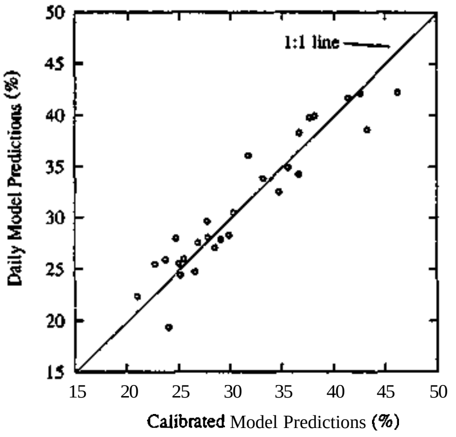

Figure 68.3 Comparison of fine fuel moisture characteristics using the calibrated model and the daily model

model to predict fuel moisture using monthly climatic data. To do so, we obtained daily climatic data from specific climatic stations in four states (Georgia, South Carolina, Virginia, and Florida) to encompass the four seasons (January, April, July, and October). Using daily climatic data, we estimated daily fine-fuel moisture (%) using the FFMC and averaged the estimates by month. Next, we averaged the daily climatic data and predicted "average monthly fuel moisture" using FFMC. Differences between the means determined from daily climatic data versus monthly estimates using average climatic data were substantial, with monthly estimates overestimating fuel moisture relative to daily climatic data by about 20 percent. To adjust for this overestimation, we applied an empirical correction by developing a regression equation that predicts monthly mean fine-fuel moisture content from FFMC predictions, average monthly wind speed, and average monthly humidity (figure 68.3). As shown by the 1 : 1 line, the correction improved fuel moisture estimates substantially.

Fuel Consumption

Fuel consumption was estimated using an empirical approach. We extracted initial fuel load, fuel moisture, and consumption data from published studies in the southeastern United States and developed a regression equation predicting fuel consumption (fraction of initial weight consumed) from initial fuel moisture (%) and fuel load (kg/m^{-2}). Data used in the regression included a variety of fuel and fire types because data were insufficient to develop specific consumption regression equations for all combinations of fuel and fire type. The model had reasonable explanatory power (i.e., fraction of initial weight consumed = 0.955 — 0.0068 * fuel moisture % - 0.0067 * fuel load; $r^2 = 0.74$, » = 37, $p < 0.0001$, $MSE = 0.11198$), and both fuel moisture and fuel load were significant parameters in the regression. The signs on the parameters of the regression indicate less consumption with wetter and heavier fuel loads. Heavier fuel loads typically contain material of larger diameters that tends not to burn completely.

Hectares Burned

Historical data on the number of hectares burned were acquired from state agencies. We requested data on forest hectares burned by fire type (wildfire, understory fire, and site-preparation or slash fire), month, and county. The data obtained varied considerably among states with respect to spatial and temporal resolution and the specificity of fire types (tables 68.1, 2). As a result, we were often required to make assumptions about type of fire and temporal distribution. Data were especially scarce for prescribed fires, and where data were available, the spatial and temporal resolution of the data were often poor. In some cases, correspondence from the state agencies indicated the most likely period when prescribed burning was conducted in their state. When applicable, we used that information to distribute annual prescribed burning data through the year. When time information was not available, we were often required to make assumptions about those factors. For example, when we received prescribed fire hectares burned data that did not specify whether the prescription was for understory burning or site preparation/slash reduction, we divided those data equally between the prescribed burning types. Furthermore, when monthly data were not available, we assumed that understory burning occurred primarily late in the fall and winter (October-March) and that site preparation/slash reduction occurred in spring and summer (April-September). Although emissions and fuel-consumption data from Florida are included in the model parameterization, we were unable to obtain burn data from Florida for 1982.

Emissions Factors

Emissions factors used in FBEM were extracted from the literature (Appendix A). We focused most of our search on studies conducted in the southeastern United States and utilized information from both field and laboratory studies. Consistent with the modeling framework outlined in figure 68.1, our goal was to obtain specific emissions factors by type of fuel and fire and to develop a refined database for all the emissions

Table 68.1 Number of hectares burned due to wildfires in 1982

	Province			
State	Coastal plain	Piedmont	Mountain	Cumberland plateau
	ha/province			
Alabama	21 035	4635	8554	2322
Georgia	5754	3759	899	na
North Carolina	22433	8935	842	na
South Carolina	14549	3142	186	na
Tennessee	na	na	2532	6728
Virginia	6135	3150	439	na

na = Province designation does not apply.

Table 68.2 Number of hectares burned (ha/province) due to site preparation and understory burning in 1982

	Site preparation				Understory			
State	CP	P	M	CuP	CP	P	M	CuP
Alabama	230526	41 376	11820	11 820	85266	15266	4374	4374
Georgia	no data				no data			
North Carolina	4176	2682	414	na	19446	6444	0	na
South Carolina	11 574	5484	654	na	109 146	22848	180	na
Tennessee	insignificant				insignificant			
Virginia	3160	1760	220	na	3160	1760	220	na

na = Province designation does not apply to this state.
CP = coastal plain
P = piedmont
M = mountain
CuP = Cumberland Plateau

we studied. There was considerable variation in availability of emissions factors. For example, the most extensive data were for particulates (tables 68.3, 4), where there was a full spectrum of fuel and fire conditions. In contrast, few data existed for NO and N_2O emissions factors, particularly for southeastern forests. The lack of data required less specific, or in some cases, average values for some combinations of fire and fuel types in tables 68.3 and 68.4. The emission factors shown in tables 68.3 and 68.4 are the average of the smoldering and flaming phases and they are averaged across studies.

For many emissions factors, values vary considerably in the flaming and smoldering phases (Appendix A) of combustion, and this variation contributes to the range of values shown in tables 68.3 and 68.4. We evaluated the potential effect of using average emission factors from data obtained in an intensive study in North Carolina (Ward et al. 1991). Flaming and smoldering phase emission factors for PM-10, CO, CO_2, NO_x, NMOC, N_2O, and CH_4 were used in FBEM to predict emissions from site-preparation burning of pine forest in North Carolina. We assumed that in these types of fires, 75% of the fuel was consumed in the flaming phase and 25% in the smoldering phase. These assumptions follow the general guidelines for flaming and smoldering consumption based on fuel size described in Peterson and Ward (1994). We also averaged the emission factors by fire phase (as is done in FBEM) and applied them to fuel-consumption estimates that were not separated by fire phase. There were differences in emissions estimates using both approaches (figure 68.4). For CO, NMOC, and CH_4, emissions using average emissions factors and total fuel consumption were greater than the fire phase specific emissions and fuel-consumption estimates by as much as 28%, with an average difference of about +15%. Values were essentially identical for the other emissions components. Results of this comparison depend on the accuracy of fire phase consumption estimates, where changes within the range of potential values (i.e., ±20%) can either eliminate or exacer-

Table 683 Mean, range, and sample size of emissions factors (g/kg) for pine forests in the southeast United States. Emission factors were derived from values obtained from the literature (Appendix A).

Emissions component	Wildfire			Slash			Understory		
	Mean	Range	*n*	Mean	Range	*n*	Mean	Range	*n*
Particulates	32.9	25-40.8	2	26.2	9.5-25.6	10	22.0	7.5-62.5	30
CO	46.8	10.5-83	2	46.8	10.5-83	2	70.9	63-114	5
CO_2	1609	1386-1760	23	1609	1386-1760	23	1598	1232-1740	3
NO_x	2.3	1.8-2.7	3	2.3	1.8-2.7	3	4.6	1.8-9.9	5
NMOC	3.8	1.2-10.1	20	3.8	1.2-10.1	20	3.8	1.2-10.1	20
THC	7.1	4.1-9.3	3	7.1	4.1-9.3	3	7.1	4.1-9.3	3
N_2O	1.3	—	1	1.3	—	1	1.3	—	1
CH_4	5.8	1.3-15	20	5.8	1.3-15	20	5.8	1.3-15	20

Table 68.4 Mean, range, and sample size of emissions factors (g/kg) for hardwoods. Emissions factors were derived from values obtained from the literature (Appendix A).

Emissions component	Mean	Range	*n*
Particulates	1.5	6.7-27	8
CO	86.1	34-183	8
CO_2	1673	1426-1790	8
NO_x	*5.6*	0.3-14.5	4
NMOC	2.3	0.6–7	8
THC	7.1	4.1-9.3	3
N_2O	0.22	0.15-0.39	6
CH_4	4.4	0.9-9.8	8

bate these differences. Our decision to use the average of smoldering and flaming phase emissions is based in part on the uncertainty of the fuel characteristics across our wide range of fire types (i.e., wildfire, site-preparation, and understory). In addition, some studies in the southeast did not separate emissions factors by fire phase, and so our database would be further restricted if separate emissions factors were used to run the model.

Example of Model Application

Input data consist of monthly data (hectares burned by wildfire, slash fire, and understory fire, and climate) for each province in a state. The distribution of pine and hardwood forest types varies by province and state, but is constant monthly. FBEM predicts province-level emissions as follows: (1) climatic data are used in the fuel-moisture submodel to estimate average fuel moisture for each province and month; (2) fuel consumption (%) is predicted using the general regression equation, which is a function of fuel moisture and initial fuel load; (3) percentage of fuel consumption is multiplied by fuel load to estimate consumption (kg ha^{-1}); (4) total fuel consumption (kg/province) for each province and fire type is determined by multiplying consumption (kg ha^{-1}) by hectares burned; *(5)* fires are distributed between pine and hardwood forest types by multiplying by the percentage distribution of each in each province; and (6) emissions for each province (kg/province) are predicted by multiplying the appropriate emissions factor (e.g., N2O for pine wildfires 1.3 g kg^{-1}) by the hectares burned.

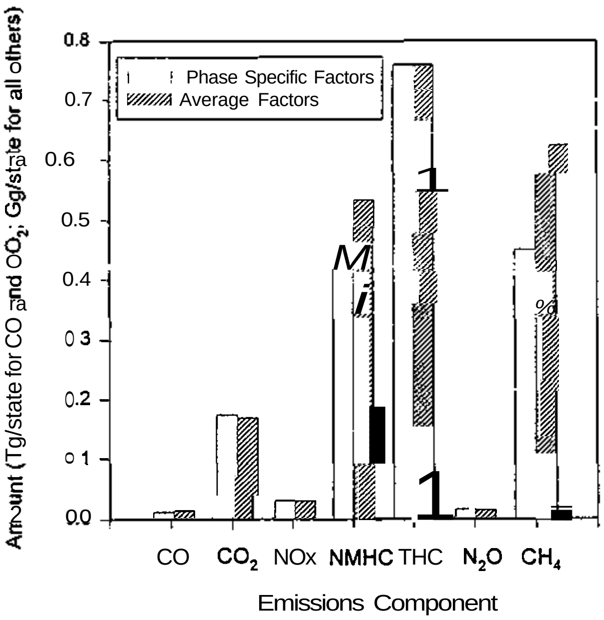

Figure 68.4 Comparison of emissions with fire phase specific emissions factors versus emissions with emissions factors averaged across fire phase in North Carolina

Table 68.5 Emissions (Gg/state) from wildfire in 1982

State	Particulates	CO	CO_2	NO_x	NMHC	THC	N_2O	CH_4
Alabama	62	152	3962	8.9	7.7	17.1	2.1	12.7
Georgia	18	42	1123	2.4	2.2	4.9	0.6	2.5
North Carolina	63	132	3700	7.4	7.6	16.0	2.3	12.3
South Carolina	31	73	1922	4.2	3.8	8.3	1.0	6.2
Tennessee	11	48	1005	3.1	1.5	4.3	0.2	0.6
Virginia	17	51	12.2	3.1	2.2	5.2	0.5	1.8

Emissions Estimates

State Totals

Emissions from wildfire varied considerably among states. Alabama and North Carolina had the highest emissions for all compounds, followed by South Carolina, Georgia, Virginia, and Tennessee (table 68.5). The most important factor driving emissions is the number of hectares burned (table 68.1), where the ranking of hectares burned by state follows the same patterns as the emissions. In addition, variation in climatic conditions (which influences fuel moisture) and distribution of forest types (which influences emissions factors) also contribute to the variation in emissions among states. For example, Georgia and Virginia had essentially equal amounts of wildfire in 1982 (i.e., 10 400 vs. 10 300 ha, respectively). However, variation in emissions ranged from 8% (CO_2) to 25% (CH_4) between those states. Differences in distribution of pine vs. hardwood forest types between states (e.g., 65% hardwood for Virginia vs. 58% hardwood for Georgia) meant that the emissions were weighted more toward the hardwood-specific emission factors (table 68.4) in Virginia. Average fuel consumption was essentially the same for both states (i.e., 66%); however, the range in fuel consumption was greater for Virginia (minimum =60%, maximum = 73%) than for Georgia (minimum = 62%; maximum = 70%).

Prescribed fire data were available for all states except Georgia, and, as previously mentioned, the temporal and fire type resolution of those data varied considerably. Hence, resolution of the emissions estimates should be viewed with caution because their accuracy depends upon the validity of the assumptions used to distribute those data by type of fire and month. Emissions from prescribed burning varied considerably among states (table 68.6). They were greatest for Alabama, followed by South Carolina, North Carolina, and Virginia. Variation in emissions was related primarily to differences in amount of land area burned, which ranged from 404 822 ha for Alabama to 10 280 ha for Virginia. As with wildfire, additional variation was related to differences in climate (as it influences fuel consumption) and to the relative distribution of pine and hardwoods. Furthermore, we accounted for two types of prescribed burning; that is, site preparation (which includes slash fires and hazard-reduction fires) and understory fires. For pines, these two types of prescribed burning had specific emission factors. Hence, differences among states in relative distribution of fires between site-preparation and understory burns also contributed to the variation observed.

The importance of wildfire versus prescribed-fire emissions varied considerably among states (tables 68.5, 6). In Tennessee, prescribed burning was so infrequent that the only source of emissions was wildfires. In North Carolina and Virginia, wildfire generally exceeded prescribed-fire emissions, and in South Carolina, emissions were about even. In contrast, emissions from Alabama were dominated by prescribed burning. We suspect that prescribed burning was a significant contributor to emissions in Georgia; however, we were unable to obtain prescribed-fire data from Georgia for 1982. As an example, in 1989, Georgia prescribed burning the same land area as Alabama (e.g., 400770 vs. 395 587 ha for Alabama and Georgia, respectively) (Peterson and Ward 1994). This similarity implies that emissions from prescribed burning in Georgia are comparable in magnitude to those in Alabama, as could be expected from similarities in physiography, mixes of forest type, and intensity of forest-management practices.

Province Totals

Emissions of all components were greatest on the coastal plain, followed by the piedmont, mountain, and Cumberland Plateau provinces. This pattern is shown for PM-10 in figure 68.2, and patterns were similar for all other emissions (data not shown). The high emissions in the coastal plain and piedmont provinces were related to the large amount of intensively managed forest land and this quantity was heavily influenced by the contributions from Alabama.

Table 68.6 Emissions (Gg/state) from prescribed fire for 1982

State	Particulates	CO	CO_2	NO_x	NMOC	THC	N_2O	CH_4
Alabama	156	281	11 276	26.9	23.1	50.8	6.3	37.8
North Carolina	7.3	19.5	477	1.4	1.1	2.4	0.3	1.8
South Carolina	26.5	85	1582	6.1	4.2	5.7	6.9	2.8
Virginia	3.5	6.0	210	0.7	0.4	1.0	0.1	0.7

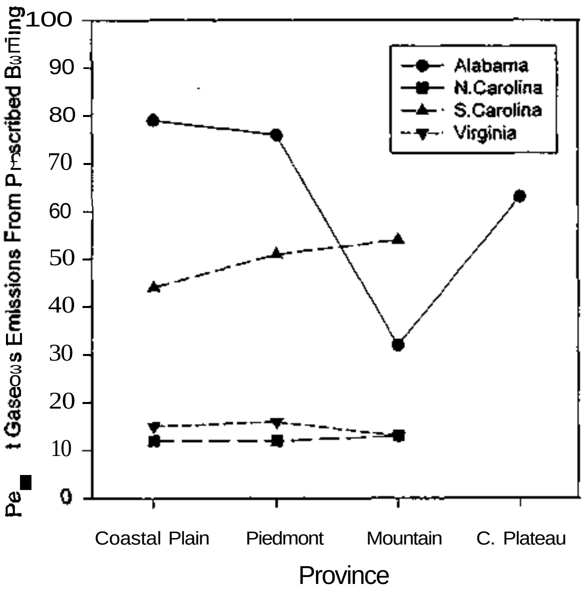

Figure 68.5 Percentage of gaseous emissions from prescribed burning, by state and province

This relationship increases the amount of land prescribed for burning for stand establishment and midrotation understory burning. For example, in Alabama, more than 70% of emissions of PM-10 and gases from the coastal plain and piedmont province originate from silvicultural uses of fire (figure 68.5). In contrast, only about 30% of the emissions originate from prescribed fire in the mountain province. Patterns were different for other states. In North Carolina and Virginia, there were no differences among provinces with respect to the relative contribution of PM-10 and gases from prescribed burning (figure 68.5). In South Carolina, the contribution from prescribed burning increased in the mountain province (figure 68.5).

Temporal Patterns

To demonstrate temporal patterns in emissions, we focused on three components: particulates, NO_x, and THC. Total emissions (i.e., wildfire plus prescribed fire) were summarized across all states by province. Notice that for some states, the temporal distribution of prescribed fires was estimated based on qualitative information (i.e., "most prescribed burns occur between February and June") provided by the states, or similar assumptions we made in distributing annual data. Monthly data were not available for any type of fire in Tennessee, and so that state is excluded from the analysis. In addition, no prescribed-fire data were available for Georgia, and so emissions estimates do not include potential contributions from site preparation and understory burning in Georgia.

Examining temporal patterns in emissions of particulates, NO_x, and THC showed a distinct pattern of elevated emissions in April for the coastal plain and piedmont provinces (figure 68.6*a*, *b*, *c*). On the coastal plain, emissions were still substantial from February through September, but they were reduced from October through January. Although of lesser magnitude, temporal patterns in the piedmont province followed a similar pattern. Peak emissions in the mountain and Cumberland Plateau provinces occurred in March, with slightly elevated values in February and April. The timing of emissions in the mountain and Cumberland Plateau provinces corresponds with typical periods of highest wildfire occurrence in these provinces.

Variation in number of hectares burned each month was the primary factor contributing to temporal variation in emissions. Temporal patterns of burning (figure 68.7) were essentially identical to the emissions estimates (figure 68.6*a*, *b*, *c*). The strong correspondence between burning patterns and emissions indicates that, at least in 1982, monthly variation in fuel moisture (as influenced by climatic conditions) was an insignificant factor regulating temporal variation in emissions.

Summary and Conclusions

FBEM is an attempt to develop a more regionally specific assessment of emissions from forest burning. We hypothesized that using regionally specific emissions factors, fuel-type distribution, and climatically influenced consumption estimates would improve the accuracy of emissions estimates. In addition, FBEM

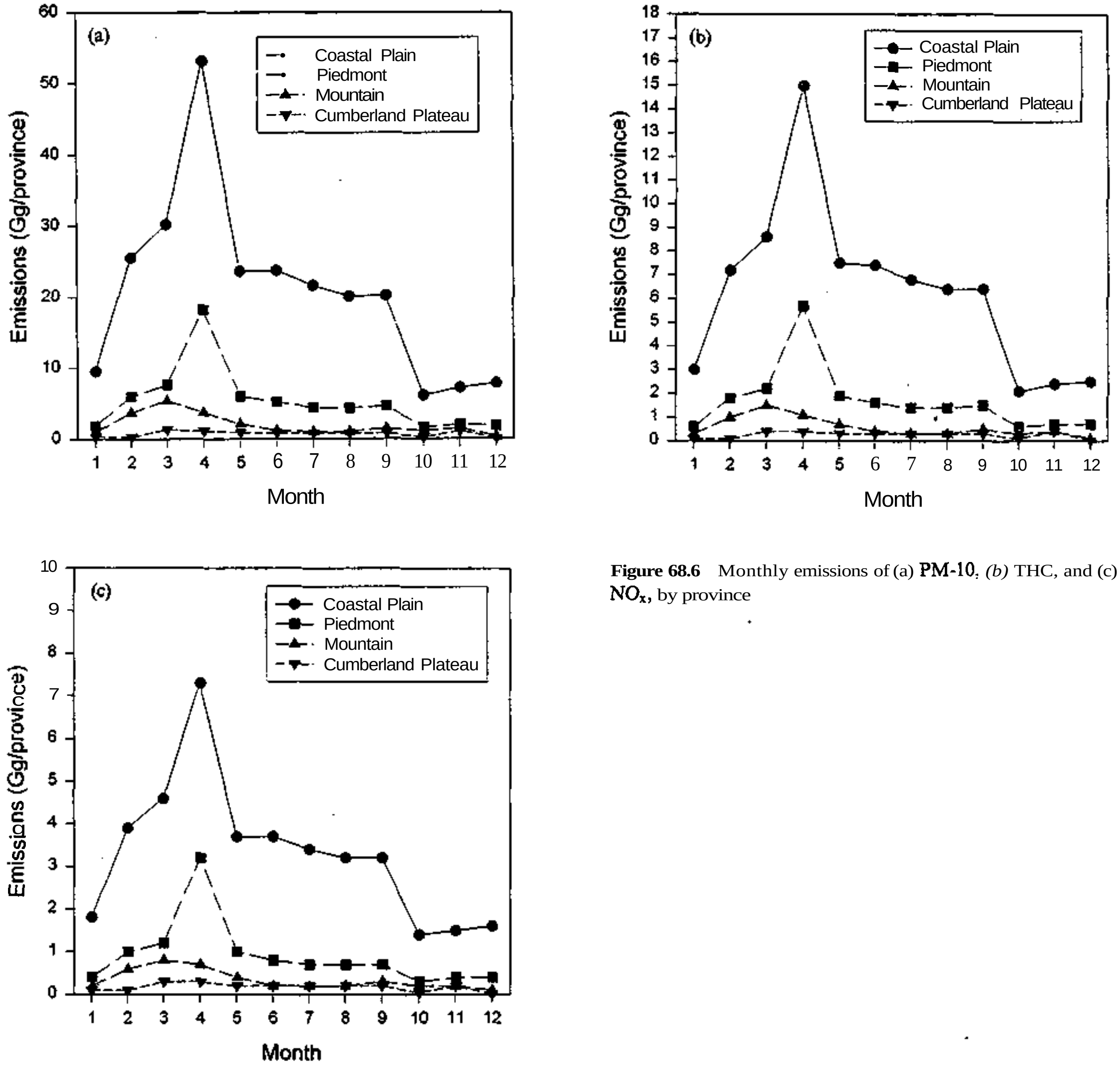

Figure 68.6 Monthly emissions of (a) PM-10, *(b)* THC, and (c) NO_x, by province

further refines the spatial and temporal distribution of emissions, and separates contributions by wildfire and prescribed fire. Our approach is a departure from previous, large-scale efforts (e.g., Laursen et al. 1992, Peterson and Ward 1994) in that FBEM relies in part on empirical relationships established from extensive data sets developed in the region. From a regulatory standpoint, knowledge of the timing, distribution, and primary contributing source is critical for properly assessing attainment or violation of air-quality standards. A major factor influencing success of this modeling approach is availability of key data sets (e.g., climatic data, spatially and temporally specific burn data, fuel loads, and specific emission factors). Our modeling shows that the major factor influencing emissions is the hectares burned. We had originally thought that older burn data (i.e., 1980s) would be more readily accessible than newer data (i.e., 1990s); however, the reverse may be true due to increased access to electronic transfer, storage, and retrieval of databases. FBEM is the first attempt to account for most of the major variables influencing emissions. We conclude, however, that emissions-factor data are limited, especially for the range of fuel and fire types in the southeast region. The simple structure of FBEM does allow for more refined estimates of emissions as the quality and quantity of data required for the model become available.

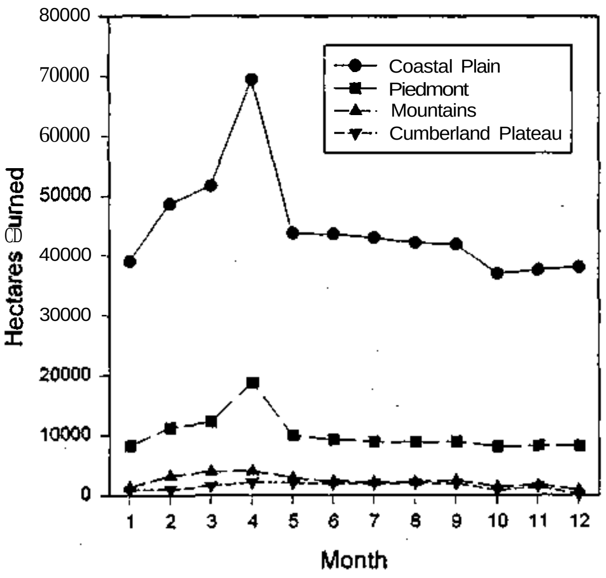

Figure 68.7 Temporal patterns of hectares burned, by province and month in 1982

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Appendix A **Emissions** Factor Data Base

Particulate-Matter Emissions from in situ Prescribed Fires in the Southeast

Backing fires

Conifer			Conifer slash		
Ref#	EFPM	Source	Ref#	EFPM	Source
186	17.5	**Johansen** et **al.** 1976	20	13.6	Nelson and Ward 1980
74	39.0	White **1987**		12.3	
				24.1	
				25.6	
				24.1	
			225	9.5	Ward 1974
				24.1	
			186	22.5	Johansen et al. 1976

Palmetto-Gallberry			Mixed		
Ref#	EFPM	Source	Ref#	EFPM	Source
186	12.5	Johansen et al. 1976	74	34.0	White 1987
20	8.1	Nelson and Ward 1980			
	18.85				
	13.8				
	11.63				
25	14.75	Ward 1983			
79	15.0	Ward 1990			
225	11.6	Ward 1974			
74	14.0	White 1987			

Grass

Ref#	EFPM	Source
74	14.0	White 1987

Heading fires

Conifer

Ref#	EFPM	Source
186	37.5	Johansen et al. 1976
79	35.0	Ward 1990
74	29.0	White 1987

Mixed

Ref#	EFPM	Source
74	24.0	White 1987

Palmetto-Gallberry

Ref#	EFPM	Source
186	62.5	Johansen et al. 1976
25	16.55	Ward 1983
79	17.0	Ward 1990
74	13.0	White 1987

Conifer slash

Ref#	EFPM	Source
225	40.8	Ward et al. 1974
186	25.0	Johansen et al. 1976

Grass

Ref#	EFPM	Source
74	22.0	White 1987

Unspecified

Conifer

Ref#	EFPM	Source
198	8.5	Cooper 1971
76	22.02	Ward et al. 1980
202	10.0	Pharo 1971
225	25.17	Ward et al. 1974

Palmetto-Gallberry

Ref#	EFPM	Source
162	10.3	Ward 1979
76	16.35	Ward et al. 1980
	13.5	

Grass

Ref#	EFPM	Source
225	17.0	Ward et al. 1974
186	7.5	Johansen et al. 1976
79	10.0	Ward 1990

Trace-Gas Emissions from in situ Prescribed Fires in the Southeast

Backing fires

Conifer

Ref#	EFCO	Source
74	114.0	White 1987

Mixed

Ref#	EFCO	Source
74	112.0	White 1987

Palmetto-Gallberry

Ref#	EFCO	Source
74	70.0	White 1987

Grass

Ref#	EFCO	Source
74	63.0	White 1987

Heading fires

Conifer

Ref#	EFCO	Source
74	83.0	White 1987

Mixed

Ref#	EFCO	Source
74	77.0	White 1987

Palmetto-Gallberry

Ref#	EFCO	Source
74	62.0	White 1987

Grass

Ref#	EFCO	Source
74	57.0	White 1987

Unspecified

Mixed

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	EFNOX	EFN2O	Source
1	111.0	4.8	6.9	1565	0.2775	0.137	Ward et al. 1991

Conifer

Ref#	EFCO	Source
202	10.5	Pharo 1971

Flaming

Mixed

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	EFNOX	EFN2O	Source
1	89.0	2.6	3.0	1665	0.289	0.153	Ward et al. 1991

Smoldering

Mixed

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	EFNOX	EFN2O	Source
1	190.0	8.9	6.9	1465	0.266	0.120	Ward et al. 1991

Particulate Matter Emissions from in situ Wildfires in the Southeast

Mixed

Ref#	EFPM	Source
198	29.0	Cooper 1972
202	29.0	Pharo 1971

Conifer

Ref#	EFPM	Source
202	30.0	Pharo 1971

Trace-Gas Emissions from in situ Wildfires in the Southeast

Mixed

Ref#	EFCO	EFNOX	Source
202	3.0	5.5	Pharo 1971

Particulate-Matter Emissions from Test Fires in a Lab, Southeast

Backing

Conifer slash

Ref#	EFPM	Source
6	13.0	Patterson et al. 1984
160	5.39	Nelson 1982

Heading

Conifer slash

Ref#	EFPM	Source
6	33.8	Patterson et al. 1984
160	14.58	Nelson 1982

Unspecified

Conifer slash

Ref#	EFPM	Source
6	14.5	Patterson et al. 1984
21	50.3	Ward et al. 1982
140	53.9	Patterson et al. 1986

Grass

Ref#	EFPM	Source
76	12.68	Ward et al. 1980

Flaming

Conifer slash

Ref#	EFPM	Source
140	14.7	Patterson et al. 1986

Smoldering

Conifer slash

Ref#	EFPM	Source
140	92.5	Patterson et al. 1986

Trace-Gas Emissions from Test Fires in a Lab, Southeast

Backing

Conifer

Ref#	EFCO	EFTHC	EFCO2	Source
160	93.56	9.33	1746.78	Nelson 1982

Heading

Conifer

Ref#	EFCO	EFTHC	EFCO2	Source
160	94.0	7.74	1706.44	Nelson 1982

Unspecified

Conifer

Ref#	EFCO	EFTHC	EFCO2	EFNOX	Source
188	142.9	4.12	1232.6		Clements and McMahon 1984
21	53.3				Wardetal. 1982
132				3.90	Clements and McMahon 1980

Palmetto-Gallberry

Ref#	**EFNOX**	EFCO	Source
132	9.92		Clements and McMahon 1980
21		73.2	Ward et al. 1982

Grass

Ref#	EFCO	Source
21	67.3	**Ward et al.** 1982

Particulate Matter Emissions from in situ Prescribed Fires in the Northwest

Flaming phase

Conifer slash

Ref#	EFPM2.5	EFPM	Source
274	5.0	9.4	Ward et al. 1989
47	12.0		**Sandberg** and Ward 1982
65	5.0	7.5	**Sandberg** and Dost 1990
59	3.0		**Einfeld et al.** 1991
79	6.5	10.5	Ward et al. 1988
144	12.65	18.13	Ward and Hardy 1984
146	4.0		Ward and Hardy 1988
140		13.7	Patterson et al. 1986
		17.8	
		21.4	
		12.6	
		12.7	

Conifer

Ref#	EFPM2.5	EFPM	Source
146	7.0		Ward and Hardy 1988
	6.0		
65	6.75	10.75	Sandberg and Dost 1990

Hardwoods

Ref#	EFPM2.5	EFPM	Source
274	6.1	11.5	Wardetal. 1989
65	7.5	13.5	Sandberg and Dost 1990
146	6.0		Ward and Hardy 1988

Mixed

Ref#	EFPM2.5	EFPM	Source
274	7.45	12.34	Ward et al. 1989
11		25.5	**Susott** et al. 1991

Grass

Ref#	EFPM2.5	EFPM	Source
271		7.5	Ferry et al. 1985

Chapparal

Ref#	EFPM2.5	EFPM	Source
65		7.5	Sandberg and Dost 1990

Smoldering phase

Conifer slash

Ref#	EFPM2.5	EFPM	Source
274	17.1	24.3	Wardetal. 1989
47	27.0		Sandberg and Ward 1982
65	7.0	16.5	Sandberg and Dost 1990
59	**11.5**		Einfeldetal. 1991
79	15.0	22.0	Wardetal. 1988
144	12.76	15.12	Ward and Hardy 1984
146	**4.0**		Ward and Hardy 1988

Conifer

Ref#	EFPM2.5	EFPM	Source
65	16.0	25.0	Sandberg and Dost 1990

Hardwoods

Ref#	EFPM2.5	EFPM	Source
274	11.7	19.0	Ward et al. 1989
65	16.0	27.0	Sandberg and Dost 1990
146	13.0		Ward and Hardy 1988

Mixed

Ref#	EFPM2.5	EFPM	Source
274	13.06	17.49	Ward et al. 1989
11		27.75	Susott et al. 1991

Unspecified

Conifer slash

Ref#	EFPM2.5	EFPM	Source
274	11.0	19.8	Ward et al. 1989
12	35.1	44.5	Radke et al. 1991
	24.6	34.3	
	17.1	30.2	
	18.2	20.3	
	10.7	11.1	
59	8.1		Einfeld et al. 1991
155		4.5	Sandberg et al. 1975
		8.5	Gerstle and Kemnitz 1967
271			
27	10.2		Sandberg 1985
	10.48		
	9.95		
	10.83		

Hardwoods

Ref#	EFPM2.5	EFPM	Source
274	11.2	18.7	Ward et al. 1989
12	7.9	10.8	Radke et al. 1991
	5.5	6.9	
	12.9	13.3	

Mixed

Ref#	EFPM2.5	EFPM	Source
274	10.9	14.78	Ward et al. 1989
12	16.2	21.7	Radke etal. 1991
	19.9	23.4	

Particulate Matter Emissions from Fires in a Lab, Northwest

Flaming

Conifer			Conifer slash		
Ref#	EFPM	Source	Ref#	EFPM	Source
46	2.5	Sandberg 1974	46	9.5	Sandberg 1974
	7.5				

Smoldering

Conifer			Conifer slash		
Ref#	EFPM	Source	Ref#	EFPM	Source
46	10.5	Sandberg 1974	46	13.5	Sandberg 1974
	8.0				

Overall

Conifer			Conifer slash		
Ref#	EFPM	Source	Ref#	EFPM	Source
46	3.0	Sandberg 1974	46	12.0	Sandberg 1974

Particulate-Matter Emissions from in situ Wildfires in the Northwest

Conifer

Ref#	EFPM2.5	EFPM	Source
12	19,5	29.3	Radke et al. 1991
	26.4	32.5	
	17.6	18.33	

Trace-Gas Emissions from in situ Wildfires in the Northwest

Conifer

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	EFNOX	EFN2O	Source
4	112	3.3	1.87	1714	2.3	0.18	Laursen et al. 1992
	96	2.6	1.57	1695	0.92	0.27	
	89	2.9	1.89	1788	1.6	0.15	
12	106	3.0	1.77	1626	2.54		Radke et al. 1991
	89	2.6	1.25	1637	0.81	0.27	

Trace-Gas Emissions from in situ Prescribed Fires in the Northwest

Flaming phase

Conifer

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	Source
59	35.0			1733	Einfeld et al. 1991
274	58.0	1.9	1.95	1696.5	Ward et al. 1989
144	89.0	2.64	2.23	1654.2	Ward and Hardy 1984

Hardwood

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	Source
274	45.8	2.2	2.6	1694.7	Ward et al. 1989

Douglas fir/hemlock

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	Source
274	71.5	2.27	2.08	1692.3	Ward et al. 1989

Long-needled pine

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	Source
274	44.7	1.47	1.77	1700.3	Ward et al. 1989

Tractor-piled

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	Source
274	22.0	1.25	1.15	1745.8	Ward et al. 1989

Crane-piled

Ref#	EFCO	EFCH4	EFNMHC	EFC02	Source
274	50.5	4.8	4.13	1674.8	Ward et al. 1989

Smoldering phase

Conifer

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	Source
59	117.2			1576	Einfeld et al. 1991
274	187.0	7.45	4.5	1443.7	Ward et al. 1989
144	211.5	8.55	3.2	1386.4	Ward and Hardy 1984

Hardwood

Ref#	EFCO	EFCH4	EFNMHC	EFCO2	Source
274	182.9	9.8	7.0	1425.5	Ward et al. 1989

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