## 13.1 Wildfires And Prescribed Burning

### 13.1.1 General[1]

A wildfire is a large-scale natural combustion process that consumes various ages, sizes, and types of flora growing outdoors in a geographical area. Consequently, wildfires are potential sources of large amounts of air pollutants that should be considered when trying to relate emissions to air quality.

The size and intensity, even the occurrence, of a wildfire depend directly on such variables as meteorological conditions, the species of vegetation involved and their moisture content, and the weight of consumable fuel per acre (available fuel loading). Once a fire begins, the dry combustible material is consumed first. If the energy release is large and of sufficient duration, the drying of green, live material occurs, with subsequent burning of this material as well. Under proper environmental and fuel conditions, this process may initiate a chain reaction that results in a widespread conflagration.

The complete combustion of wildland fuels (forests, grasslands, wetlands) require a heat flux (temperature gradient), adequate oxygen supply, and sufficient burning time. The size and quantity of wildland fuels, meteorological conditions, and topographic features interact to modify the burning behavior as the fire spreads, and the wildfire will attain different degrees of combustion efficiency during its lifetime.

The importance of both fuel type and fuel loading on the fire process cannot be overemphasized. To meet the pressing need for this kind of information, the U. S. Forest Service is developing a model of a nationwide fuel identification system that will provide estimates of fuel loading by size class. Further, the environmental parameters of wind, slope, and expected moisture changes have been superimposed on this fuel model and incorporated into a National Fire Danger Rating System (NFDRS). This system considers five classes of fuel, the components of which are selected on the basis of combustibility, response of dead fuels to moisture, and whether the living fuels are herbaceous (grasses, brush) or woody (trees, shrubs).

Most fuel loading figures are based on values for "available fuel", that is, combustible material that will be consumed in a wildfire under specific weather conditions. Available fuel values must not be confused with corresponding values for either "total fuel" (all the combustible material that would burn under the most severe weather and burning conditions) or "potential fuel" (the larger woody material that remains even after an extremely high intensity wildfire). It must be emphasized, however, that the various methods of fuel identification are of value only when they are related to the existing fuel quantity, the quantity consumed by the fire, and the geographic area and conditions under which the fire occurs.

For the sake of conformity and convenience, estimated fuel loadings estimated for the vegetation in the U. S. Forest Service Regions are presented in Table 13.1-1. Figure 13.1-1 illustrates these areas and regions.

Table 13.1-1 (Metric And English Units). SUMMARY OF ESTIMATED FUEL CONSUMED BY WILDFIRES[a]

| National Region[b] | Estimated Average Fuel Loading | |
|---|---|---|
| | Mg/hectare | ton/acre |
| Rocky Mountain | 83 | 37 |
| Region 1: Northern | 135 | 60 |
| Region 2: Rocky Mountain | 67 | 30 |
| Region 3: Southwestern | 22 | 10 |
| Region 4: Intermountain | 17.8 * | 8 |
| Pacific | 43 | 19 |
| Region 5: California | 40 | 18 |
| Region 6: Pacific Northwest | 135 | 60 |
| Region 10: Alaska | 36 | 16 |
| Coastal | 135 | 60 |
| Interior | 25 | 11 |
| Southern | 20 | 9 |
| Region 8: Southern | 20 | 9 |
| Eastern | 25 | 11 |
| North Central | 25 | 11 |
| Region 9: Conifers | 22 | 10 |
| Hardwoods | 27 | 12 |

[a] Reference 1.
[b] See Figure 13.1-1 for region boundaries.
* Feb. 12, 2002 - Correction: This number was changed from 40 to 17.8.

## 13.1.2 Emissions And Controls[1]

It has been hypothesized, but not proven, that the nature and amounts of air pollutant emissions are directly related to the intensity and direction (relative to the wind) of the wildfire, and are indirectly related to the rate at which the fire spreads. The factors that affect the rate of spread are (1) weather (wind velocity, ambient temperature, relative humidity); (2) fuels (fuel type, fuel bed array, moisture content, fuel size); and (3) topography (slope and profile). However, logistical problems (such as size of the burning area) and difficulties in safely situating personnel and equipment close to the fire have prevented the collection of any reliable emissions data on actual wildfires, so that it is not possible to verify or disprove the hypothesis. Therefore, until such measurements are made, the only available information is that obtained from burning experiments in the laboratory. These data, for both emissions and emission factors, are contained in Table 13.1-2. It must be emphasized that the factors presented here are adequate for laboratory-scale emissions estimates, but that substantial errors may result if they are used to calculate actual wildfire emissions.

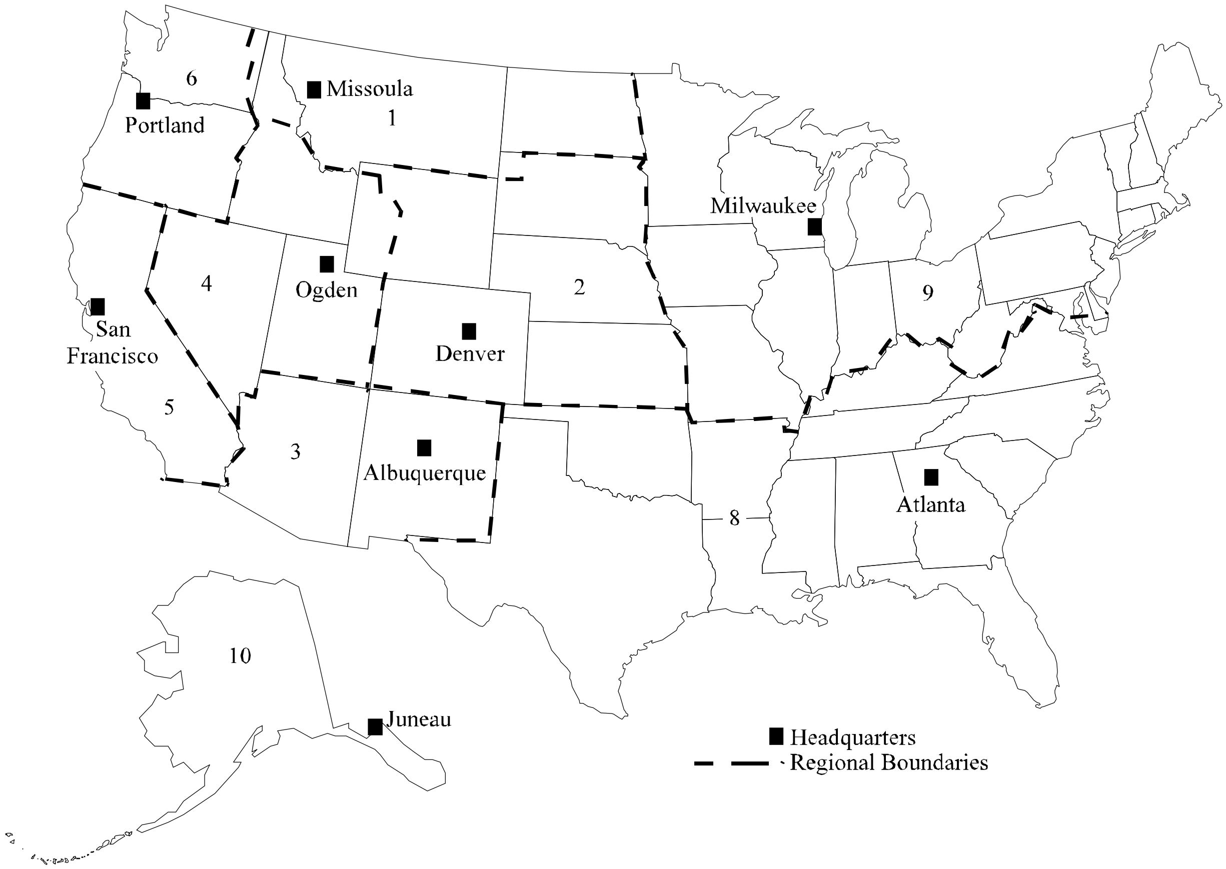


Figure 13.1-1. Forest areas And U. S. Forest Service Regions.

The emissions and emission factors displayed in Table 13.1-2 are calculated using the following formulas:

$$F_i = P_i L \qquad (1)$$

$$E_i = F_i A = P_i L A \qquad (2)$$

where:

$F_i$ = emission factor (mass of pollutant/unit area of forest consumed)
$P_i$ = yield for pollutant "i" (mass of pollutant/unit mass of forest fuel consumed)
= 8.5 kilograms per megagram (kg/Mg) (17 pound per ton [lb/ton]) for total particulate
= 70 kg/Mg (140 lb/ton) for carbon monoxide
= 12 kg/Mg (24 lb/ton) for total hydrocarbon (as $CH_4$)
= 2 kg/Mg (4 lb/ton) for nitrogen oxides ($NO_x$)
= negligible for sulfur oxides ($SO_x$)
L = fuel loading consumed (mass of forest fuel/unit land area burned)
A = land area burned
$E_i$ = total emissions of pollutant "i" (mass pollutant)

Table 13.1-2. EMISSIONS AND EMISSION FACTORS FOR FOREST WILDFIRES

EMISSION FACTOR RATING: D

| Geographic Area | Area Consumed By Wildfire[a] (hectares) | Wildfire Fuel Consumption (Mg/hectare) | Emission Factors (kg/Hectare) | | | | Emissions (Mg) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Particulate | Carbon Monoxide | Volatile Organics[b] | Nitrogen Oxides | Particulate | Carbon Monoxide | Volatile Organics[b] | Nitrogen Oxides |
| Rocky Mountain | 313,397 | 83 | 706 | 5,810 | 996 | 166 | 220,907 | 1,819,237 | 311,869 | 51,978 |
| Northern (Region 1) | 142,276 | 135 | 1,144 | 9,420 | 1,620 | 269 | 162,268 | 1,339,283 | 229,592 | 38,265 |
| Rocky Mountain (Region 2) | 65,882 | 67 | 572 | 4,710 | 808 | 135 | 37,654 | 310,086 | 53,157 | 8,860 |
| Southwestern (Region 3) | 83,765 | 22 | 191 | 1,570 | 269 | 45 | 15,957 | 131,417 | 22,533 | 3,735 |
| Intermountain (Region 4) | 21,475 | 40 | 153 | 1,260 | 215 | 36 | 3,273 | 26,953 | 4,620 | 770 |
| Pacific | 469,906 | 43 | 362 | 2,980 | 512 | 85 | 170,090 | 1,400,738 | 240,126 | 40,021 |
| California (Region 5) | 18,997 | 40 | 343 | 2,830 | 485 | 81 | 6,514 | 53,645 | 9,196 | 1,533 |
| Alaska (Region 10) | 423,530 | 36 | 305 | 2,510 | 431 | 72 | 129,098 | 1,063,154 | 182,255 | 30,376 |
| Pacific Northwest (Region 6) | 27,380 | 135 | 1,144 | 9,420 | 1,620 | 269 | 31,296 | 257,738 | 44,183 | 7,363 |
| Southern | 806,289 | 20 | 172 | 1,410 | 242 | 40 | 138,244 | 1,138,484 | 195,168 | 35,528 |
| Southern (Region 8) | 806,289 | 20 | 172 | 1,410 | 242 | 40 | 138,244 | 1,138,484 | 195,168 | 35,528 |
| North Central and Eastern | 94,191 | 25 | 210 | 1,730 | 296 | 49 | 19,739 | 162,555 | 27,867 | 4,644 |
| (Region 9) | 141,238 | 25 | 210 | 1,730 | 296 | 49 | 29,598 | 243,746 | 41,785 | 6,964 |
| Eastern Group (With Region 9) | 47,046 | 25 | 210 | 1,730 | 296 | 49 | 9,859 | 81,191 | 13,918 | 2,320 |
| Total | 1,730,830 | 38 | 324 | 2,670 | 458 | 76 | 560,552 | 4,616,317 | 791,369 | 131,895 |

[a] Consumption data are for 1971.
[b] Expressed as methane.

For example, suppose that it is necessary to estimate the total particulate emissions from a 10,000-hectare wildfire in the Southern area (Region 8). From Table 13.1-1, it is seen that the average fuel loading is 20 Mg/hectare (9 tons/acre). Further, the pollutant yield for particulates is 8.5 kg/Mg (17 lb/ton). Therefore, the emissions are:

$$E = (8.5 \text{ kg/Mg of fuel}) (20 \text{ Mg of fuel/hectare}) (10{,}000 \text{ hectares})$$

$$E = 1{,}700{,}000 \text{ kg} = 1{,}700 \text{ Mg}$$

The most effective method of controlling wildfire emissions is, of course, to prevent the occurrence of wildfires by various means at the land manager's disposal. A frequently used technique for reducing wildfire occurrence is "prescribed" or "hazard reduction" burning. This type of managed burn involves combustion of litter and underbrush to prevent fuel buildup under controlled conditions, thus reducing the danger of a wildfire. Although some air pollution is generated by this preventive burning, the net amount is believed to be a relatively smaller quantity then that produced by wildfires.

## 13.1.3 Prescribed Burning[1]

Prescribed burning is a land treatment, used under controlled conditions, to accomplish natural resource management objectives. It is one of several land treatments, used individually or in combination, including chemical and mechanical methods. Prescribed fires are conducted within the limits of a fire plan and prescription that describes both the acceptable range of weather, moisture, fuel, and fire behavior parameters, and the ignition method to achieve the desired effects. Prescribed fire is a cost-effective and ecologically sound tool for forest, range, and wetland management. Its use reduces the potential for destructive wildfires and thus maintains long-term air quality. Also, the practice removes logging residues, controls insects and disease, improves wildlife habitat and forage production, increases water yield, maintains natural succession of plant communities, and reduces the need for pesticides and herbicides. The major air pollutant of concern is the smoke produced.

Smoke from prescribed fires is a complex mixture of carbon, tars, liquids, and different gases. This open combustion source produces particles of widely ranging size, depending to some extent on the rate of energy release of the fire. For example, total particulate and particulate less than 2.5 micrometers (µm) mean mass cutpoint diameters are produced in different proportions, depending on rates of heat release by the fire.[2] This difference is greatest for the highest-intensity fires, and particle volume distribution is bimodal, with peaks near 0.3 µm and exceeding 10 µm.[3] Particles over about 10 µm, probably of ash and partially burned plant matter, are entrained by the turbulent nature of high-intensity fires.

Burning methods differ with fire objectives and with fuel and weather conditions.[4] For example, the various ignition techniques used to burn under standing trees include: (1) heading fire, a line of fire that runs with the wind; (2) backing fire, a line of fire that moves into the wind; (3) spot fires, which burn from a number of fires ignited along a line or in a pattern; and (4) flank fire, a line of fire that is lit into the wind, to spread laterally to the direction of the wind. Methods of igniting the fires depend on forest management objectives and the size of the area. Often, on areas of 50 or more acres, helicopters with aerial ignition devices are used to light broadcast burns. Broadcast fires may involve many lines of fire in a pattern that allows the strips of fire to burn together over a sizeable area.

In discussing prescribed burning, the combustion process is divided into preheating, flaming, glowing, and smoldering phases. The different phases of combustion greatly affect the amount of emissions produced.[5-7] The preheating phase seldom releases significant quantities of material to the atmosphere. Glowing combustion is usually associated with burning of large concentrations of woody fuels such as logging residue piles. The smoldering combustion phase is a very inefficient and incomplete combustion process that emits pollutants at a much higher ratio to the quantity of fuel consumed than does the flaming combustion of similar materials.

The amount of fuel consumed depends on the moisture content of the fuel.[8-9] For most fuel types, consumption during the smoldering phase is greatest when the fuel is driest. When lower layers of the fuel are moist, the fire usually is extinguished rapidly.[10]

The major pollutants from wildland burning are particulate, carbon monoxide, and volatile organics. Nitrogen oxides are emitted at rates of from 1 to 4 g/kg burned, depending on combustion temperatures. Emissions of sulfur oxides are negligible.[11-12]

Particulate emissions depend on the mix of combustion phase, the rate of energy release, and the type of fuel consumed. All of these elements must be considered in selecting the appropriate emission factor for a given fire and fuel situation. In some cases, models developed by the U. S. Forest Service have been used to predict particulate emission factors and source strength.[13] These models address fire behavior, fuel chemistry, and ignition technique, and they predict the mix of combustion products. There is insufficient knowledge at this time to describe the effect of fuel chemistry on emissions.

Table 13.1-3 presents emission factors from various pollutants, by fire and fuel configuration. Table 13.1-4. gives emission factors for prescribed burning, by geographical area within the United States. Estimates of the percent of total fuel consumed by region were compiled by polling experts from the Forest Service. The emission factors are averages and can vary by as much as 50 percent with fuel and fire conditions. To use these factors, multiply the mass of fuel consumed per hectare by the emission factor for the appropriate fuel type. The mass of fuel consumed by a fire is defined as the available fuel. Local forestry officials often compile information on fuel consumption for prescribed fires and have techniques for estimating fuel consumption under local conditions. The *Southern Forestry Smoke Management Guidebook*[5] and the *Prescribed Fire Smoke Management Guide*[15] should be consulted when using these emission factors.

The regional emission factors in Table 13.1-4 should be used only for general planning purposes. Regional averages are based on estimates of the acreage and vegetation type burned and may not reflect prescribed burning activities in a given state. Also, the regions identified are broadly defined, and the mix of vegetation and acres burned within a given state may vary considerably from the regional averages provided. Table 13.1-4 should not be used to develop emission inventories and control strategies.

To develop state emission inventories, the user is strongly urged to contact that state's federal land management agencies and state forestry agencies that conduct prescribed burning to obtain the best information on such activities.

Table 13.1-3 (Metric Units). EMISSION FACTORS FOR PRESCRIBED BURNING[a]

| Fire/Fuel Configuration | Phase | Pollutant (g/kg) | | | | | | Fuel Mix (%) | EMISSION FACTOR RATING |
|---|---|---|---|---|---|---|---|---|---|
| | | Particulate | | | Carbon Monoxide | Volatile Organics | | | |
| | | PM-2.5 | PM-10 | Total | | Methane | Nonmethane | | |
| Broadcast logging slash | | | | | | | | | |
| Hardwood | F | 6 | 7[b] | 13 | 44 | 2.1 | 3.8 | 33 | A |
| | S | 13 | 14[b] | 20 | 146 | 8.0 | 7.7 | 67 | A |
| | Fire | 11 | 12[b] | 18 | 112 | 6.1 | 6.4 | | A |
| Conifer | | | | | | | | | |
| Short needle | F | 7 | 8[c] | 12 | 72 | 2.3 | 2.1 | 33 | A |
| | S | 14 | 15[c] | 19 | 226 | 7.2 | 4.2 | 67 | A |
| | Fire | 12 | 13[c] | 17 | 175 | 5.6 | 3.5 | | A |
| Long needle | F | 6 | 6[d] | 9 | 45 | 1.5 | 1.7 | 33 | B |
| | S | 16 | 17[d] | 25 | 166 | 7.7 | 5.4 | 67 | B |
| | Fire | 13 | 13[d] | 20 | 126 | 5.7 | 4.2 | | B |
| Logging slash debris | | | | | | | | | |
| Dozer piled conifer | | | | | | | | | |
| No mineral soil[d] | F | 4 | 4 | 5 | 28 | 1.0 | ND | 90 | B |
| | S | 6 | 7 | 14 | 116 | 8.7 | ND | 10 | B |
| | Fire | 4 | 4 | 6 | 37 | 1.8 | ND | | B |

Table 13.1-3 (cont.).

| Fire/Fuel Configuration | Phase | Pollutant (g/kg) | | | | | | Fuel Mix (%) | EMISSION FACTOR RATING |
|---|---|---|---|---|---|---|---|---|---|
| | | Particulate | | | Carbon Monoxide | Volatile Organics | | | |
| | | PM-2.5 | PM-10 | Total | | Methane | Nonmethane | | |
| 10 to 30% Mineral soil[e] | S | ND | ND | 25 | 200 | ND | ND | ND | D |
| 25% Organic soil[e] | S | ND | ND | 35 | 250 | ND | ND | ND | D |
| Range fire | | | | | | | | | |
| Juniper slash[f] | F | 7 | 8 | 11 | 41 | 2.0 | 2.7 | 8.2 | B |
| | S | 12 | 13 | 18 | 125 | 10.3 | 7.8 | 15.6 | B |
| | Fire[g] | 9 | 10 | 14 | 82 | 6.0 | 5.2 | 12.5 | B |
| Sagebrush[f] | F | 15 | 16 | 23 | 78 | 3.7 | 3.4 | | B |
| | S | 13 | 15 | 23 | 106 | 6.2 | 7.3 | | B |
| | Fire[g] | 13 | 15 | 23 | 103 | 6.2 | 6.9 | | B |
| Chaparral shrub communities[h] | F | 7 | 8 | 16 | 56 | 1.7 | 8.2 | | A |
| | S | 12 | 13 | 23 | 133 | 6.4 | 15.6 | | A |
| | Fire | 10 | 11 | 20 | 101 | 4.5 | 12.5 | | A |
| Line fire | | | | | | | | | |
| Conifer | | | | | | | | | |
| Long needle (pine) | Heading[j] | ND | 40 | 50 | 200 | ND | ND | | D |
| | Backing[k] | ND | 20 | 20 | 125 | ND | ND | | D |
| Palmetto/gallberry[j] | Heading | ND | 15 | 17 | 150 | ND | ND | | D |
| | Backing | ND | 15 | 15 | 100 | ND | ND | | D |
| | Fire | ND | 8 - 22 | ND | ND | ND | ND | | D |
| Chaparral[k] | Heading | 8 | 9 | 15 | 62 | 2.8 | 3.5 | | C |
| Grasslands[j] | Fire | ND | 10 | 10 | 75 | ND | 0 | | D |

Table 13.1-3 (cont.).

[a] References 7-8. Unless otherwise noted, determined by field testing of fires ≥ 1 acre size. F = flaming. S = smoldering. Fire = weighted average of F and S. ND = no data.
[b] For PM-10, Reference 7. EMISSION FACTOR RATING: C.
[c] For PM-10, References 3,7. EMISSION FACTOR RATING: D.
[d] For PM-10, References 3,7. EMISSION FACTOR RATING: D.
[e] Reference 12. Determined using laboratory combustion hood.
[f] Reference 16.
[g] Fuel mix uncertain, because of short, intense flaming phase. Use fire average for emission inventory purposes.
[h] References 17-18.
[j] References 13-14. Determined using laboratory combustion hood.
[k] References 13-14.

Table 13.1-4 (Metric Units). EMISSION FACTORS FOR PRESCRIBED BURNING BY U. S. REGION

| Regional Configuration And Fuel Type[a] | Percent Of Fuel[b] | Pollutant[c] | | | |
|---|---|---|---|---|---|
| | | Particulate (g/kg) | | | |
| | | PM-2.5 | PM-10 | PM | CO |
| Pacific Northwest | | | | | |
| Logging slash | | | | | |
| Piled slash | 42 | 4 | 5 | 6 | 37 |
| Douglas fir/Western hemlock | 24 | 12 | 13 | 17 | 175 |
| Mixed conifer | 19 | 12 | 13 | 17 | 175 |
| Ponderosa pine | 6 | 13 | 13 | 20 | 126 |
| Hardwood | 4 | 11 | 12 | 18 | 112 |
| Underburning pine | 5 | 30 | 30 | 35 | 163 |
| Average for region | 100 | 9.4 | 10.3 | 13.3 | 111.1 |
| Pacific Southwest | | | | | |
| Sagebrush | 35 | | 9 | 15 | 62 |
| Chaparral | 20 | 8 | 9 | 15 | 62 |
| Pinyon/Juniper | 20 | | 13 | 17 | 175 |
| Underburning pine | 15 | | 30 | 35 | 163 |
| Grassland | 10 | | 10 | 10 | 15 |
| Average for region | 100 | | 13.0 | 17.8 | 101.0 |
| Southeast | | | | | |
| Palmetto/gallbery | 35 | | 15 | 16 | 125 |
| Underburning pine | 30 | | 30 | 35 | 163 |
| Logging slash | 20 | | 13 | 20 | 126 |
| Grassland | 10 | | 10 | 10 | 75 |
| Other | 5 | | 17 | 17 | 175 |
| Average for region | 100 | | 18.8 | 21.9 | 134 |

Table 13.1-4 (cont.).

| Regional Configuration And Fuel Type[a] | Percent of Fuel[b] | Pollutant[c] | | | |
|---|---|---|---|---|---|
| | | Particulate (g/kg) | | | |
| | | PM-2.5 | PM-10 | PM | CO |
| Rocky Mountain | | | | | |
| Logging slash | 50 | | 4 | 6 | 37 |
| Underburning pine | 20 | | 30 | 35 | 163 |
| Grassland | 20 | | 10 | 10 | 75 |
| Other | 10 | | 17 | 17 | 175 |
| Average for region | 100 | | 11.9 | 13.7 | 83.4 |
| North Central and Eastern | | | | | |
| Logging slash | 50 | | 13 | 17 | 175 |
| Grassland | 30 | | 10 | 10 | 75 |
| Underburning pine | 10 | | 30 | 35 | 163 |
| Other | 10 | | 17 | 17 | 175 |
| Average for region | 100 | | 14 | 16.5 | 143.8 |

[a] Regional areas are generalized, e. g., the Pacific Northwest includes Oregon, Washington, and parts of Idaho and California. Fuel types generally reflect the ecosystems of a region, but users should seek advice on fuel type mix for a given season of the year. An average factor for Northern California could be more accurately described as chaparral, 25%; underburning pine, 15%; sagebrush, 15%; grassland, 5%; mixed conifer, 25%; and douglas fir/Western hemlock, 15%. Blanks indicate no data.
[b] Based on the judgement of forestry experts.
[c] Adapted from Table 13.1-3 for the dominant fuel types burned.

## 13.1.4 Wildfires and Prescribed Burning—Greenhouse Gases

Emission factors for greenhouse gases from wildfires and prescribed burning are provided based on the amount of material burned. Emission factors for methane ($CH_4$) and nitrous oxide ($N_2O$) based on the mass of material burned are provided in Table 13.1-5. To express emissions based on area burned, refer to Table 13.1-1 for estimated average fuel loading by region. The $CH_4$ emission factors have been divided into the type of forests being studied for specific plant species. Emissions of $CO_2$ from this source as well as other biogenic sources are part of the carbon cycle, and as such are typically not included in greenhouse gas emission inventories.

Table 13.1-5. WILDFIRE AND PRESCRIBED BURNING GREENHOUSE GAS EMISSION FACTORS

EMISSION FACTOR RATING: C

| Regional/Fuel Type[a] | Pollutant (lb/ton) | |
|---|---|---|
| | $CH_4$ | $N_2O$ |
| Agricultural Residues | 5.4[b] | 0.46 |
| Amazon | 8.5[c] | |
| Boreal and Coniferous Forests | 11.1[c] | |
| Savanna | 3.7[c] | |
| Temperate and Boreal Forests | 12.2 | |

[a] References 19-22. To convert lb/ton to kg/Mg multiply by 0.5.
[b] For more details see Table 2.5-5 of Section 2.5 Opening Burning.
[c] Emission factor developed based on combustion efficiency (ratio of carbon released as $CO_2$).

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