Research and Development of Emission Inventories for Planned Burning Activities for the Central States Regional Air Planning Association

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ABSTRACT

The Central States Regional Air Planning Association (CENRAP) is researching visibility-related issues for its region (Texas, Oklahoma, Louisiana, Arkansas, Kansas, Missouri, Nebraska, Iowa, and Minnesota) and is developing a regional haze plan in response to the U.S. Environmental Protection Agency's (EPA) mandate to protect visibility in Class I areas. Episodic combustion events (such as agricultural burning, prescribed burning, open burning of wastes, structural fires, and wildfires) sometimes contribute to regional or localized haze events in the CENRAP region. Activity data were gathered by conducting and analyzing the results of telephone surveys of county agricultural extension agents and by gathering information from state, tribal, private, and federal land managers. Emissions were calculated by using the First-Order Fire Effects Model (FOFEM) and by applying Geographic Information Systems (GIS) databases of land use, land cover, and vegetation. The results were distributed to the National Regional Planning Organization (RPO) modeling grid at a fine grid resolution of 12 km × 12 km. In addition, emissions were temporally allocated and chemically speciated. Emission inventories for prescribed and agricultural burning were developed for 2002, and data analyses were performed to assess their impacts on visibility in the CENRAP region.

INTRODUCTION

In support of the CENRAP's need to develop a regional haze plan, Sonoma Technology, Inc. (STI) developed planned burning emission inventories for the region. Regional haze is visibility impairment caused mainly by particles of less than 2.5 microns in diameter ($PM_{2.5}$). $PM_{2.5}$ directly emitted from emissions sources is termed "primary $PM_{2.5}$". $PM_{2.5}$ that forms from photochemical reactions of gaseous precursors, including sulfur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOC), and ammonia (NH_3), is termed "secondary $PM_{2.5}$". To prepare this planned burning inventory, emissions of primary $PM_{2.5}$ and the $PM_{2.5}$ precursors listed above were estimated.

$PM_{2.5}$ may be directly emitted from sources such as emissions sources of fugitive dust and combustion soot, which are sources of "primary $PM_{2.5}$". Additional mechanisms also occur allowing $PM_{2.5}$ to be formed in the atmosphere; this activity is termed "secondary formation". Examples include condensable organic aerosols that can form from air emissions of semi-volatile and heavy organic compounds and $PM_{2.5}$ that can form from photochemical reactions of gaseous precursors, including SO_x, NO_x, VOC, and NH_3. Analyses of speciated $PM_{2.5}$ samples enhance the understanding of the types of emission sources that contribute to regional haze issues in different areas. In urban and ammonia-depleted areas of the eastern United States, secondary sulfate contributes a more significant amount of $PM_{2.5}$ than it does in the western United States. Conversely, secondary nitrate is more important in urban and ammonia-rich areas of the western United States than it is in eastern areas. In both the eastern and western United States, the carbonaceous fraction of $PM_{2.5}$ is significant in urban areas. In rural areas, geologic dust can also be an important contributor to $PM_{2.5}$.

Of particular interest in the CENRAP region is the contribution of $PM_{2.5}$ from wood and grassland burning to visibility impairment at Class I areas. Smoke from these fires emits organic carbon (OC) and elemental carbon (EC); the latter is sometimes referred to as soot or black carbon (BC). OC is emitted by many sources, both combustion and evaporative, while EC is emitted only by combustion sources, such as fossil fuel combustion (i.e., power plants, car exhaust, etc) or woodland or grassland burning. Potassium (K) is also emitted during burning of natural materials and can be used as a marker for woodland or grassland burning.

Historically, few areas of the CENRAP region have experienced significant air quality problems. Therefore, they have not been required to perform air quality monitoring or develop emission inventories. The most comprehensive source of emissions estimates currently available for the region is the EPA's National Emissions Inventory (NEI). The NEI reports that $PM_{2.5}$ emissions from planned burning activities in the CENRAP region are 110,000 tons per year, about 9% of the total $PM_{2.5}$ inventory for the region (Table 1). The NEI indicates that planned burning emissions are particularly significant in the states of Louisiana and Texas.

Table 1. 1999 NEI estimates of $PM_{2.5}$ emissions in the CENRAP region.

	$PM_{2.5}$ (tons)		
State	All Sources	Planned Burning	Percent
Arkansas	91,294	6,735	7.4%
Iowa	108,641	402	0.4%
Kansas	158,521	9,502	6.0%
Louisiana	94,522	34,099	36.1%
Minnesota	163,542	2,874	1.8%
Missouri	183,245	1,147	0.6%
Nebraska	131,486	2,576	2.0%
Oklahoma	149,015	7,137	4.8%
Texas	223,427	45,748	20.5%
Total	1,303,694	110,220	8.5%

As part of its regional haze research, the CENRAP will conduct comprehensive air quality modeling of visibility during 2002. To support this modeling, a bottom-up planned burning emission inventory incorporating year-2002-specific fire history data and addressing the following uncertainties of the NEI was needed:

- Prescribed burning activities fluctuate dramatically from year to year. Fluctuations are due to policy decisions about the need for wildfire risk management, current climate conditions (drought versus wet conditions), and assessments of the density of undergrowth and fuel. Because of these wide fluctuations, emission inventories of prescribed burning are nearly impossible to predict or project on the basis of historical inventories or trends.
- The NEI is estimated on an annual average basis. Regional haze has a seasonal character and is partly driven by photochemical processes. Adjustments are necessary to develop seasonal, diurnal, and, possibly, day-of-week emission estimates.

TECHNICAL APPROACH

Overview

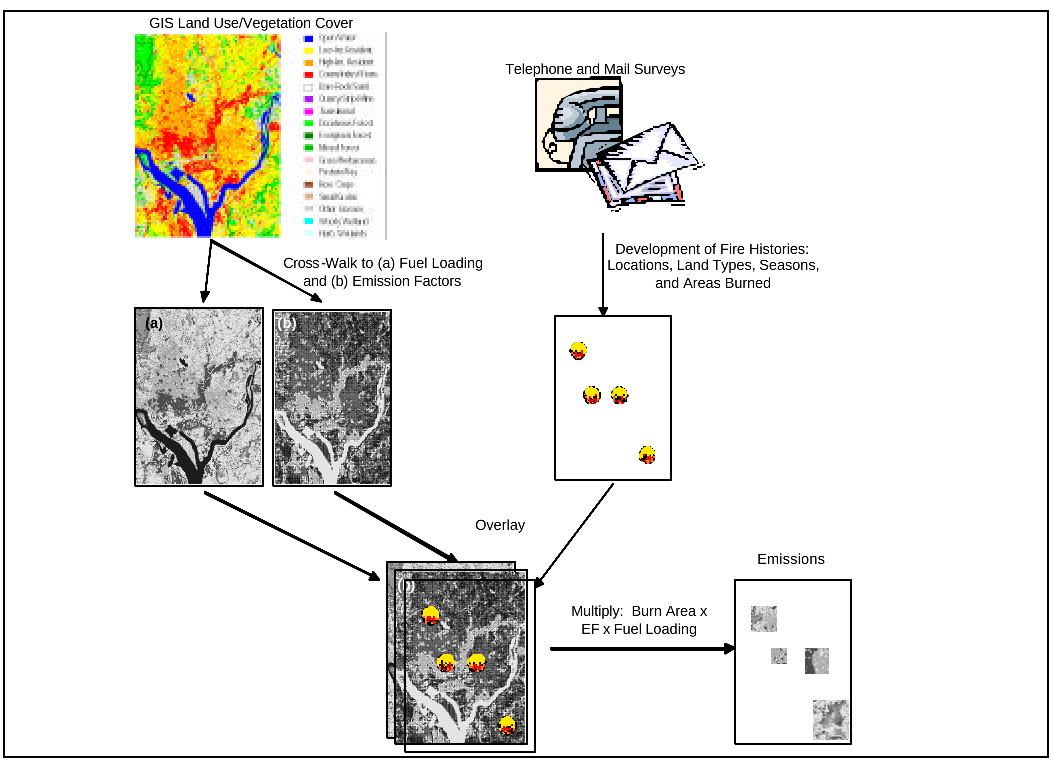
Emissions estimates were prepared for prescribed and agricultural burning activities on federal, state, tribal, and private lands in the CENRAP region. These bottom up estimates were prepared using the First-Order Fire Effects Model (FOFEM) emission factors and fuel loadings compiled from published literature, Geographic Information Systems (GIS) databases of land cover and vegetation, and activity data gathered through telephone and mail surveys.

The FOFEM model, a computing tool developed through the Joint Fire Science Program (JFSP), was used to generate estimates of fuel loadings and emission rates for prescribed burns. FOFEM was run for local vegetation types using fuel moisture inputs acquired from the Weather Information Management System (WIMS), a database of daily weather observations collected from approximately 1500 fire weather stations throughout the United States. Outputs from FOFEM were combined with the prescribed burning history information to calculate emissions for prescribed burns that occurred in 2002.

For agricultural burning, emission factors and fuel-loading factors for a variety of crop types are published in the EPA's guidance document, "Compilation of Air Pollutant Emission Factors (AP-42)"[1.] and by Jenkins et al.[2] From these data sources, fuel loading factors and emission factors were identified for a wide variety of crop types and applied to county-specific agricultural burning activity data to generate emissions estimates. The agriculture burning activity data were obtained through systematic telephone and mail surveys of county agricultural extension services (AES).

For both prescribed and agricultural burning activities, the EPA's Biogenic Emissions Landcover Database (BELD) Version 3 was used to generate spatial distributions of vegetation types, which in turn were used to select vegetation-specific fuel loading factors output by FOFEM.[3] To do this, cross-reference tables were established to relate the vegetation types in the BELD database with (1) vegetation types in FOFEM and (2) crop types for which emission factors and fuel loadings are available. Maps of vegetation and crop types were then developed and overlaid with the locations of planned fires. This enabled an association of vegetation types with the location of each fire occurrence. Emission factors generated by FOFEM or acquired from the sources described above were combined with the fire location and vegetation data to produce county-level emission inventories of agricultural and prescribed burning. Figure 1 illustrates and summarizes the process by which emissions estimates were developed.

Figure 1. Illustration and summary of the process used to develop emissions estimates for planned and agricultural fires.



Methods for Developing Prescribed Burning Emissions Estimates

Emission Factors and Fuel Loadings

The purpose of prescribed burning is to clear undergrowth in timberlands or grasslands to prevent wildfires or make various types of land improvements. Burning practices and frequency vary regionally due to differences in local weather and forest/land types. Emission rates are specific to the type of material burned and burn management practices. Some degree of reporting and record-keeping is required by state, federal, and tribal agencies for wildfire management; however, access to and interpretation of these records are difficult. Even less information is available for planned burning of undergrowth for private land improvement. As with agricultural burning, substantial effort is required to develop activity data that can be used for regional-scale emissions assessments.

Before FOFEM could be applied to the CENRAP region, it was necessary to determine the vegetation types in the CENRAP region included in the FOFEM model and the moisture content of various fuel types at the times and places where prescribed burning events occurred. FOFEM allows users to choose between two vegetation cover classifications: the National Vegetation Classification System (NVCS) and the Society of American Foresters/Society for Range Management (SAF/SRM) cover types. (A third option, the Fuel Characteristic Classification [FCC], does not extend to all regions of the country.) To determine which of the NVCS or SAF cover types are found in the CENRAP region, a cross-reference system was developed between the FOFEM and BELD databases by matching BELD vegetation types to NVCS coverage types wherever possible. SAF data were used only when clear matches could not be made to NVCS vegetation types.

Fuel moisture content is the quantity of water in a fuel particle expressed as a percentage of the oven-dry weight of the fuel.[4] FOFEM requires settings for three fuel moisture classifications. Fuel moisture data were acquired from the Wildland Fire Assessment System (WFAS)—a database of the National Interagency Fire Center (NIFC) in Boise, Idaho. WFAS is based on daily weather observations taken at about 1500 fire weather stations throughout the United States and entered into the WIMS.

Once vegetation types and fuel moisture levels were determined, FOFEM was run for each unique combination of vegetation type and moisture level to generate emission rates in pounds per acre burned. Outputs from these FOFEM runs were then used to produce a look-up table of emission factors by vegetation type and moisture condition. For each prescribed burning event, WIMS data from the nearest fire weather station were used to determine fuel moisture contents for the event and BELD data to determine the type of vegetation burned. This information was used to select and apply an appropriate emission factor from the FOFEM look-up table.

Fire Activity Data

The prescribed burn activity data compiled for state and private lands in the CENRAP consist of detailed data obtained from smoke management programs, state fire marshals, or state forest services; summary data obtained from state agencies and allocated by county; summary data estimated by applying federal surrogates to state lands and allocated by county; and county-level data based on the results of the rangeland burning survey questions.

The National Interagency Fire Management Integrated Database (NIFMID) was used to identify prescribed fires occurring on Department of the Interior (DOI) lands (U.S. Fish and Wildlife Service [USFWS], National Park Service [NPS], and Bureau of Indian Affairs [BIA][5]). This database contains fire type (prescribed, wildfire, etc.), start and end dates, extent (acres), and location (geographic coordinates and township/range/section). The NIFMID also contains data for some USFS fires, although these data appear to be more complete for some states than for others. The National Fire Plan Operations and Reporting System (NFPORS), contains fire occurrence data for the USFS for 2002. Although these data were requested, they were not provided within the time limit of this project. Ultimately, NFPORS records were obtained from regional USFS personnel for Minnesota and Missouri only. For the remaining CENRAP states, NIFMID data were used to characterize USFS fires. Additional prescribed burn data for federally managed lands were included in data acquired from state smoke management programs.

Each CENRAP state has unique regulations regarding prescribed burning on state and private lands; records of prescribed burns are compiled at different levels within each state. Consequently, several sources of information contributed to the prescribed burn activity data for state, private, and tribal lands. When good information about prescribed burns on state lands could not be acquired, the percentage of federal lands burned within the state in the year 2002 was used as a surrogate for the percentage of state lands burned. The total acreage of burned state lands was allocated according to the proportion of state lands within each county. Table 2 summarizes the types of prescribed burn activity data that were acquired and the agency that provided the data for each state.

Table 2. Sources of activity data acquired for prescribed burns on state and private lands.

State	Agency	Type of Program	Data Included
Arkansas	Arkansas Forestry Commission	Smoke management program	Date, extent, location coordinates of large scale prescribed burns in 2002
Iowa	Bureau of Wildlife	Performs a large portion of the state's prescribed burns on public grasslands.	Nothing compiled above the county level
Kansas	Kansas State Fire Marshal	Fire incidents in Kansas reported by local fire departments, including some prescribed burns	Dates and counties where controlled burns were reported in 2002
Louisiana	Louisiana Forestry Division	Smoke management program	Number of burns (and acreage) by multi-county district for public and private lands in 2002.
Minnesota	Minnesota Interagency Fire Center	Smoke management program	Date, extent, location coordinates of large prescribed burns in 2002
Missouri	Forestry Section - Missouri Department of Conservation	Department of Conservation	Summary of acres burned on state and private lands in Missouri during 2002
Nebraska	Nebraska Game and Parks Commission	Prescribed burns permit program	Records are not compiled above the county level
Oklahoma	Oklahoma Forestry Service	Controlled burn authorization system	Date, type of fuel, extent, and location of prescribed burns in eastern Oklahoma on state forest and private lands in 2002
Oklahoma	Department of Wildlife Conservation (DWC)	Department of Conservation	Number of acres burned on lands managed by the DWC in 2002
Texas	Texas Parks and Wildlife Department	Burns that occur in state parks	Data, location (county), extent, type of fuel

To ensure that burning on tribal lands was captured in data sources, tribes that collectively hold over 95% of the tribal lands in the CENRAP region were contacted to confirm burn reports to either the BIA or the Minnesota Interagency Fire Center. Burning on private land was assumed to be done by individual parties and related to agricultural practices (therefore, captured in the agricultural survey data) or to the burning of waste (therefore, not considered within the scope of this project).

Rangeland burning occurs extensively on private lands throughout the CENRAP states, particularly in Kansas, Nebraska, Oklahoma, and central and west Texas. To obtain activity data for rangeland burning events in the CENRAP region, the agricultural burning survey given to county AES offices included questions about rangeland burning designed to determine the fraction of rangeland acreage typically burned each year and the timing of such burn events. The survey results yielded activity data for private lands for all CENRAP states. Additional prescribed burning information was obtained for private lands in some CENRAP states.

Spatial and Temporal Allocation and Chemical Speciation of Emissions

Fire occurrence locations for prescribed burns were often provided as point coordinates (i.e., latitude and longitude), township/range assignments, or county name. In addition, the begin date and duration of prescribed burns were often reported. When incident-level reports of prescribed burns were available—i.e., when specific location and date information were known—these incidents could be precisely located, time-resolved, and included in the emission inventory as if they were point sources (rather than area sources). Approximately 40% of the prescribed burning inventory was prepared for the point source inventory. (Arkansas, Minnesota, and eastern Oklahoma were able to provide incident-level databases of prescribed burn activity.) Incident-level prescribed burns were simply treated as point sources and assigned to their reported coordinates, which were assumed to be the centroids of the burned areas. This simplified approach to locating prescribed burn incidents was sufficient because none of the reported burn areas was larger than the 12-km x 12-km grid cell resolution.

When the specific locations of fires were not reported, a spatial surrogate approach was used to spatially distribute emissions at the sub-county level (by grid cell), and temporal profiles were estimated on the basis of available data. Prescribed burns were spatially distributed to rural grasslands and forested lands, while agricultural burns were spatially distributed to agricultural lands by crop type based on data obtained from the agricultural burning surveys. Fire history data collected for prescribed burns on federal lands specified the dates on which the burns began and ended. These data were used to generate state-specific temporal profiles to allocate emissions from prescribed burning to the proper months of the year and days of the week. Also, examining the number of burns completed in one day versus those spanning multiple days enabled an estimate of the fraction of prescribed burning that occurred during the day versus the fraction that occurred at night. In the absence of date-specific information for prescribed burns on state lands, temporal profiles derived from federal prescribed burns were applied to burns on state lands.

County-specific vegetation profiles from the BELD data were matched to each fire location to determine the vegetation types associated with each fire. The vegetation data (used by the FOFEM model), fire size, period of burn, and associated fuel moisture data were used to calculate emission factors and emissions for each fire. PM and VOC emissions were chemically speciated according to speciation profiles developed by the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB).

Methods for Developing Agricultural Burning Emissions Estimates

Emission Factors and Fuel Loadings

Agricultural burning is primarily a means of clearing harvested lands. Because the CENRAP region is largely agricultural, related activities are likely to be sources of significant episodic combustion emissions in most counties. Allen and Dennis (Allen and Dennis, 2000; Dennis et al., 2002) recently completed study of emissions from fires in Texas, which included agricultural and rangeland burning in 1996 and 1997.[6,7] According to their assessments, agricultural activities emitted over 66,000 tons of $PM_{2.5}$ and accounted for 84% of over 3.3 million acres of vegetation burned in Texas during those two years.

Emissions from agricultural burning activities are dependent on the types of vegetation burned and the manner of combustion and can be estimated using the following equation:

Equation (1) $$E = FL * EF * A$$

Where:

E = emissions (lb)
FL = fuel loading (tons/acre)
EF = emission factor (lb/ton)
A = number of acres burned

In its Compendium of Air Pollutant Emission Factors, (AP-42) [1] (U.S. Environmental Protection Agency, 2003), the EPA provides fuel loadings and emission factors for PM, carbon monoxide (CO), methane (CH_4), and non-methane hydrocarbons (NMHC) for a variety of field and orchard crops. [3] In some cases, AP-42 emission factors are provided for different burning techniques: headfire burning (when a fire is started on the upwind side of a field) and backfire burning (when a fire is started downwind). In addition, a more recent study at the University of California at Davis derived emission factors for the combustion of barley straw, corn stover, rice straw, wheat straw, and almond tree prunings (Jenkins et al., 1996).[2] In this study, emission factors for CO, total hydrocarbons (THC), NO_x, SO_2, and PM were based on measurements collected during wind tunnel tests.

Fuel loadings and emission factors were obtained from a variety of sources. For barley, corn, rice, wheat, and almonds, emission factors were derived entirely from the Jenkins' study [2] using average emission rates and moisture contents from two wind tunnel configurations. An emission factor for VOC was derived from Jenkins' THC values by using the fraction of reactive gases equal to 0.5698 that was published in a CARB guidance document.[2,8] For the remaining crops, emission factors for NO_x and SO_2 were set equal to Jenkins' average values for field or orchard crops, and emissions factors for VOC were calculated from the CH_4 and NMHC values reported in AP-42, again by using the CARB fraction of reactive gases. The emission factors for CO were taken directly from AP-42; and PM_{10} and $PM_{2.5}$ were calculated from the PM values in AP-42 by using fractions of 0.9835 for PM_{10} and 0.9379 for $PM_{2.5}$ for field crops and fractions of 0.9814 for PM_{10} and 0.9252 for $PM_{2.5}$ for orchard crops based on CARB's guidance.[8] Fuel loadings were taken from AP-42 for all crop types.

<u>Activity Data</u>

Systematic telephone and mail surveys of county AES offices were conducted to obtain activity data for agricultural burning events in the CENRAP region. The survey was designed to determine the fraction of each county's acreage typically burned each year by crop type, the timing of such burn events, and the burn methods employed. Data collected through the survey was then applied to National Agricultural Statistics Service (NASS) county-level estimates of acreages grown by crop type for 2002.

An attempt was made to contact each AES office in all 969 counties of the CENRAP region to recruit AES personnel to complete a telephone survey. This data collection effort had a target response rate of 25% to 50%. Ultimately, 549 contacts were made, for a response rate of 56% (ranging state to state from 36% to 93%). By including such a large sampling from the available respondent pool and proportion of the total geographic area of the CENRAP region, the representativeness of the study was maximized and the potential uncertainties minimized.

Spatial and Temporal Allocation and Chemical Speciation of Emissions

Agricultural burning was spatially allocated using the BELD GIS database. The BELD database includes spatial distributions of crops by type at county and sub-county levels gridded to 1 km^2. Activity data obtained through the agricultural survey questionnaires about the types of crops burned at the county level were spatially allocated by matching the reported crop types from the questionnaire to the crop types in the BELD database by county. The fire activity data were applied to the area (acreage) of crops by county for the purposes of calculating countywide emissions. Spatial allocation factors were developed by gridding the agricultural burn activity data and corresponding crop types to a 12-km x 12-km grid resolution.

Agricultural burning, like other agricultural activities, has a distinct seasonal pattern that varies by crop type and region. To identify seasonal patterns in the CENRAP region, the survey of agricultural experts contained questions designed to identify times of the year when agricultural burning occurs for the crops grown in each of the CENRAP states. Survey responses were used to develop seasonal, weekly, and diurnal profiles that characterize agricultural burning activities by state and crop type.

As was the case with prescribed burns, PM and VOC emissions were chemically speciated according to profiles published by the EPA and the CARB. These references were used to create speciation profiles and cross-reference files required by the emissions processing system.

RESULTS AND DISCUSSION

Overview of Resulting Emissions Estimates

The resulting emission inventory is illustrated in Figures 2 and 3. In all cases, generally accepted emission factors and the most complete and up-to-date activity data sets that could be identified and acquired during the course of this project were applied. However, available emission factors are subject to uncertainty and continue to be the subject of research.

The emission source types in the inventory that are qualitatively considered to contribute the most uncertainty to the total estimated emissions are prescribed burning performed by the USFS on publicly managed lands and, to a lesser extent, prescribed burns performed by the forestry industry and organizations such as the Nature Conservancy (TNC) on privately held lands. New information will be needed to reduce emissions uncertainties. To help mitigate the effects of these uncertainties, we provided the CENRAP with an inventory and data file system that can be easily updated with revised emission factors and activity data as new information becomes available.

Figure 2. Total annual $PM_{2.5}$ emissions by burn type for each state of the CENRAP region.

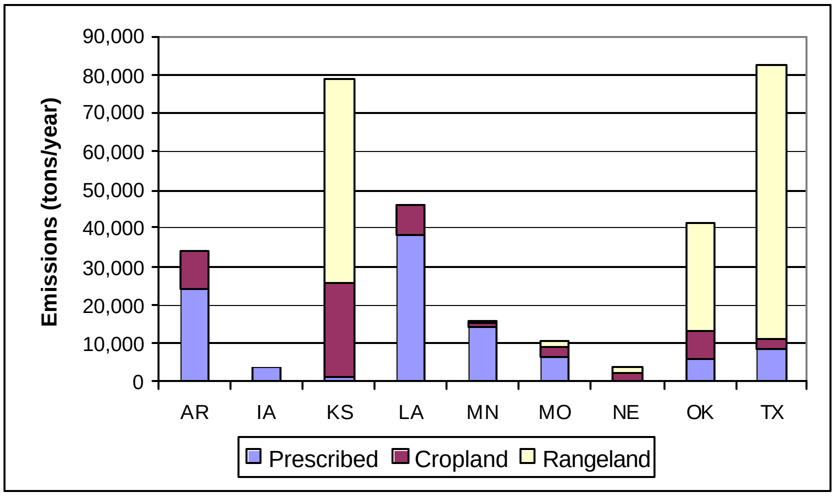
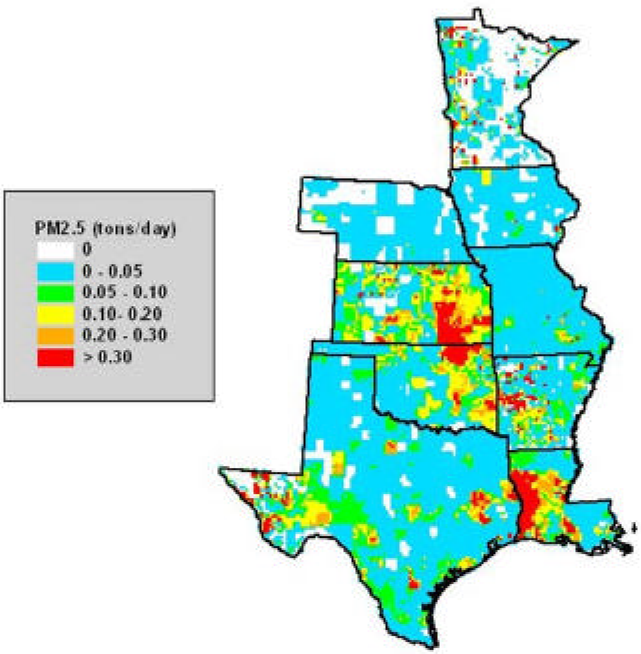


Figure 3. Example map of daily emissions densities for the CENRAP region (April 10, 2002).



Summary of Emissions Estimates for Prescribed Burning

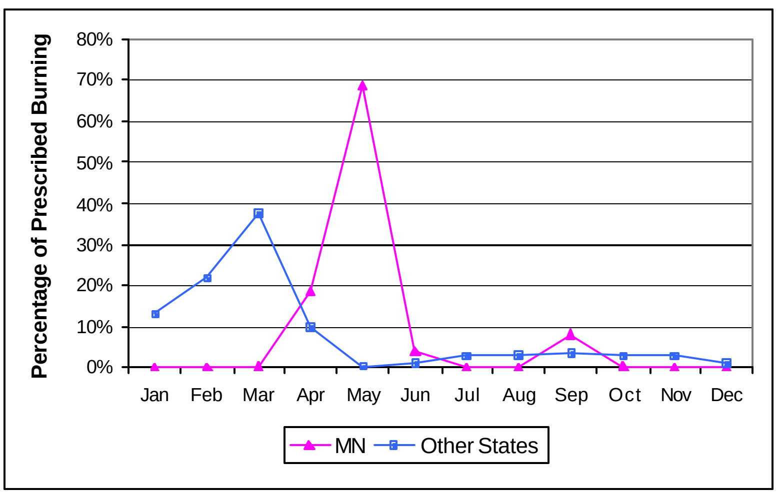
Emission estimates were generated for prescribed burning activities on federal, state, tribal, and private lands. Prescribed fires resulted in over one million acres burned in 2002 in the CENRAP region, with consequent $PM_{2.5}$ emissions of over 100,000 tons and emissions of precursors as summarized in Table 3.

Table 3. 2002 acres burned and emissions (tons) for prescribed burning in CENRAP states.

STATE	Acres Burned	PM_{10}	$PM_{2.5}$	NO_x	SO_2	NH_3	VOC
Arkansas	244,146	28,130	23,838	1,961	1,577	2,910	17,444
Iowa	21,449	4,072	3,457	166	195	257	2,547
Kansas	35,400	1,390	1,176	210	107	136	846
Louisiana	348,404	45,137	38,247	3,088	2,529	4,609	27,973
Minnesota	81,336	16,541	14,030	705	801	1,096	10,315
Missouri	64,781	7,460	6,338	536	417	756	4,633
Nebraska	5,403	345	292	31	21	20	214
Oklahoma	93,479	7,161	6,063	693	458	752	4,413
Texas	114,283	9,969	8,443	870	603	1,125	6,153
Total	1,008,681	120,206	101,883	8,260	6,707	11,662	74,538

The seasonal variability of prescribed burning emissions follows a bimodal pattern, with a large peak in spring and a smaller peak in fall. Factors that influence the seasonal variability of burning include weather conditions, fuel moisture content, and the intended environmental consequences of the burn (such as the eradication of specific plant species).[9] Analysis of fire history records showed that all CENRAP states except Minnesota followed a similar seasonal pattern for prescribed burning. The longer winters in Minnesota delay the spring peak from March to May, and fall prescribed burns in Minnesota occur primarily in September rather than being spread evenly over the later summer and fall months as in other states as shown in Figure 4.

Figure 4. Monthly variation in emissions from prescribed burning.



Assessment of Emissions from Prescribed Burning

The bottom up activity data gathered for the prescribed burning portion of this inventory increase the reliability of the emissions estimates generated. Virtually all burn records for federal lands (and some state burns) include fire date and location information that enables the use of day-specific fuel moisture settings in calculating emission factors. Location information also enabled these burns to be treated as point sources for spatial and temporal allocation purposes. As shown in Figure 2, emissions from prescribed burning are most significant in western Arkansas/Louisiana to eastern Texas/Oklahoma. This phenomenon is expected because prescribed burning is more widely practiced in the southern United States than in other areas.[10] Moreover, the estimate of 114,283 acres burned on wildlands in

Texas is within the range of prescribed burning estimates developed in 1996 and 1997, when 63,790 and 160,890 acres, respectively, were burned.[7]

Prescribed burning accounts for about 30% of the annual planned burning $PM_{2.5}$ emissions in the CENRAP region. However, emissions from this source category actually exceeded those from agricultural burning for five states: Arkansas, Iowa, Louisiana, Minnesota, and Missouri. When only those states are considered, prescribed burning accounts for about 80% of the annual planned burning $PM_{2.5}$ emissions. Uncertainties related to prescribed burning emissions estimates emanate from differences in fire activity tracking and reporting in each state. For example, although burns on federal lands managed by the Department of the Interior (including burns performed by the USFWS, NPS, and BIA) are well-characterized in the inventory, data on burns performed by the USFS appear to be incomplete for some states. USFS regional smoke managers named the NFPORS as the most comprehensive collection of USFS burn data; however, NFPORS records were obtained only for Minnesota and Missouri within the time frame of the project. For the remaining states, data obtained from NIFMID and provided by various state agencies characterized USFS burns; data sets appear to be more complete for some states (such as Arkansas) than for others (such as Louisiana).

Differences between states are even more pronounced for burns occurring on privately held lands. Such burns are performed by individuals, private companies, and organizations such as TNC and the Audubon Society. However, permitting or reporting requirements are inconsistent among the nine CENRAP states, and few states were able to provide reliable data on these burns. Attempts to contact private companies and organizations were also unsuccessful. It should be noted, though, that most burns on private lands are likely to be related to agriculture or waste management (such as the burning of logging residue by forestry companies or pile burns by land developers).[11,12] Agricultural burns were accounted for in the agricultural survey; however, waste management burns were not included in the scope of this project.

Summary of Emissions Estimates for Agricultural Burning

Emission estimates were generated for agricultural burning activities on private rangeland and cropland in each CENRAP state. Agricultural burning resulted in about 13 million acres burned in 2002 in the CENRAP region, with consequent $PM_{2.5}$ emissions of over 200,000 tons (see Table 4).

Table 4. 2002 acres burned and emissions (tons) for agricultural burning in CENRAP states.

STATE	Acres Burned	PM_{10}	$PM_{2.5}$	NO_x	SO_2	NH_3	VOC
Arkansas	655,307	10,771	10,227	3,692	637	2,100	6,254
Iowa	2,247	44	42	5	1	4	20
Kansas	5,205,313	102,315	77,805	29,562	11,005	11,924	56,483
Louisiana	486,441	8,384	7,888	3,845	609	2,453	7,066
Minnesota	101,925	1,944	1,729	358	69	248	1,155
Missouri	290,978	4,958	4,314	1,907	520	693	2,500
Nebraska	215,526	4,647	3,609	643	244	553	2,950
Oklahoma	2,303,359	45,231	35,228	18,645	6,653	5,124	23,992
Texas	3,798,581	104,709	74,393	13,647	8,725	12,573	63,396
Total	13,059,677	283,003	215,234	72,304	28,463	35,673	163,817

Emissions from agricultural burning contribute 70% to total estimated $PM_{2.5}$ emissions for the CENRAP region, ranging from 1% to 99% of total emissions from state to state. The most important crop/land-use types are rangeland (especially in Texas, Oklahoma, and Kansas) and wheat (especially in Kansas, Oklahoma, and Arkansas). Sugarcane burning is significant in Louisiana. Figure 5 illustrates estimated emissions by state and crop type. Figure 6 depicts the geographic allocation of agricultural burn emissions throughout the CENRAP region.

Figure 5. Statewide $PM_{2.5}$ emissions from agricultural burning.

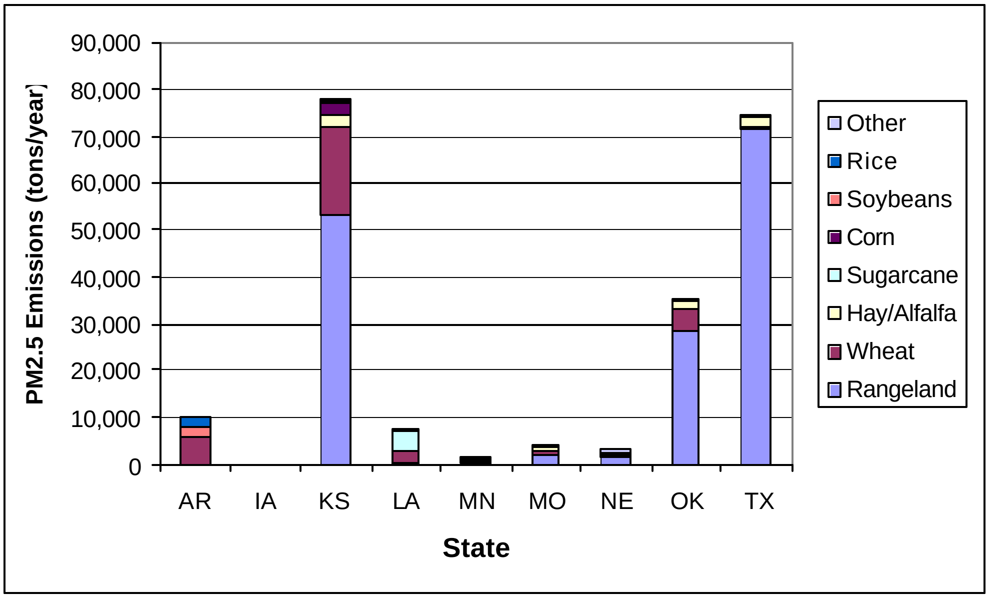
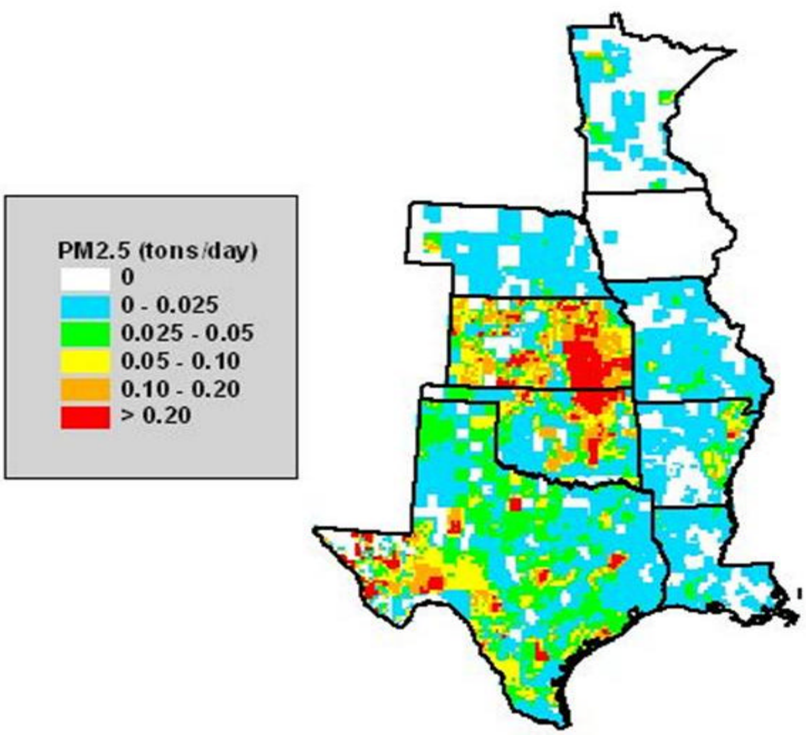
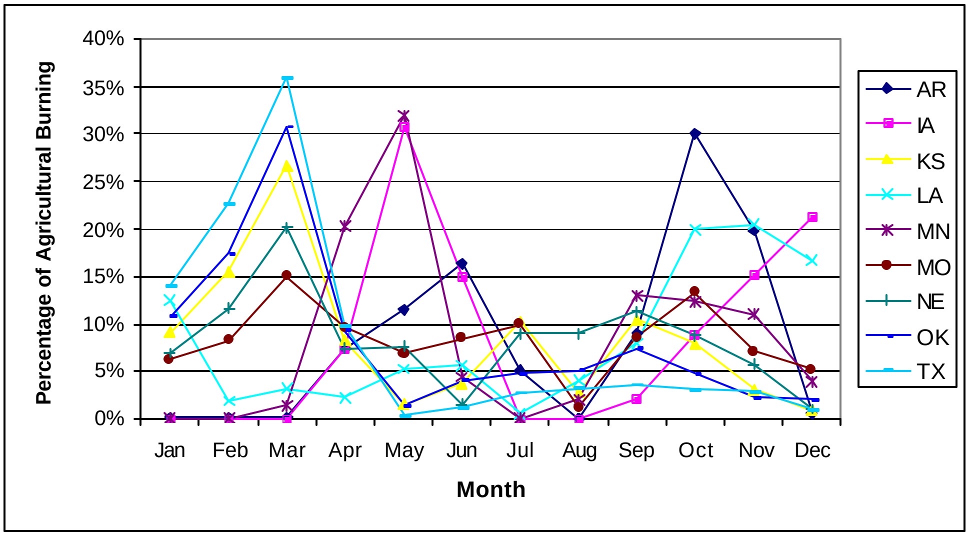


Figure 6. Example depiction of the spatial distribution of daily $PM_{2.5}$ emissions from agricultural burning in the CENRAP domain.



Emissions from agricultural burning tend to follow a bimodal pattern of seasonal variability, with large peaks in the spring and smaller peaks in the fall (see Figure 7). For most states, March is the month with the highest emissions from agricultural burning, although northern states like Minnesota and Iowa show a spring peak in May. In Arkansas and Louisiana, the highest emissions occur in September and October, respectively, which is due to the large acreages of winter wheat burned in Arkansas and sugarcane burned in Louisiana.

Figure 7. Monthly variation in emissions from agricultural burning by state.



The bottom up survey data collected for agricultural burning activities made it possible to generate emissions estimates that account for county-level burn practices in each CENRAP state, including information on the timing and techniques used to burn individual crops. This study indicates that agricultural burning practices vary widely from state to state and even among counties within a state. For example, 54 of the 56 counties surveyed in Iowa, and 50 of the 77 counties surveyed in Minnesota, reported no agricultural burning. Among states that burn extensively, practices vary by crop type. The survey indicates that burning is widely used in Arkansas to destroy wheat stubble; over 40% of the crop is burned each year. By contrast, no other state that grows substantial amounts of wheat burns more than 15% of the crop annually.

It is also important to note that, while agricultural burning accounts for about 70% of the annual $PM_{2.5}$ emissions from planned burning activity in the CENRAP region, almost 90% of the agricultural burning emissions occurred in three states: Texas, Oklahoma, and Kansas. Moreover, about 70% of all agricultural burning emissions in the CENRAP states results from the burning of rangeland in these three states.

Uncertainties related to agricultural burning emissions result largely from an incomplete understanding of local burning regulations. For example, several states with a significant number of counties reported no agricultural burning: Iowa, Minnesota, Nebraska, and Missouri. It is unclear if these reports are due to local restrictions on agricultural burning or other factors.

Preliminary Analysis of Emissions, Air Quality, and Meteorological Data

Analyses were performed to determine if ambient data can be used to identify planned burning contributions to visibility events in Class I areas and to perform a preliminary assessment of the impact of planned burns on $PM_{2.5}$ and visibility. Ambient speciated $PM_{2.5}$ data from Class I areas (from the IMPROVE network) were used in conjunction with the estimated planned burning emissions and meteorological data to assess the seasonal chemical compositions of $PM_{2.5}$ mass and aerosol light extinction and to determine which individual species are important to mass and visibility extinction in the area. In addition, the seasonal concentrations and ratios between selected species (OC, EC, and K) were assessed to establish a baseline seasonal composition for comparison to days of poor visibility and days potentially influenced by prescribed burning. The chemical compositions of $PM_{2.5}$ and aerosol light extinction were assessed on the 20% best and 20% worst visibility days to determine which species most impact visibility. The IMPROVE OC, EC, and K concentration data were used to assess days when extensive burning occurred near a monitoring site and to assess if wood smoke influences could be seen in the ambient measurements. Emissions data were assessed for days when elevated OC, EC, and K concentrations occurred at IMPROVE sites to determine whether days of elevated concentrations corresponded to known burns in the emission inventory. Lastly, air mass trajectories were analyzed on selected days to determine if meteorology (i.e., transport) explained the observed effects and the extent to which meteorology affected haze.

Findings from the ambient air quality analysis indicate that speciated $PM_{2.5}$ data can be used to determine influence from planned burns when the meteorology is conducive to transport from the burn area to a Class I site. Smoke constituents, specifically EC and K, are not a significant fraction of the $PM_{2.5}$ mass and light extinction, even on days when there was evidence of planned burning influence. Ammonium sulfate, which is not derived from burning, is the dominant constituent of the $PM_{2.5}$ mass and light extinction in a given season and especially on the 20% worst visibility days. This finding is consistent with previous work in the Midwest and the CENRAP region including Big Bend National Park and Seney Wildlife Refuge.

On select days, influence from known prescribed burns was evident, though it was generally less than 10% of the $PM_{2.5}$ mass and light extinction. Improved spatially and temporally resolved emission inventories and additional case studies may show different results. The specific influence of smoke on $PM_{2.5}$ mass and light extinction could be better quantified with more analyses, including source apportionment.

RECOMMENDATIONS

Recommendations for Future Emission Inventory Improvements

Data for burns performed by the USFS appear to be incomplete for some states. USFS regional smoke managers named NFPORS as the most comprehensive collection of USFS burn data; however, NFPORS records were obtained only for Minnesota and Missouri within the time frame of this project. Therefore, we recommend that efforts be made to acquire NFPORS data for the remaining CENRAP states. When NFPORS data are acquired, they should be used to identify USFS fires that were omitted from the data sets used to produce this inventory.

In addition, TNC protects roughly 1.5 million acres of land across the CENRAP region and conducts some prescribed burning on these lands. While some TNC burns were captured in the data acquired for this project, the completeness of these data is unclear. TNC reports burns to the NFI and agreed to make NFI data available, although the data were not provided within the time frame of this project. It is recommended that NFI data be acquired and incorporated into future inventory efforts.

Variability in burning activities among states is more pronounced for burns occurring on private lands. These types of burns are typically performed by individuals, private companies, and organizations (i.e., TNC and the Audubon Society). However, the permitting and reporting requirements among the nine CENRAP states are inconsistent, and few states were able to provide reliable data for these types of burns. Attempts to contact private companies and organizations were also unsuccessful. Future work should be directed at better characterizing burns on private lands.

Uncertainties related to agricultural burning emissions are largely due to an incomplete understanding of local regulations pertaining to agricultural burning activities. A substantial number of counties in Iowa, Minnesota, Nebraska, and Missouri reported no agricultural burning activity in 2002. Future efforts should be directed at understanding county-level open burning restrictions and how they are enforced. Further discussions with county AES offices, as well as with individual farmers, could be used to acquire this information.

Emission factors are often a subject of research. Consequently, it is recommended that efforts be made to identify and incorporate improved emission factors related to prescribed and agricultural burning as they are published. Although the default fuel loading values by vegetation type contained in the FOFEM model were judged to be sufficiently representative of conditions in the CENRAP region, some effort should be made to study and verify the representativeness of these fuel loadings. For example, during the course of this project, personnel at the USFS in Minnesota indicated that the default fuel loadings in FOFEM are regularly updated as part of their statewide burn analyses. Minnesota provided adjusted fuel loadings for several vegetation and fuel types, most of which are related to "blowdown" burns (the burning of vegetation after storms to reduce fire hazard). These adjusted fuel loadings resulted in $PM_{2.5}$ emission factors that were up to 70% higher than those calculated with FOFEM default loadings. When the adjusted emission factors were applied to 3700 acres of blowdown burns, the prescribed burning portion of the $PM_{2.5}$ inventory for Minnesota increased by about 5%.

In addition to the recommendations discussed above, alternative and newly emerging data sources such as satellite data and related products recently developed by NOAA[13] should be explored to help characterize fire locations and day-specific activity levels.

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KEY WORDS

Emission inventory
Prescribed burning
Agricultural burning
Fire
VOC
NO_x
$PM_{2.5}$
PM_{10}
SO_x
NH_3
IMPROVE
CENRAP
Texas
Oklahoma
Louisiana
Arkansas
Kansas
Missouri
Nebraska
Iowa
Minnesota
FOFEM