Development of a biomass burning emissions inventory by combining satellite and ground-based information

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Abstract. A 2005 biomass burning (wildfire, prescribed, and agricultural) emission inventory has been developed for the contiguous United States using a newly developed simplified method of combining information from multiple sources for use in the US EPA's National Emission Inventory (NEI). Our method blends the temporal and spatial resolution of the remote sensing information with the ground based fire size estimate. This method is faster and considerably less expensive than the method used for the 2002 National Emissions Inventory and is more accurate than methods used for 2001 and prior years. In addition, the 2005 fire inventory is the first EPA inventory utilizing remote sensing information. A comparison with the 2002 inventory for wildfire, prescribed, and agricultural fires indicates a large year-to-year variability in wildfire emissions and less variation for prescribed and agricultural fires. Total PM2.5 emissions from wildfires, prescribed burning, and agricultural burning for the contiguous United States were estimated to be 109,000 short tons, 209,000 short tons, and 232,000 short tons, respectively, for 2005. Our total emission estimate for 2005 is 550,000 short tons. Our analysis shows that year-to-year spatial variability accounts for the substantial difference in the wildfire emission estimates.

Keywords: Biomass Burning emission inventory, Satellite-based, Ground-based, wildfires.

1 INTRODUCTION

The information in the National Emissions Inventory (NEI) for wildland fires, until recently, has been extremely limited about the specific location and timing of major fire events. For years 2001 and earlier, biomass-burning related emissions are spatially resolved for the conterminous 48 states (CONUS) from state to county to grid and temporally resolved from annually to hourly via allocation factors. For these years (2001 and earlier), this rather imprecise spatial and temporal resolution of the biomass inventory had been the standard method used in the NEI. For the 2002 NEI, a detailed fire inventory was prepared by the Regional Planning Organizations (RPOs) and combined into a single national inventory by the EPA[1]. For this inventory, emission estimates were made in short tons (S/T) = (907.184 kg). In this paper, we retain the use of the short ton units to be consistent with the EPA standard unit used in emission inventories. However, the process used in the 2002 NEI was time-consuming and very expensive. For regional air quality modeling, there is a need for spatially and temporally resolved fire emissions. The 2006 NARSTO (formerly North American Research Strategy for Tropospheric Ozone) report [2] has specifically indicated that emissions from open biomass burning, including wildfires, agricultural and forest prescribed burning need to be characterized with greater accuracy. We make a distinction between agricultural burning and prescribed burning because the emission inventory uses

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different source classification codes to distinguish these two fires. These emissions sources are identified as first-priority for development efforts and systematic emission inventory improvement. For years after 2002, it will be prohibitively expensive to create a detailed fire inventory at the national level as was done for the 2002 NEI because the cost was on the order of 500,000 dollars. Therefore, an approach to estimating wildland fire emissions that is better than the pre-2002 method and not as time consuming as the 2002 NEI is desired for future years. In an earlier study, Roy et. al. [3] has improved the spatial and temporal resolution of fire emissions using Moderate Resolution Imaging Spectro-radiometer (MODIS) pixel counts by re-allocating emissions on a state by state basis. Roy et. al. [3] provided a fair improvement in CMAQ (Community Multiscale Air Quality Model) predictions for PM2.5 and organic carbon compared to surface observations. The square of the correlation coefficient improved from 0.28 to 0.81 in Figure 5 of Roy et. al. [3]. Soja et. al. [4] has done a detailed matching of fires to satellite detects for specific months and for specific states. This method shows promise in estimating fire sizes directly from all satellite sources without the use of ground information but at this stage has not yet been done for the whole CONUS. Wiedenmyer et. al. [5] has also estimated biomass burning emissions using satellite information and a different fuel loading modeling.

Our paper improves upon Roy et. al. in two ways: (1) the allocation of wildfire emissions is done on a per fire basis and on a per day basis (2) the emission estimates are based on the temporal and spatial information in the MODIS pixel counts geo-referenced to a fuel loading database. Our paper details an improved and streamlined method for estimating biomass burning emissions for the CONUS by merging satellite detected fire information with ground based information and applying the method for 2005. This is one of the most comprehensive fire inventories to date that has been developed on a national basis. Our paper differs from Wiedenmyer et. al. [5] in that we match our satellite detects to the ground based information on a per fire basis and on a per day basis whereas in Wiedenmyer et. al. [5] the emission inventory is determined by the availability of the satellite detections.

2 METHODOLOGY

Biomass burning emissions were estimated by using the ground-based wildfire information to match wildfire events to specific MODIS pixels. The remaining unmatched MODIS pixels were then divided into two groups based on a detailed land-use dataset to distinguish agricultural fires from non-agricultural fires. Emission estimates were then derived for both matched and unmatched portions of the inventory. We first summarize the data sets used in our approach.

2.1 Datasets

We obtained the 2005 Incident Status Summary reports (aka ICS 209 reports) from the National Interagency Fire Center's FAMWEB (Fire and Aviation Management Homepage)[6]. These reports contain ground-based information available on a national basis for fire incidents that meet certain criteria: 100+ acres in timber or 300+ acres in grass/shrub, Wildland Fire Use (WFU) events and wildland fires in confinement strategy, incidents to which an Incident Management Team (IMT) is assigned, or any other significant events on lands under federal protection or federal ownership. A total of 4.4 million acres were reported in the 2005 ICS 209 reports for the CONUS.

We also obtained data from the MODIS instrument onboard the National Aeronautics & Space Administration's (NASA's) Earth Observing System satellites (Terra and Aqua). The MODIS-equipped satellites are polar orbiting with one daytime equatorial crossing and a one square kilometer resolution (pixel) product. Fire-counts are obtained from MODIS instruments aboard these two different satellites having 10:30 AM/PM and 1:30 AM/PM (local time) equatorial crossings, respectively for a total of four passes per day. During 2005 a total of 91,246 fire counts were detected over the CONUS. We have accounted for multiple detections on a single day by using the net total of fire counts over the course of the day to determine fire locations.

Our land use dataset is the Biogenic Emissions Land-Cover Database version 3.0 [7] (BELD3) which is a 1-km national database of 230 different land-use types. The land-cover types particularly useful for this inventory development were regions of agricultural use. We used the National Fire Danger Rating System (NFDRS) fuel model database mapped across the lower 48 states at 1 km resolution to determine the fuel model. The map of fuel models was derived from a combination of satellite imagery used to create a land cover database for the CONUS and ground data sampled from across the CONUS. To calculate emissions we used the Fire Emission Production Simulator (FEPS)-based lookup table included in Appendix C in the inter-RPO 2002 National Emission Inventory Report [8]. The FEPS-based lookup table requires qualitative fuel moisture information. We obtained historical thousand hour fuel moisture from the publicly available archive of the internet-based Wildland Fire Assessment System (WFAS)[9]. Thousand-hour dead fuel moisture is a seven day average of the moisture content of dead organic fuels 3 to 6 inches in diameter, expressed as a percentage of the oven dry weight of a sample controlled entirely by exposure to environmental conditions computed from day length, hours of rain, and daily temperature/humidity ranges. The current implementation of WFAS provides a national view of weather and fire potential, including national fire danger and weather maps and satellite-derived "Greenness" maps.

2.2 Large Fires Inventory

We defined fires that were reported as burning greater than 10,000 perimeter acres as "large". These fires were matched to MODIS pixels using one or more county Federal Information Processing Standard (FIPS) codes associated with the fire. For a MODIS pixel to match to an ICS-209 reported fire the MODIS pixel had to be in one or more user-specified counties on the same day for which acres burned were reported. An example of a "large" fire is the Cave Creek Fire in Arizona shown in Fig. 1. We see that the MODIS pixels are located in two adjacent counties in Arizona. This is confirmed with the US Forest Service Fire Perimeter map also shown in Fig. 1 [10]. Note that the maps are somewhat skewed due to differences in the geospatial projections in the mapping software used for each. A total of 67 wildland and Wildland Fire Use (WFU) fires were identified as "large" during 2005. The total acres from these "large" fires was 2.4 million acres and represents about 55% of the total acres in the wildfire inventory for 2005. Of these 2.4 million acres, 1.3 million matched with 8,887 MODIS pixels in the CONUS. The remaining 1.1 million acres were retained for emission estimates. These remaining "large" fire acres were associated with multi-day fires for which no MODIS pixels matched on a specific day but matching MODIS pixels were found on prior or subsequent days during the fire event. This suggests that the dates in the ICS-209 reports can be imprecise.

2.3 Small Fires Inventory

We defined fires that were reported as burning less than 10,000 perimeter acres as "small". These fires were matched to MODIS pixels using a national 12 km grid. If the MODIS pixel was within the same grid cell on the same day as the ICS-209 reported fire, it was matched to the ICS-209 report (case 1). If an ICS-209 fire had no matching MODIS pixels in the same 12 km grid cell on the same day, the search for a MODIS pixel was expanded to include the adjacent eight 12 km grid cells (case 2). If this failed, then the search was expanded to include the adjacent eight 12 km grid cells plus or minus one day from the date in the ICS-209 report (case 3). In all cases, the MODIS date and location "replaced" the information in

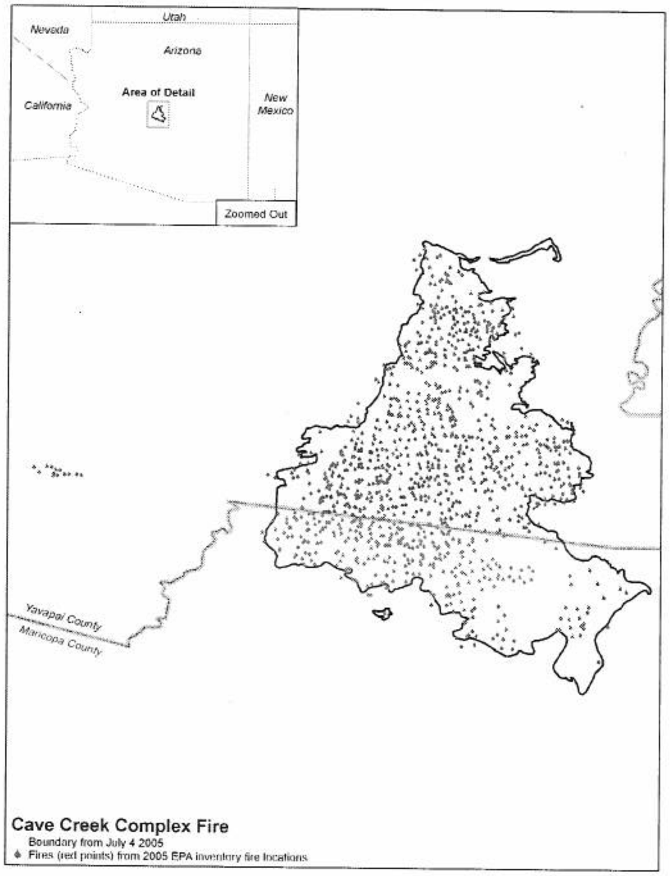


Fig. 1. Cave Creek Fire Complex Fire Perimeter as documented by the US Forest Service overlaid with the matched MODIS pixels used in the 2005 inventory over a two county area.

the ICS-209 report. If multiple MODIS pixels were determined to match, the acres and emissions associated with that fire were distributed equally among all MODIS pixel matches. For the "small" fires, a total of 4800 MODIS pixels matched 0.8 million acres. Only a small number of prescribed fires and the remaining wildfires are included in "small" fires. Agricultural Fires are not included since these fires are not in the ICS-209 reports. Figure 2 is an example of the matching of pixels to an ICS-209 report for a small fire (the Deer Creek Fire). The red marker indicates the location of the ICS-209 report. We note that the date of the ICS-209 report was one day before the MODIS pixels. This represents case 3 described previously where we searched one day later than the date of the ICS-209 report. Figure 3 shows the fire perimeter map for the Deer Creek Fire obtained from the Southwest Oregon firemaps.org public website [11]. We see that the location of the fire in the ICS-209 report was likely the ignition point of the fire and that the MODIS detected the fire only on the following day. This fire was contained quickly and burned 1548 acres. For the "small" fires, a total of 4800 MODIS pixels matched 0.8 million acres.

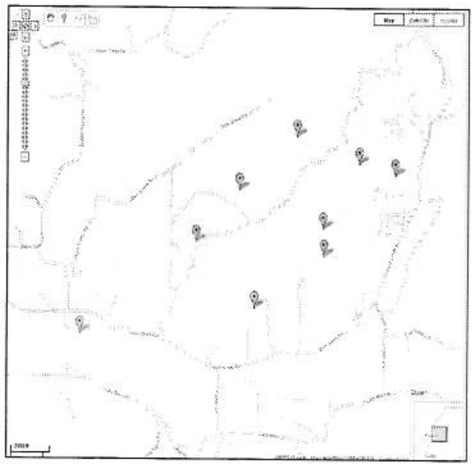


Fig. 2. Google Map showing ICS 209 fire centroid compared to MODIS pixel detects for the Deer Creek Fire in August 2005. Blue pixels are MODIS and Red is the ICS 209 centroid.

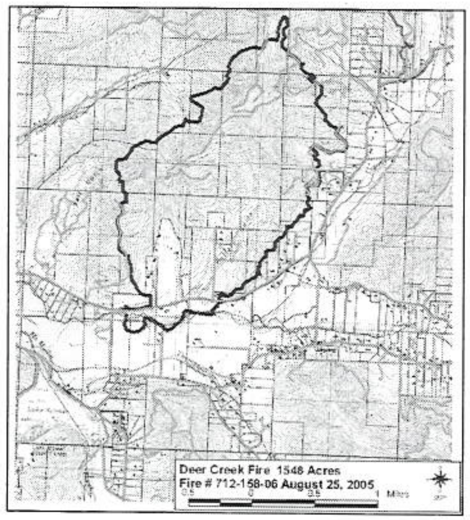


Fig. 3. Fire Perimeter Map for the Deer Creek Fire. The grey lines indicate roads. Source: Oregon Department of Forestry.

2.4 Remaining Ground Reports

Any acres from the ICS 209 reports that were not matched with MODIS pixels were retained for the emission estimates. There were a total of 1.2 million acres (or 27% of the ICS 209 acres) in this category. These fires were retained because we realize that the MODIS pixel counts do not represent all fires. Therefore, these fires are retained in the activity database and emission estimates can still be obtained for these "wildfire" events.

2.5 Agricultural Burning

After matching the "large" and "small" fires to MODIS pixels, the remaining unmatched MODIS pixels were then divided into three categories: agricultural burning, hurricane-debris burning and unmatched MODIS pixels The BELD3 1km land cover dataset was used with the MODIS pixels to disaggregate the MODIS pixels occurring over agricultural areas. If the land use area associated with a MODIS pixel was at least 25% agriculture, it was placed in the Agriculture Burning category and used in the Agricultural Burning emission estimates. We did not estimate burn area for the Agricultural fires. We used a relationship between pixels and emissions on a regional basis to determine emissions per agricultural pixel. A total of 28,947 MODIS pixels were categorized as Agricultural burning.

2.6 Remaining MODIS pixels

For the remaining MODIS pixels, an examination of those occurring during September – December of 2005 in the Gulf coast region suggested that a number of the fire detects were associated with debris burning from the extreme hurricane activity (Katrina, Rita) at the end of 2005. Therefore pixels located in the Gulf Coast counties listed in Table 1 during these months were classified as pile burns of hurricane related debris. There was a total of 1,227 MODIS pixels classified this way. Most of these pixels were stationary for a number of days, suggesting that the activity was due to pile burning of debris. The remaining 47,385 MODIS pixels were placed in a category of unclassified and assigned a fire size of 60 acres/pixel. The estimate of 60 acres/pixel is discussed in the next section. These "unclassified" fires were included in the prescribed burning emission estimate that is discussed in section 2.7.

Table 1. Counties and Parishes in Louisiana and Mississippi associated with hurricane debris burning September – December 2005.

Cameron parish, Louisiana
Vermillion parish, Louisiana
St. Tammany parish, Louisiana
Terrebonne parish, Louisiana
Lafourche parish, Louisiana
Harrison county, Mississippi
Pearl River county, Mississippi
Hancock county, Mississippi

2.6.1 Determination of Blackened Acres to Pixel Count Ratio.

We obtained the inter-RPO emission inventory for 2002 and used the entire set of wildfire and prescribed burning acreage estimates for the August-December time period. We also obtained the MODIS pixel counts for the same period for which both Aqua and Terra satellites were available. The Aqua Satellite was not operational until the latter part of 2002 and this is why the August-December period was selected. We then used the matching procedure outlined above for these fires to obtain a "matching" MODIS to inter-RPO fire event inventory. These "matches" were subtotaled to estimate the number of matching MODIS pixels on a per fire basis. Figure 4 shows a scatter plot comparing MODIS pixels to acres for these 2002 fires. The slope of the line of best-fit was constrained to pass through the origin but we show only fires greater than 100 acres or 10 pixels in the figure for clarity in the log-log scale plot. A rounded estimate of 60 acres per pixel was then obtained. The rationale for this approach is that there is a certain amount of variability in the sizes of fire and so only a rough estimate was justifiable. We note that the inter-RPO used "blackened" acres in their inventory so the acre to pixel ratio represents "blackened" acres to pixels.

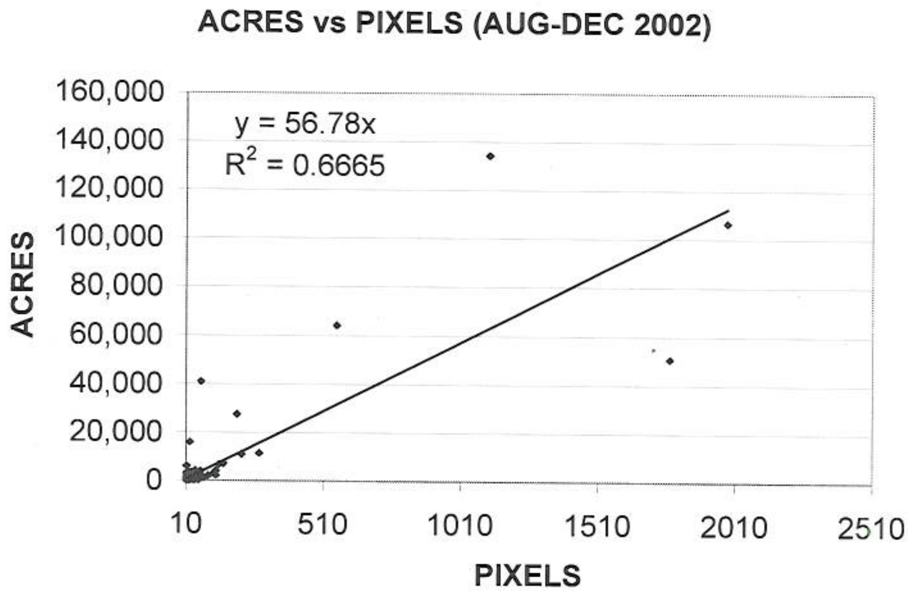


Fig. 4. Scatter plot showing the relationship between 2002 National Emission Inventory acres and MODIS pixels for "matched" fires. Each dot represents a particular fire.

2.7 Emission Estimates for Wildfire Activity

Fires that were identified as wildfires or as wildland fire use (WFU) fires in the ICS 209 reports were the basis for activity data that were used for emission estimates. Emission estimates are based on the following equation

$$E_{poll} = a \cdot f \cdot F \cdot e_{poll} \qquad (1)$$

where a is the perimeter acres burned, f is the fraction of the area that is assumed to be blackened, F is the fuel consumption and e_{poll} is the emission factor for each pollutant. The perimeter acres for each fire are based directly on the ICS-209 reports for that fire. The blackened factor was assumed to be 0.66 as documented in the inter-RPO report for 2002. The fuel consumption and the emission factor were derived from the FEPS-based look-up table in Appendix C of [8] using the National Fire Danger Rating System (NFDRS) fuel models. To obtain the fuel moisture regime as indicated in the lookup table, we obtained monthly fuel moisture data sets from the Wildland Fire Assessment System. For each fire, the nearest observed fuel moisture station was used to estimate the fuel moisture for that fire. This method was applied for each fire day for the "large" fires, the "small" fires and the fires that had no matching MODIS pixels. This calculation was also performed at each MODIS pixel when available. In the inter-RPO 2002 inventory, the calculation was done at the same location for the entire duration of fire with no spatial variability in the fuel loading. For the 2001 inventories and earlier, all fire emissions were estimated as area source emissions covering an entire county. In 2005, all fires associated either with a satellite detect or a ground based report are treated as point source emissions. This is an important fundamental improvement in the fire emission inventory. In addition, assuming fires to be like point sources allows for the effects of plume rise to be represented in an air quality simulation.

2.8 Emission Estimates for Prescribed Fires and Unclassified Fires

The ICS-209 reports contained only a small number of prescribed fires that were identified as such. These fires along with the unclassified fires from satellite detects were used to create a portion of the prescribed fire inventory. The emission calculation was identical to that of wildfires except that the blackened acre fraction was equal to 1. These emissions are designated $E_{pt,2005}$ and comprise the point source component. Given the under detection of prescribed fires by the MODIS instrument, an adjustment was made to the total emission estimates from prescribed fires to account for the under reporting of prescribed fires in the ground data and the under detection by MODIS. We used the 2002 prescribed inventory along with the National Interagency Fire Center (NIFC) prescribed fire activity for 2005 and 2002 to make a monthly county-level emissions adjustment as indicated in equation (2).

$$\begin{aligned} E_{ar,2005} &= \frac{a_{NIFC,2005}}{a_{NIFC,2002}} \cdot E_{NEI,2002} - E_{pt,2005} \quad && if\ \frac{a_{NIFC,2005}}{a_{NIFC,2002}} \cdot E_{NEI,2002} > E_{pt,2005} \\ E_{ar,2005} &= 0 && if\ \frac{a_{NIFC,2005}}{a_{NIFC,2002}} \cdot E_{NEI,2002} \le E_{pt,2005} \end{aligned} \tag{2}$$

where $E_{ar,2005}$ is the area source emission adjustment for 2005 prescribed fires on a per county and monthly basis, $E_{NEI,2002}$ is the 2002 EPA National Emission Inventory of Prescribed Burning on a per county and monthly basis , $E_{pt,2005}$ is the 2005 prescribed and unclassified emission estimate subtotaled on a county and monthly basis, $a_{NIFC,2005}$ is monthly regional prescribed acres reported by NIFC for 2005,and $a_{NIFC,2002}$ is the monthly regional prescribed acres reported by NIFC for 2002.

2.9 Emission Estimates for Agricultural Fires

Since the 2002 National Emission Inventory contains only emission estimates and no acre estimates for a limited number of CONUS states for agricultural burning, we did not try to establish a relationship between acres burned and MODIS pixels in 2005. In addition, the fire pixel count product which we used was not available from both satellites for the first seven months of 2002 and that some algorithm changes were made to the fire detection after 2002 and before 2005. Therefore, we used the NEI emission estimates for 2002 for agricultural burning and compared them to the 2005 MODIS pixels identified as agricultural burning. For those states in 2002 that reported agricultural burning emissions, we created a scatter plot of annual PM2.5 emissions from 2002 versus the total number of MODIS pixels from 2005 identified as agricultural burning (Fig. 5). For a MODIS pixel to be classified as agricultural burning, at least 25% of the pixel area had to be agricultural. If the pixel area was less than 1 square kilometer, then we used the matching BELD3 grid cell to determine if the MODIS pixel was agricultural. If the pixel area was greater than 1 square kilometer, we used the adjacent 8 BELD3 grid cells and the matching grid cell to determine if at least 25% of the area was agricultural. The BELD3 land cover database provided agricultural fractions on one square kilometer grid. The reasonable correlation of the square of the correlation coefficient of 0.71 in Fig. 5 suggested that we could use a pixel to emission relationship to estimate agriculture emissions for 2005 both from states that reported in 2002 and apply the relationship to those states that did not report in 2002. For the Western Regional Air Partnership (WRAP), Central Regional Air Planning Association 1(CENRAP) and Visibility

Improvement State and Tribal Association of the Southeast (VISTAS) (RPOs), we calculated an emissions to pixel ratio per pollutant per region per year and applied this factor to the sum of 2005 MODIS pixels per county per day to create an area source emission estimate. The regional emission to pixel factor was based on the average of pixels to PM2.5 emissions across all states in a region. For all the other RPOs, we used a national average of pixels to emissions ratio and applied this factor to the sum of 2005 MODIS pixels per county per day to create an area source emission estimate. Most states in the WRAP, CENRAP, and VISTAS regions reported agricultural burning emissions in 2002 and so the relationship was based on a majority of states in the RPO. Most of the states in the other two RPOs, Mid-Atlantic/Northeast Visibility Union (MANE-VU) and (Midwest Regional Planning Organization) MWRPO did not report agricultural emissions in 2002 and so we used a national average for these. We note that agricultural burning is dominated by the WRAP, CENRAP and VISTAS states. Table 2 summarizes the pixel to PM2.5 emission relationship used in our inventory development. We developed similar factors for all seven criteria pollutants. We note that our emission estimate may too high using this method. A discussion of this can be found in section 3.3.

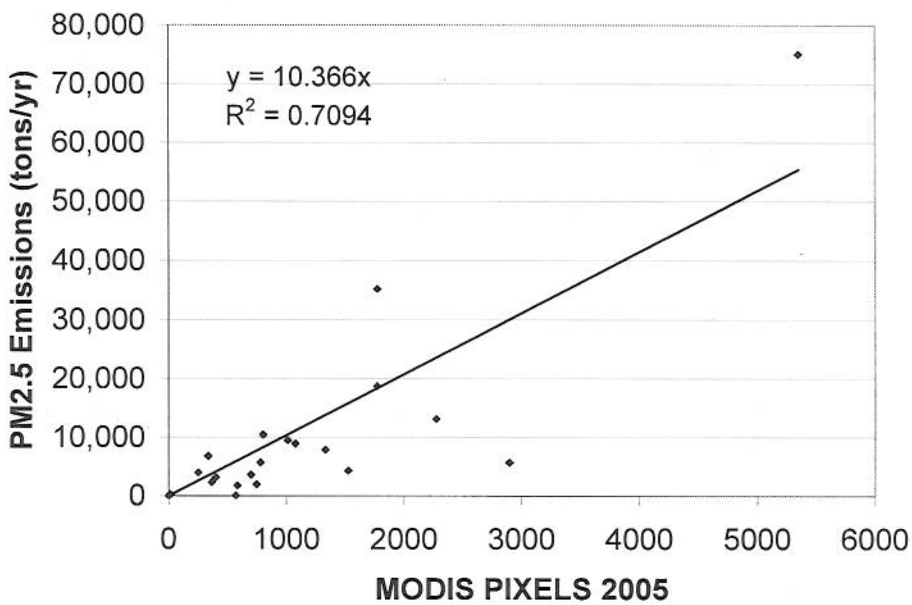


Fig. 5. Scatter plot of 2005 MODIS pixels versus 2002 Agricultural Burning Emission Estimates on a per state annual basis. Only states that reported Agricultural Burning in 2002 are shown.

Table 2. Agricultural Burning PM2.5 Emission to Pixel Relationship used for the 2005 emission inventory.

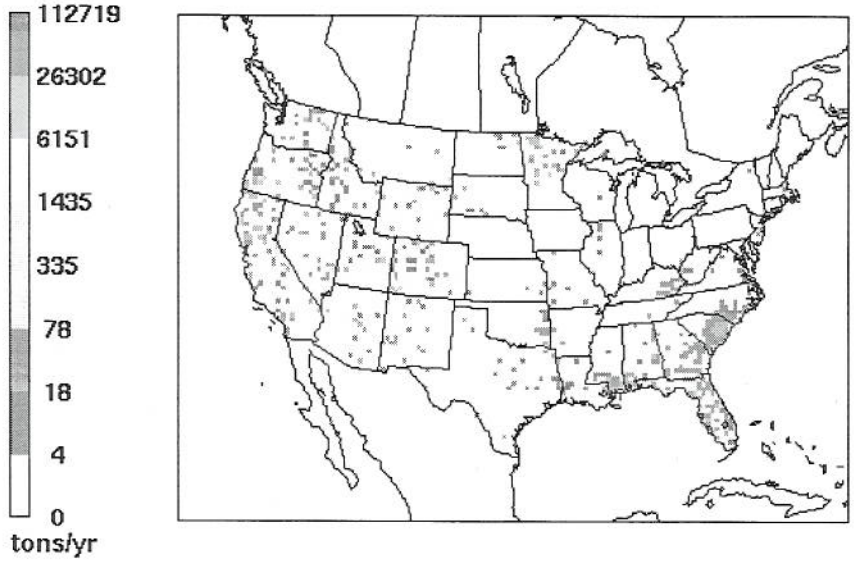
Region	Number of states reporting in 2002	Total number of states in Region	PM2.5 Emissions per pixel (tons/pixel)	Standard Deviation
WRAP	6	13	9.2	4.7
CENRAP	9	9	6.5	6.4
VISTAS	9	10	11.6	5.4
National	23	48	8.0	6.0

3 DISCUSSION OF RESULTS AND COMPARISON WITH 2002 NATIONAL EMISSION INVENTORY

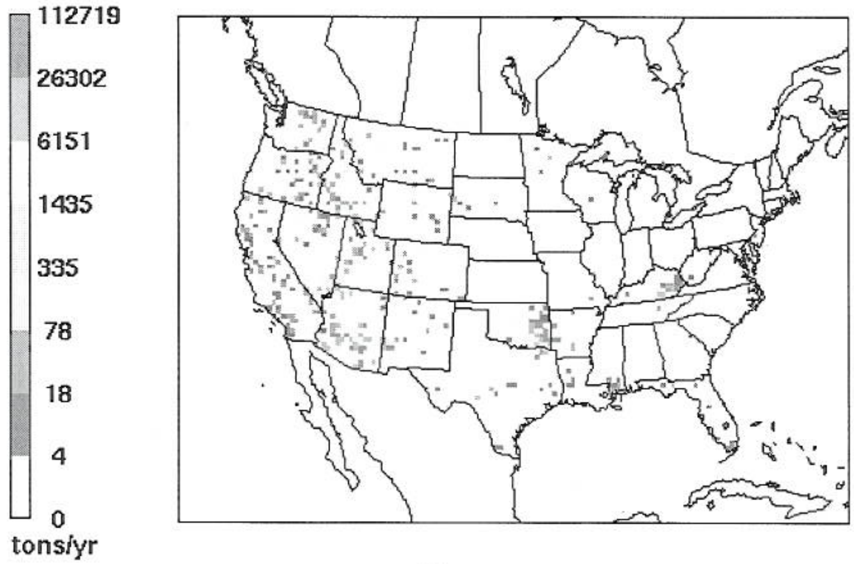
In this section we will look at our newly derived 2005 emission inventory for wildfires, prescribed burning, and agricultural burning and compare it to the 2002 NEI for each of the above categories. We will consider the overall spatial variability in the inventories as well as the temporal variability over the CONUS.

3.1 Wildfire Inventory

The area burned estimate for the 2005 Wildfire inventory was entirely based on the ICS 209 reports for wildfires. The MODIS satellite information essentially provided more accurate spatial and temporal representation of the area burned. In this sense, our wildfire inventory is essentially a reallocation using MODIS pixels of the acres burned combined with an emission estimation algorithm similar to that used in inter-RPO 2002 emission inventory. However, as we will examine in more detail, our emission estimation method also had critical differences compared to the 2002 inter-RPO inventory. We first examined the blackened area burned in 2005 and compared it to 2002. In 2002, the inter-RPO reported 3.2 million blackened acres for the CONUS compared with 2.9 million blackened acres in 2005. The ICS 209 reports for 2005 reported 4.4 million perimeter acres and we used a constant factor of 0.66 to estimate blackened acres. This factor is consistent with that documented in the 2002 inter-RPO report. This difference of 10% is consistent with the reported wildfire acres from the National Interagency Coordination Center annual statistics for wildfires after accounting for the differences between blackened acres versus perimeter acres and for Alaska which is reported in the national totals but is not included here in this paper. We note that for Alaska, 2.1 million perimeter acres burned in 2002 compared with 4.4 million acres in 2005. We therefore have confidence that the ICS 209 reports that we obtained and checked for 2005 contained the majority of the acres burned in 2005. With a 10% change in acres burned in the CONUS, we were surprised that the PM2.5 emission estimates for 2005 compared to 2002 were different by 76%. For 2005, the PM2.5 emission estimate for wildfires was 109,000 short tons per year compared to 459,000 short tons per year for 2002. Figure 6 shows the annual emission estimate for 2002 and 2005 for wildfires. We note that the wildfires in 2002 were concentrated on the western Pacific coastal range and on the front range of the Rockies. In 2005, the wildfires were concentrated in the Great Basin areas of Arizona and Idaho. Further examination of 2005 compared to 2002 shows a different distribution of National Fire Danger Rating System (NFDRS) Fuel Models.



(a)



(b)

Fig. 6. (a) 2002 Inter-RPO PM2.5 Emission estimates for wildfires. Total PM2.5 = 458,789 short tons. (b) 2005 PM2.5 Emission estimates for wildfires. Total PM2.5 = 108,763 short tons. Note the logarithmic color scale.

Figure 7 shows the distribution of the NFDRS fuel model by acres burned for 2002 and 2005. Appendix A of the inter-RPO report provided clear definitions of the various fuel classes in the NFDRS. We note that in 2005, a significant number of acres burned were in fuel class T (sagebrush-grass) which has a relatively low fuel loading. In 2002 there were a significant number of fires with fuel classes G, and H (short needle trees) which have much higher fuel loading values. The spatial differences between the 2002 and 2005 does not totally account for the differences in emissions between 2002 and 2005. We applied our 2005 method to 2002 using all available MODIS pixels for 2002 (one satellite from Jan-July) and two satellites from August – December. We re-estimated the emissions for 2002 using an identical method as compared to 2005 and this resulted in an emission estimate of 360,000 short tons per year, a 20% difference compared to the inter-RPO estimate. Further examination of the 2002 inter-RPO inventory revealed that the emission estimates for a large number of fires were based on fire-specific fuel loading and fuel models that were in many cases higher than what was reported in Appendix C of the inter-RPO report. Therefore the 76% difference in Emissions between 2002 and 2005 was partly due to differences in the methodology but more importantly shows the inter-annual variability in the emissions from wildfires from year to year. Emission Factors used for the two years were identical and based on the factors found in the Appendix C of the inter-RPO report. This level of variability suggests that wildfire emissions have a much larger year to year variability than the area burned from wildfires. In addition, there remains larger uncertainty in the emission estimates because of the differences in fuel loading and fuel models. Other fuel models and fuel loadings could produce different emission estimates for the same year. We note that this implies a higher level of uncertainty in our emission estimates. A full discussion of uncertainty in our emission estimates is beyond the scope of this paper.

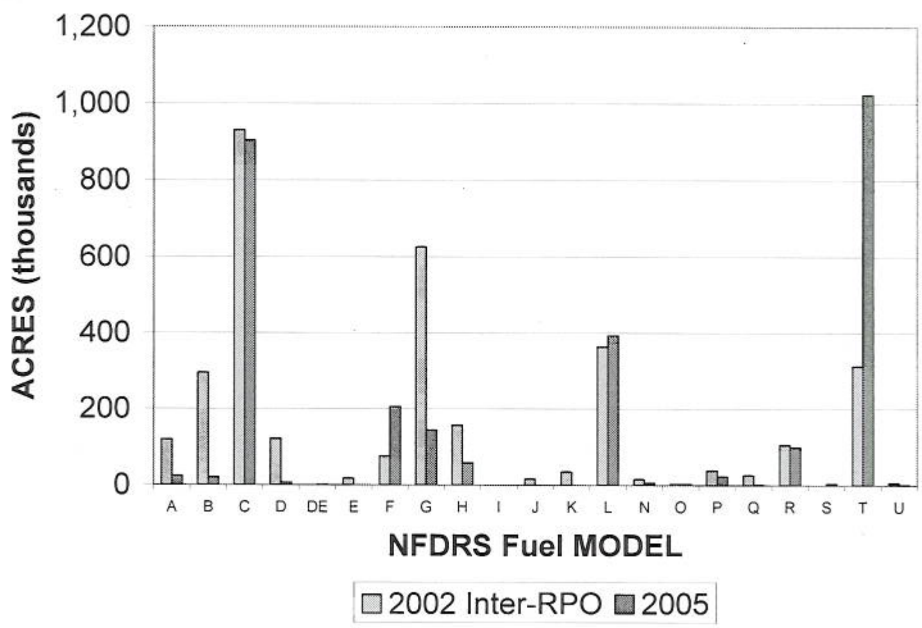


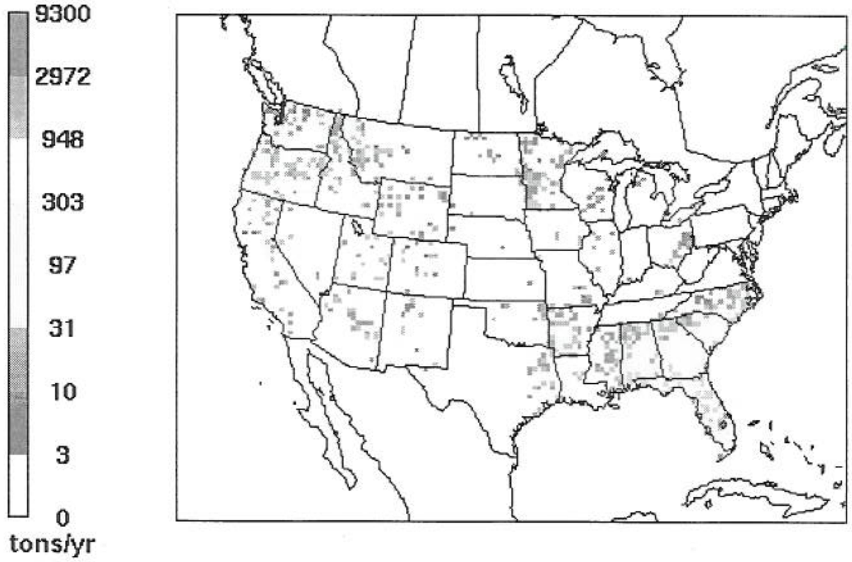
Fig. 7. Comparison for NFDRS Fuel Model by Acres for the Inter RPO wildfire inventory and the 2005 inventory.

3.2 Prescribed Fire Inventory

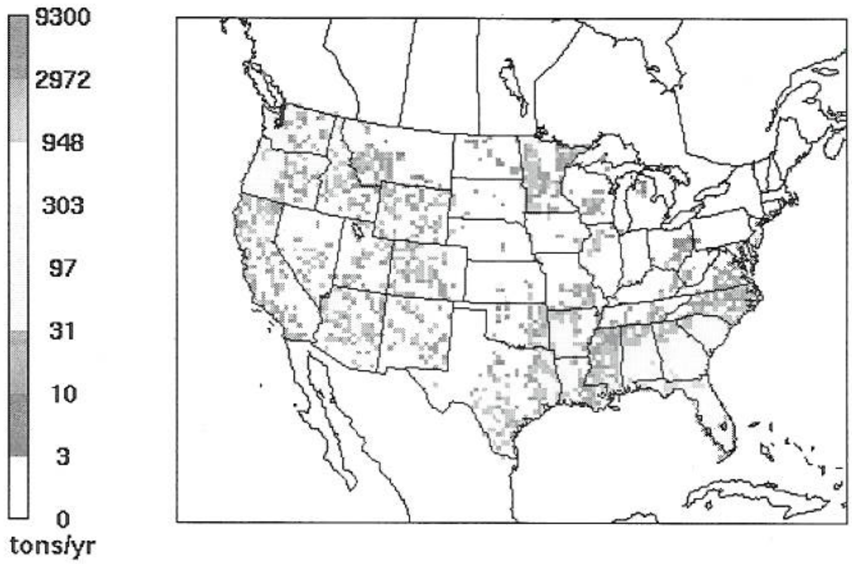
The area burned estimate for the 2005 Prescribed fire inventory was estimated based on a few ICS 209 reports of prescribed fires, a significant number of unclassifiable MODIS detects, and a scaling factor adjustment from the 2002 Inventory. We note that prescribed fires are often undetected by the MODIS instrument and for some states not well reported. Therefore we made more assumptions about the emissions and activity for the 2005 prescribed fire inventory giving it less certainty. The resources available for the 2002 prescribed fire inventory were not available for 2005 and so we estimated 2005 emissions using 2002 as a guide. Our underlying assumption was that on a national scale, the emissions from prescribed fires are fairly constant from year to year. We used an annual scaling factor (ratio of 2005 to 2002 acres) based on the regional National Interagency Fire Center reports and applied the scaling factor on a per county and month basis. Therefore we are not surprised that our emission estimates from prescribed fires for 2005 (209,000 short tons of PM2.5) compared to 2002 (171,000 short tons of PM2.5) were 22% higher. In addition our scaling adjustment partially compensates for any error in our acres to pixel relationship used for the unclassified fires since we only adjust emissions for counties that are lower in 2005 compared to 2002. Figure 8 shows the annual estimate of PM2.5 from prescribed fires for 2002 and for our annual estimate for 2005. We note that 56% of the emissions shown Fig. 8(b) is based on the application of Eqn. (2). The remaining emission estimates were based on actual MODIS detects from 2005 and the few ICS 209 reports of prescribed burning. Our method for estimating prescribed burning for 2005 does have a few drawbacks. First our estimate is only accurate on a monthly time scale on a county-level basis. Thus, day-specific prescribed burning is not captured by the inventory. Secondly, without day-specific information for prescribed burning, we cannot model the plume rise associated with these fires.

3.3 Agricultural Fires

Our agricultural fire emission estimates for 2005 were based on the 2005 MODIS detects that we matched to the BELD3 land cover database and on the 2002 agricultural burning estimates from EPA's 2002 NEI. We note that the 2002 agricultural burning estimates in the NEI included only 23 states. The 2002 NEI for agricultural burning was based on state-supplied data. Having national coverage for the agricultural burning from the MODIS instrument enabled us to create a better spatial representation of the agricultural emissions in 2005 compared to 2002. Figure 9 shows the 2002 NEI for agricultural burning and our 2005 estimate. Note the large areas especially in the upper Midwest, west and Northeast where no emissions were reported. In the 2002 NEI, approximately 225,000 short tons of PM2.5 were estimated compared with 232,000 short tons in 2005; a 3% increase. The small increase is expected because for the 23 states that reported emissions in 2002, about 85% of the MODIS agricultural pixels were "matched" to these states. The remaining 15% of the MODIS pixels belonged to the 26 states that did not report agricultural burning emissions in 2002. We note that our method can easily overestimate agricultural emissions three reasons 1) our assumption that the 2005 agricultural emissions are comparable to the 2002 agricultural emission on a state by state basis. 2) Our 25% criteria for determining agricultural MODIS pixels may be too liberal and 3) the regression in Figure 5 may be affected by outliers. A more robust method would be to estimate the number of MODIS pixels per acre for a given year and apply known emission factors based on the assumed acreage. However, we do not have national area estimates for agricultural burning for either 2002 or 2005.

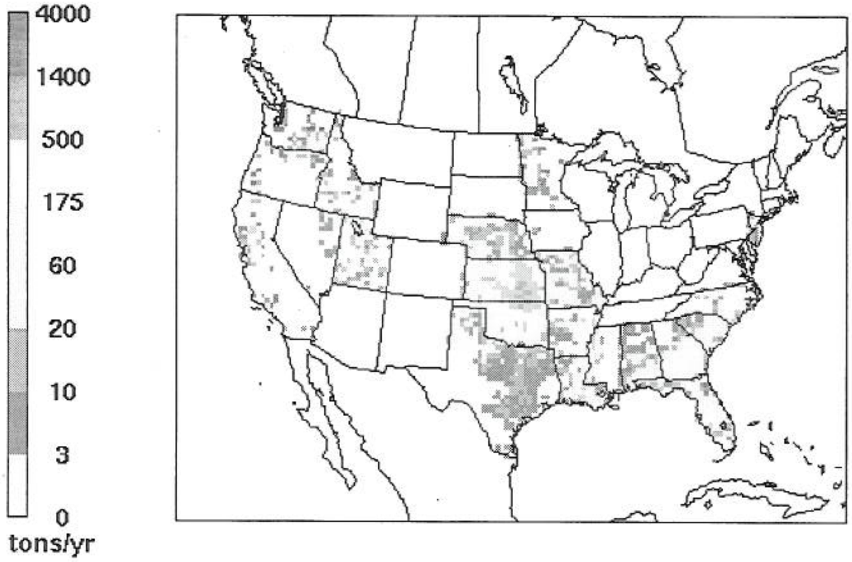


(a)

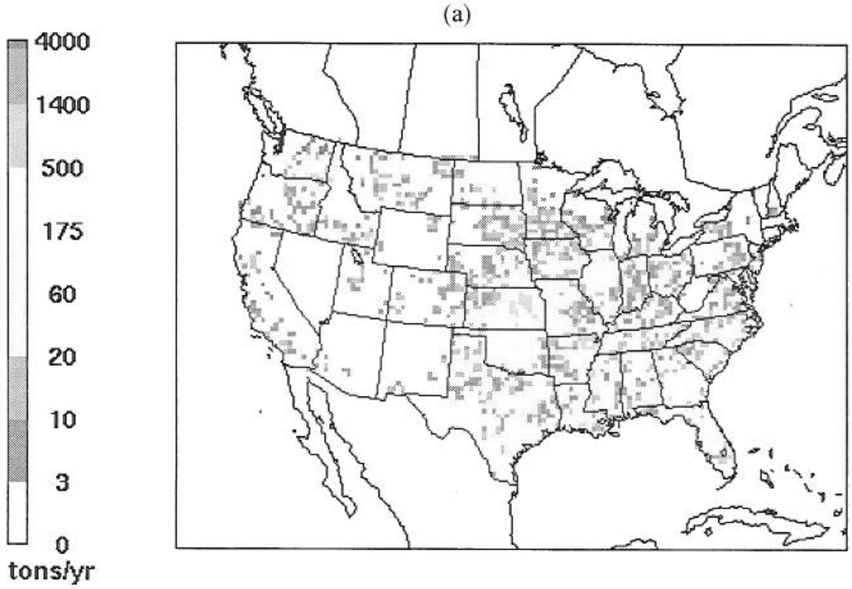


(b)

Fig. 8 (a) 2002 EPA Prescribed Fire Inventory included in the 2002 NEI. Total PM2.5 = 170,842 short tons (b) Annual 2005 Prescribed Fire Inventory including our emission adjustments and the unclassifiable fire detects from MODIS. Total PM2.5 = 208,719 short tons.



(a)



(b)

Fig. 9. (a) EPA 2002 NEI agricultural burning PM2.5 emissions from 23 reporting states (tons/year) Total PM2..5 = 224,684 short tons(b) 2005 Agricultural PM2.5 Burning Emissions (tons/year). Total PM2.5 = 232,048 short tons

4 CONCLUSIONS

We have summarized the development of the Biomass Burning (Wildfire, Prescribed Fires and Agricultural Fire) Emissions Inventory for the year 2005 over the CONUS by merging ground-based fire information and MODIS detections. This is the first national EPA emission inventory developed using satellite information from MODIS. In addition, the cost for developing the 2005 inventory is less than 10% of the cost associated with the development of the 2002 NEI (which is unlikely to be repeated for any future years). Our results for 2005 (compared to 2002) show a high year to year variability in wildfire emissions. Our total emission estimate for 2005 is 550,000 short tons. A 10% change in wildfire acres burned resulted in a 76% change in PM2.5 emissions compared with the 2002 NEI. Prescribed fire emission estimates are less certain than wildfires but are assumed to have less year to year variation. The MODIS satellite provides improved spatial and temporal information for agricultural burning fires. Our method discussed in this paper provides an improved methodology for estimating biomass burning emissions. However, we note that biomass burning emission estimates are very difficult to validate. In addition, there is uncertainty in all the components of the biomass burning emission calculation: fuel loading, emission factors, and fire sizes. Certainly, a good prescribed fire reporting system (including agricultural burning) would reduce the uncertainty and improve the emission estimates. These emission estimate improvements should help to improve our air quality predictions from our air quality models.

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