SATELLITE-DERIVED PM2.5 EMISSIONS FROM WILDFIRES FOR AIR QULAITY FORECAST

Xiaoyang Zhang[1], Shobha Kondragunta, Felix Kogan, Jerald D. Tarpley
Wei Guo[2]
NOAA/NESDIS/STAR, 5200 Auth Road, Camp Springs, MD 20746
[1]Earth Resources Technology, Inc., 8106 Stayton Drive, Jessup, MD 20794
[2]I.M. System Group, Inc
Shobha.Kondragunta@noaa.gov, Xiaoyang.Zhang@noaa.gov
Christopher Schmidt
Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, Madison, WI

ABSTRACT

NOAA/NESDIS developed a new algorithm to derive biomass burning emissions of PM2.5 from remotely sensed fire products in near real time for regional and global air quality applications. The algorithm for deriving emissions from wildfires depends on several key inputs such as fuel loading, fraction of fuel consumed and emission factor in addition to fire locations and sizes. The algorithm involved in this study are developing (a) a new fuel load database using maximum monthly MODIS Leaf Area Index (LAI) and allometric models that relate leaf foliage biomass with other biomass components in forests, shrubs, and grasses, (b) a fuel moisture category using AVHRR Normalized Vegetation Index (NDVI) product for the determination of combustion and emission factor database. The algorithm was applied to derive PM2.5 emissions from half hourly observations of GOES fire events from 2002-2004 over the Contiguous United States (CONUS). The resultant PM2.5 emissions in 2002 were compared to those available from EPA's National Emissions Inventory.

INTRODUCTION

Biomass burning releases trace gaseous (such as CO, CO_2 and CH_4) and aerosol emissions which play a significant role in atmospheric chemistry. These emissions and their transportations contribute significantly to the uncertainty in climate change[1], and affect both local and global air quality which impacts on human health and environmental pollution[2,3,4,5]. Currently, the aerosol emissions, particularly smoke particulates, from biomass burning are one of the major sources in uncertainty of air quality forecast using models such as the Community Multi-scale Air Quality (CMAQ)[6], and are critical air pollutants subject to the National Ambient Air Quality Standards (NAAQS) established by the US Environmental Protection Agency (EPA) [7].

The emissions from biomass burning, therefore, have recently emerged as an important research topic. To estimate the emissions, two main approaches are generally applied. A recently developed approach is the direct measurement of emissions from satellite observations of Fire Radiative Power (FRP)[8,9,10]. In this method, temporal FRP over a fire event is integrated to measure the total Fire Radiative Energy (FRE), which is then converted into the estimates of the rate and total biomass combusted. This method provides a great potential to directly estimate emissions although the uncertainty is currently high[10].

Alternatively, emissions from biomass burning are modeled from various parameters, particularly, fuel loading and fire. Fuel loading is a very complex parameter, which is the main source of uncertainty in emission estimates[11]. Because of the difficulty in parameterizing fuel loading, various different values have been used in emission modeling. The commonly used fuel loadings include static values in large scales[12,13,14], field measurements in local areas, ecoregions-based representatives in regional areas [15]. The most widely used fuel data in the Continuous United States (CONUS) are derived from National Fire Danger Rating System (NFDRS)[16,17], which are associated with fuel models using in a lookup table. A similar fuel dataset called the Fuel Characteristic Classification System (FCCS) has recently been

developed[18] (http://faculty.washington.edu/dmck/feradata/FCCS-lower48.zip), and provides much detailed types of ecosystems and fuel types. The quality of such fuel data depends greatly on the class schemes of ecoregions and the representatives of fuel values.

Burned area is another major parameter in emission modeling. In investigating historical fire emissions, the burned areas from wildland fires are usually derived from potential natural vegetation and ecological fire regime information[19] and from local and national fire services or agencies[20,21,22]. Recently, satellite observations have provided a means to more accurately monitor burned areas. As a result, fire-counts from various satellites, such as the Along Track Scanning Radiometer (ATSR), the Advanced Very High Resolution Radiometer (AVHRR), and the Moderate Resolution Imaging Spectroradiometer (MODIS) have been used as a proxy for the investigation in biomass burning[23,24]. The counts of fire (hot spot) pixels generally overestimate burned areas because satellite can usually detects the fire occurrences in much small size than the pixel in the moderate and coarse resolution data. For example, MODIS can detect a fire with a size of approximately 100 m^2 but its spatial resolution in a pixel is 10^6 m^2 [25]. On the other hand, the instantaneous observations for twice (AVHRR) or four times (Terra plus Aqua MODIS) within a day and cloud cover often result in missing detections of some temporal fire events. Consequently, this may underestimate real burned areas. The burned areas (or burn scars) detected from satellites (such as MODIS) demonstrate great potential for emission calculations; however, they are not available until the fires are over[26]. Such data can not be applied to calculate real (near-real) time burning emissions. Alternatively, Geostationary Operational Environmental Satellites (GOES) are demonstrated to be able to estimate smoke aerosol emissions in nearly real time for forecast because of the high temporal observations[27,28].

To reduce the uncertainties in air quality forecast, NOAA Air Quality program has requested NESDIS (National Environmental Satellite, Data, and Information Services) to develop near real time aerosol emissions for biomass burning events. To research this goal, we used multiple satellite instruments to retrieve spatially-distributed parameters for the modeling of PM2.5 (particulate matter with diameters less than 2.5μm) emissions. Particularly, a new fuel dataset was developed from MODIS land cover type, leaf area index (LAI), and vegetation percent cover at a spatial resolution of 1 km. Fire sizes in subpixels were derived from GOES WF_ABBA (Wildfire Automated Biomass Burning Algorithm) fire product with a half-hour interval. The combustion and emission factors were associated with fuel moisture derived from AVHRR vegetation health condition. The resultant emissions were analyzed in a temporal and spatial distribution and evaluated using different fuel loading data.

MODELING BIOMASS BURNING EMISSIONS

Emissions from biomass burning are controlled by four fundamental parameters. These parameters are burned area, fuel loading (biomass density), the fraction of combustion, and the fraction of emissions for trace gases and aerosol. To model the biomass burning emissions, Seiler and Crutzen[2] (1981) developed a standard formula by integrating these parameters as the following:

$$E = ABCF \qquad (1)$$

where E represents the emissions from biomass burning (ton); A is the burned area (ha); B is biomass density (ton/ha); C is the fraction of biomass consumed during a fire event; and F is the fraction of the consumed biomass released as trace gases and smoke particulates. This simple model has been widely used to estimate the emissions in regional and global scales[1,20, 24,29, 30].

To accurately estimate the smoke particulate released from biomass burning, we employed this format of model but improved parameterizations in both temporal and spatial resolutions. Thus, the emission model was modified as the following format:

$$E = \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{j=1}^{J}\sum_{i=1}^{I} A_{ijkl} M_{ijk} C_{ijkl} F_{ijkl} \qquad (2)$$

where E is the particulate emission in a certain time period; i and j define the fire (pixel) locations; l is the fuel type; k is the time period; A is the burned area; M is the amount of fuel mass available for combustion; C is the combustion factor, and F is the emission factor for particles PM2.5.

CALCULATION OF FUEL LOADING

Fuel loading in this study is basically divided into live fuel loading and dead fuel loading. The live fuel loading consists of foliage and branch biomass in forests, shrub biomass, and grass (including crop) biomass. The dead fuel loading is composed of litter and coarse woody detritus. To determine fuel loading for each pixel, we developed a MODIS Vegetation Property-based Fuel System (MVPFS). These data ware primarily calculated from percent vegetation cover in MODIS continuous field product, LAI, and land cover types at a spatial resolution of 1 km.

MODIS LAND DATA

We collected LAI data from 2002 to 2004 across the CONUS. The MODIS LAI product (MOD15A2) provides global green leaf area index at a spatial resolution of 1 km and a temporal resolution of 8 days[31]. This index is retrieved using look-up tables generated from rigorous three-dimensional radiative transfer theory and six major biomes. The LAI product has been validated using field measurements and high resolution ETM data in semiarid woodlands and savannas, and forests across the world.

The MODIS vegetation continuous field (MOD44B) algorithm produces percent of tree cover, percent nontree vegetation (shrubs, crop, and herbaceous), and percent bare ground[32]. This algorithm employs a regression tree and a stepwise regression to produce percent cover from MODIS land bands with a spatial resolution of 500m. Currently, the available vegetation continuous field product was derived from MODIS data ranging November 2000 to December 2001.

Land-cover data used in this study were derived from the MODIS land-cover product at a 1 km resolution. The primary land-cover types in this product are 17 land cover classes following the International Geosphere-Biosphere Programme (IGBP) Scheme[33]. Based on MODIS land cover product produced in 2001, 2002, and 2003, we generated a land cover dataset by selecting the cover type in a pixel with the highest accuracy assessment value.

DETERMINATION OF LIVE FUEL LOADING

Live fuel loading in forests was derived from foliage biomass and branch biomass, which is a function of percent vegetation cover, leaf area index, and land cover types. Foliage biomass (M_f) is a function of LAI and specific leaf area (SLA). It can be calculated using the following formula[34]:

$$M_f = LAI/SLA \qquad (3)$$

The SLA is defined in mass units of carbon and is converted to dry weight (m^2/kg). The value varies with vegetation types, which is higher in thin and light leaves (such as grass) than dense conifer needles. To determine the SLA values for different land cover types, we compared the mean values concluded from various field measurements[35] and the model-based values in processing the MODIS Gross Primary Productions (GPP) and Net Primary Productions (NPP) products at a global scale[34]. After investigating the foliage biomass of conifer in the western North America[36], we selected SLA for needleleaf forests from dataset developed by White et al. (2002) [35] and others from the MODIS GPP/NPP model.

The LAI in equation (3) was referred as to the maximum monthly LAI. This LAI value was retrieved from an annual time series of MODIS LAI product to reduce the noise in the LAI time series and seasonal variation in LAI values. Further, to reduce the uncertainty caused by interannual variability induced by climate change and other factors, the maximum monthly LAI in 2002, 2003, and 2004 were averaged to represent the maximum LAI. Because the LAI in a 1 km pixel rarely represented a uniform vegetation type, it was further separated for forests and non-forest vegetation in subpixels using land cover type, vegetation continuous field, and the LAI ratios among different land cover types[37]. As a result, we used the LAI values in subpixels to calculate the foliage biomass using equation (3) for forests, shrubs, and grasses.

Depending on the variation in foliage biomass, the branch biomass in forests was calculated from the generalized foliage-based allometric models[37]:

$$M_b = \delta M_f^{\gamma} \quad (4)$$

where M_b is biomass in branch (kg); M_f represents monthly maximum foliage biomass (kg); γ and δ are coefficients with the values of 1.46 and 1.099 in the eastern USA (1.025 and 1.277 in the western USA) for needleleaf forests, and 4.087 and 1.156 for broadleaf forests.

For shrubs, the total aboveground biomass is a function of crown area/vegetation cover[38]. To calculate shrub biomass, a regression model developed in the western US[39,40,41] was applied to the CONUS.

$$M_s = 1.09\times10^5 - 2.161\times10^3 V_c + 1.078\times10^2 V_c^2 \quad (5)$$

where M_s is shrub biomass (kg/km^2) and V_c is the horizontal projection of shrub cover above the plot surface (%) which is equivalent to vegetation cover in shrubs.

LITTER AND COARSE WOODY DETRITUS

The litter production is primarily composed of material such as leaves, fine wood, and fine roots, while coarse woody detritus is usually larger than 7cm in diameter[42]. The pools of litter and coarse woody debris (CWD) were investigated by compiling biomass density measurements for various vegetation types[43,44].

Employing the relationship of vegetation type with litter and CWD developed by Matthews (1997), we generated the litter fuel loading and CWD at a 1 km resolution. Specifically, the Matthews' vegetation types[43] in temperate and tropical/subtropical climate were reclassified to MODIS IGBP land cover types using a crosswalk rule. The corresponding fuel data for each land cover type were selected or averaged.

To estimate little and CWD more realistically, we also included vegetation percent cover for each land cover type. The non-forest vegetation within the forest land cover types was assumed as the mixture of grasses and shrubs because they were not able to be further separated. On the other hand, the trees in the land cover types of non-forests were considered as mixed forests. Thus, the related fuel loading in each pixel was refined using the following equation:

$$M_{lw} = M_{lwf} V_{cf} + M_{lws} V_{cs} \quad (6)$$

where M_{lw} is litter or CWD density in a pixel (kg/m^2); M_{lwf} and M_{lws} are litter or CWD density (kg/m^2) for forests and non-forest vegetation, seperately; V_{cf} and V_{cs} are percent forest cover and non-forest vegetation cover.

FIRE DATA AND PROCESSING

NOAA WF_ABBA produces fire product from GOES East and West data in an interval of half hour[45]. The WF_ABBA detects instantaneous fire sizes in subpixels using 3.9 µm and 10.7 µm infrared bands by locating and characterizing hotspot pixels from a 4 km resolution of GOES data. This product contains the time of fire occurrences, fire location in latitude and longitude, instantaneous estimates of subpixel fire size, and fire flag (ranging from 0 to 5) which represents the quality assurances of the fire detections. The fire size is only retrieved for pixels with best quality but not for the fire pixels that are saturated, cloudy, and with high, medium, or low probabilities. To minimize false fires, the WF_ABBA product used a temporal filter to exclude the fire pixels that were only detected once within the past 12 hours.

We collected the GOES WF_ABBA fire data between April 2002 (no data available for January-March) and December 2004 in this study. To generate a consistent dataset of fire sizes, we replaced the pixels that the subpixel fire sizes were not calculated. Specifically, if a missing value occurred at the beginning of a fire event, the average fire size from 2002-2004 was taken as a representative, which was 0.153 km^2. If a missing value occurred during a fire event, it was replaced using the previous neighbor value. In addition, the cumulative fire size in a pixel must not be in excess of the GOES pixel size (4x4 km^2).

FRACTIONS OF COMBUSTIONS AND EMISSIONS

The fractions of combustions and emissions were assumed to be a function of fuel moisture. The combustion factors were calculated from the following model[46]:

$$C_l = \left(1 - e^{-1}\right)^{mcf} \qquad (7)$$

where C_l represents the fraction of fuel loading consumed for fuel type l which is canopy, shrub, and grass, separately; and *mcf* is the moisture category factor (Table 1). To determine the *mcf* value for each fuel type, the fuel moisture condition was classified from AVHRR data which were described in the following section.

The fraction of combustion for litter was assumed to be 100% under various moisture conditions. However, the value for CWD was calculated using the formula[46]:

$$C_w = 0.6\left(0.31 + \left(0.03 * \left(0.31 - mcf\right)\right)\right) \qquad (8)$$

The fraction of PM2.5 emissions also varies with moisture conditions. The variation is generally slight for various moisture conditions (Table 2). However, the value for coarse wood was more sensitive to moisture conditions than those for other fuel types.

DETERMINATION OF MOISTURE CATEGORY

To determine fuel moisture condition required for calculating the fractions of combustions and emissions, we employed Vegetation Condition Index (VCI) produced by NOAA AVHRR product as a proxy. The weekly VCI provides accurate drought information for various environments[51], and was derived from the Normalized Difference Vegetation Index (NDVI) using the following equation[47,48]:

$$VCI = 100 \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \qquad (9)$$

where $NDVI_{max}$ and $NDVI_{min}$ in a pixel are the maximum and minimum values in the corresponding week from 1985-2004. The weekly VCI values were produced from the NOAA Global Area Coverage (GAC) using smoothed weekly NDVI datasets at a spatial resolution of 4 km since 1985.

To fit the requirements in determining the fuel moisture category factors, we equally divided the weekly VCI values into five different categories which represented fuel moisture conditions of very dry, dry, moist, wet, and very wet, separately (Figure 1). As a result, these categories were used to calculate the weekly fractions of combustions and emissions.

COMPARISON OF EMISSIONS FROM DIFFERENT FUEL LOADING

Since fuel loading is currently incomplete and is one of the main sources of uncertainty in estimating biomass burning emissions, we investigated the effects of fuel loading on emission estimates by comparing our results with emissions derived from NFDRS and FCCS fuel loadings. The NFDRS fuel map consists of 21 fuel models, and each fuel model is assigned a set of live and dead fuel loadings. These fuel loadings were modified for various different applications. The FCCS fuel dataset is more sophistic, which qualifies live and dead fuel loadings for 16 types of fuels for 150 fuelbed types across the CONUS (http://faculty.washington.edu/dmck/feradata/FCCS-lower48.zip). The fuelbed was classified using ecoregions, potential natural vegetation, and land use. The quantitative estimates of fuel loadings within the fuelbeds were derived from georeferenced stand-level data on the six ranger districts in the forest. Both the NFDRS and the FCCS datasets did not provide fuel information in agriculture areas. In addition, the fuel loading values are the same for large polygon regions and produces sharp boundary between neighbor values although the spatial resolution is 1km.

We further compared our emission estimates against the Inter-RPO 2002 National Wildfire Emission Inventory (NEI) developed by Air Sciences Inc[49]. The NEI was generated using the field-observed fire data (>0.0405km^2) from federal and state databases, the fuel data derived from NFDRS fuel model or regional composites.

The comparisons were implemented using daily emissions from years 2002, 2003, and 2004, separately. The indices used in the comparisons were coefficient of determination (R^2), root mean square (RMS) difference, and percent systematic RMS difference.

RESULTS

MVPFS FUEL LOADINGS

The fuel loading derived from MODIS data is displayed in Figure 2. The forest canopy biomass, including forest foliage biomass (Figure 2A) and branch biomass (Figure 2B), is large in the Pacific Northwest evergreen needleleaf forests with values of 10 tons/ha in foliage biomass, and 27 tons/ha in branch biomass. It is followed by biomass in the eastern US. In contrast, the canopy biomass is very limited in the center and southwestern US. On average, the foliage biomass is less than 7 tons/ha in 90% of the forest areas, and the branch biomass is generally less than 30 tons/ha. The variation in biomass is significantly associated with the forest cover percent in a pixel.

The biomass in shrubs and grasses is generally less than 5 ton/ha (Figure 2C and 2D). The shrub biomass is larger in the forest land cover types. The high values are mainly distributed in the eastern US and northern west US while the low values present in the open shrublands in the southern west US. In contrast, grass biomass dominates in central agriculture areas and western grasslands and savanna areas.

The litter and CWD are much larger in forests than in non-forest land cover regions (Figure 2E and 2F). The magnitude CWD values are as high as 30 ton/ha in northern needleleaf forests while the values are very small in central agriculture areas. The litter displays similar pattern but the values are relatively small.

PM2.5 EMISSIONS

Figure 3 presents the spatial patterns in PM2.5 emissions across the CONUS. The high emissions are mainly distributed in the western US followed by those in the southeastern US while the values are much smaller in the central agricultue areas for all the three years. However, the occurrence of small fire emissions is very frequent in the areas around Kansas, Oklahoma, and Missouri. The annual emissions are 1.7×10^5 tons in 2002 (April to December), 1.6×10^5 tons in 2003, and 0.9×10^5 tons in 2004. The emissions at a state level varies greatly. The states with large proportion of the total annual emissions are Oregon (22.5%), California (13.7%), and Colorado in 2002; Montana (18.6%), California (12.8%), and Idaho (10.4%) in 2003; and California (18.8%), Florida (11.16%), and Washington (7.1%) in 2004 (Figure 4). This pattern is comparable with fire sizes. The fire sizes in California account for 15% of the annual fires in the CONUS from 2002-2004. The other states with large fire sizes are Oregon, Colorado, and Arizona in 2002; Montana, Idaho and Texas in 2003; and Arizona, Texas, and Florida in 2004.

The PM2.5 emission presents strong seasonal cycles (Figure 5). The emission is highest in July and August, which accounts for more than 40% of the total annual emissions. In contrast, the emission from November to next February is very small, which only accounts for less than 10% of annual emissions. This seasonality varies interanually, which is much stronger in 2002 and 2003 than in 2004. This temporal pattern is strongly associated with the variations in GOES WF_ABBA fires (Figure 6). During the summer period the fires occur often in the western US because the climate is dry and vegetation contains low moisture.

The PM2.5 emissions are mainly released from forest fires (Figure 7). It accounts for more than 56% of the total annual emissions for 2002, 2003, and 2004. The emission values are followed by those released from shrublands and savannas in 2002 and 2003, and from croplands and savannas in 2004. Generally, the amount of PM2.5 emissions does not coincide well with the fire sizes in different land cover types. Fire size is large in forests, which is about 25% of the total annual fires, followed by those in shrublands, agriculture areas, grasslands, and savannas in 2002 and 2003 (Figure 8). In contrast, the fire size is similar in forests and crop lands, but smaller in shrub, grass and savannas in 2004.

VARIATIONS IN PM2.5 EMISSIONS ESTIMATED USING DIFFERENT DATASETS

Figure 9 presents the daily PM2.5 emissions from National Emission Inventory (NEI) and those estimated from GOES fires combining with MVPFS, NFDRS, and FCCS fuels, separately. These data exhibit a similar temporal pattern in 2002 (April-December), and the daily emissions in this study accounts for more than 50% of variations in the NEI. However, the magnitude value in NEI is much

larger than those derived from GOES fires. This result is likely associated with the following factors. (1) The burned areas in large fire events are underestimated in the GOES fire product. For example, the burned area in the Hayman fire from the NEI is 443 km^2 in June 2002 while the cumulative instantaneous fire sizes from GOES data are 126 km^2. One of the reasons is that GOES data detect fire size in subpixels while NEI reports the area of fire regions. (2) The PM2.5 emissions in NEI were calculated using the modified-NFDRS fuel data, which is close to our estimates using NFDRS fuel data. (3) The emission factors are generally higher in the calculation of PM2.5 emissions in the NEI, which is 33.26 lb/ton in the smoldering phase and 22.74-31.44 lb/ton in the flaming phase. In contrast, the emission factors used in this study range 7.9 to 25.8 lb/ton which are similar to those used in the calculation of emissions in North America[16].

The PM2.5 emissions calculated from MVPFS fuel data are significantly associated with those calculated using NFDRS and FCCS fuel loadings. The magnitude value from NFDRS fuel loadings is largest, and followed by those from FCCS and MVPS fuel loadings (Figure 9). However, the spatial and temporal patterns are complex. The correlations are strongly significant between daily PM2.5 emissions derived from different fuel datasets but the coefficient values change in different years (Table 3). The high correlations in emissions present between MVPFS and FCCS in 2002, MVPFS and NFDRS in 2003 and 2004. The RMS differences in emissions are small between MVPFS and FCCS for these three years (Table 3), while the large differences are between MVPS and NFDRS in 2002 and 2004, and between FCCS and NFDRS in 2003. Among the differences, the systematic emission differences between MVPFS and NFDRS, between NESDES and FCCS, and between FCCS and NFDRS range 67-74%, 31-63%, and 47-64%, respectively. These results suggest that the magnitude of PM2.5 emissions estimated using MVPFS fuel loading is very similar to those from FCCS fuel loadings, but not to NFDRS fuel loadings. Note that the differences change with year because the PM2.5 emissions occur in different locations.

DISCUSSION AND CONCLUSIONS

The MODIS land data combined with allometric models provide a robust tool to establish fuel loading datasets (MVPFS) over a large coverage. This MVPFS provides different fuel loading values for each pixel rather than uniformly for a large polygon. Moreover, this dataset is easy to update using time series of remotely sensed data. The dead fuel loadings (litter and CWD) are currently derived based on a lookup table, which could be improved using robust methods in future.

The PM2.5 emissions vary greatly with ecosystems, state, season, and year. Seasonal patterns in the fires and emissions are constant. The fires and emissions mainly occur between June and August in the CONUS. However, the magnitude PM2.5 emissions vary greatly in different years, where the PM2.5 emissions are much smaller in 2004 than 2002 and 2003. Although the fire size could be very large in shrublands and croplands, the emissions are mainly released from forest fires, which account for 56% of the total annual emissions. Across the CONUSA, California always produces large amount of PM2.5 emissions every year. Relatively, Oregon, Colorado, Montana, Washington, and Idaho are also the main sources of PM2.5 emissions in some individual years.

The PM2.5 emissions estimated from different fuel datasets vary considerably although they are significantly correlated. Evidently, spatially-distributed fuel loading plays an important role in emission estimates accurately. Instantaneous fire sizes retrieved from GOES satellite can statistically represent the burned areas. However, some of the fires may not be detected in GOES data because of cloud cover and other artifacts, and large burned areas are greatly underestimated because of the saturate in the inferred reflectances. Besides, instantaneous fire size is not the same as burned area. Efforts are underway to investigate correlation of the GOES fire sizes with MODIS fire products and burned scars.

The fuel moisture defined by AVHRR NDVI is important for combustion and emission factors. Relatively, the weekly AVHRR NDVI-controlled fuel moisture accounts for small amount of variations in emission estimates. It is likely due to the factor that current values of combustion and emission factors are relatively coarse.

Acknowledgments. This research was supported by NOAA Joint Center for Satellite Data Assimilation. The views, opinions, and findings contained in those works are these of the author(s) and should not be interpreted as an official NOAA or US Government position, policy, or decision.

REFERENCES

[1]Soja, A.J., Sukhinin, A.I., Cahoon, D.R., Shugart, H.H., Stackhouse, P.W. "AVHRR-derived fire frequency, distribution and area burned in Siberia,", International Journal of Remote Sensing, 2004, 25 (10): 1939-1960

[2]Seiler, W. and Crutzen, P.J., "Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning,", Climatic Change, 1980, 2, 207-247

[3]Schultz, M.G., Diehl, T., Brasseur, G.P., Zittel, W. "Air pollution and climate-forcing impacts of a global hydrogen economy**,",** Science, 2003, 302 (5645): 624-627.

[4]Phuleria, H.C., Fine, P.M., Zhu, Y.F., Sioutas, C. "Air quality impacts of the October 2003 Southern California wildfires,", Journal Of Geophysical Research-Atmospheres, 2005,110 (D7): Art. No. D07S20.

[5]Sapkota, A., Symons, J.M., Kleissl, J., Wang, L., Parlange, M.B., Ondov, J., Breysse, P.N., Diette, G.B., Eggleston, P.A., Buckley, T.J. "Impact of the 2002 Canadian forest fires on particulate matter air quality in Baltimore City,**",** Environmental Science & Technology, 2005, 39 (1): 24-32.

[6]Byun D.W., "Dynamically consistent formulations in meteorological and air quality models for multiscale atmospheric studies. Part I: Governing equations in a generalized coordinate system,", Journal Of The Atmospheric Sciences, 1999, 56 (21): 3789-3807.

[7]EPA. "National Ambient Air Quality Standards (NAAQS). Research Triangle Park. NC, USA", 2003 http://www.cpa.goviairs/criteria.htntl.

[8]Wooster, M.J., Zhang, Y.H., "Boreal forest fires burn less intensely in Russia than in North America,", Geophysical Research Letters, 2004, 31, L20505, doi:10.1029/2004GL020805.

[9]Roberts, G., Wooster, M.J., Perry, G.L.W., Drake, N., Rebelo, L.M., Dipotso, F. "Retrieval of biomass combustion rates and totals from fire radiative power observations: Application to southern Africa using geostationary SEVIRI imagery,", Journal of Geophysical Research, 2005, 110:D21111, doi:10.1029/2005JD006018.

[10]Ichoku, C. and Kaufman, Y. J. "A Method to Derive Smoke Emission Rates From MODIS Fire Radiative Energy Measurements,", IEEE Transactions On Geoscience And Remote Sensing, 2005, 43(11):2636-2649.

[11]French, N.H.F., Goovaerts, P., Kasischke, E.S. "Uncertainty in estimating carbon emissions from boreal forests fires,", Journal of Geophysical Research, 2004, 109: D14S08, doi:10.1029/2003JD003635.

[12]Goode, J.G., Yokelson, R.J., Ward, D.E., Susott, R.A., Babbitt, R.E., Davies, M.A., Hao, W.M. "Measurements of excess O-3, CO2, CO, CH4, C2H4, C2H2, HCN, NO, NH3, HCOOH, CH3COOH, HCHO, and CH3OH in 1997 Alaskan biomass burning plumes by airborne fourier transform infrared spectroscopy (AFTIR),", Journal Of Geophysical Research-Atmospheres, 2000, 105(D17): 22147-22166.

[13]Liu, Y. "Variability of wildland fire emissions across the contiguous United States", Atmospheric Environment, 2004, 38: 3489–3499.

[14]Freitas, S.R., Longo, K.M., Diasb, M.A.F.S, Diasb, P.L.S., Chatfield, R., Prins, E., Artaxo, P., Grell, G.A., Recuero, F.S. "Monitoring the transport of biomass burning emissions in South America,", Environmental Fluid Mechanics, 2005, 5 (1-2): 135-167.

[15]Wiedinmyer, C., Quayle, B., Geron, C., Belote A., McKenzie, D., Zhang, X., O'Neill, S., and Wynne, K.K., "Estimating emissions from fires in north America for air quality modeling,", Atmospheric Environment, 2006, in press.

[16]Deeming, J.E., Gurgan, R.E., Cohen, J.D., *The National Fire-Danger Rating System-1978*. Ogden, UT: United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-39, 1977, 66p.

[17]Burgan, R.E., Klaver, R.W., and Klaver, J.M., “Fuel models and fire potential from satellite and surface observations,”, Int. J. Wildland Fire, 1998, 8: 159-170.
[18]Sandberg , D.V., Ottmar, R.D., Cushon, G.H. “Characterizing fuels in the 21st Century,”, International Journal Of Wildland Fire, 2001,10 (3-4): 381-387.
[19]Leenhouts, B. “Assessment of biomass burning in the coterminous United States,”, Conservation Ecology [online], 1998, 2(1): 1-24. URL: ttp://www.consecol.org/vol2/iss1/art1.
[20]French, N.H.F., Kasischke, E.S., and Williams, D.G. “Variability in the emission of carbon-based trace gases from wildfire in the Alaskan boreal forest,”, Journal of Geophysical Research, 2003, 108, doi:10.1029/2001JD000480.
[21]EPA.”Documentation for the Draft 1999 National Emissions Inventory (Version 3.0) for Criteria Air Pollutants and Ammonia (Area Sources)”. Prepared by E.H. Pechan & Asso.. Inc. Office of Air Quality Planning and Standards, 2003, Research Triangle Park, NC, USA.
[23]Eva, H., and Lambin, E.F. “Burnt area mapping in Central Africa using ATSR data,”, International Journal Of Remote Sensing, 1998; 19(18): 3473-3497.
[24]Duncan, B. N., Martin, R. V., Staudt, A. C., Yevich, R., and Logan, J. A., “Interannual and seasonal variability of biomass burning emissions constrained by satellite observations,”, J. Geophys. Res., 2003, 108 (D2): 4100, DOI: 10.1029/2002JD002378.
[25]Giglio, L., Descloitres, J., Justice, C. O., and Kaufman, Y. J. “An enhanced contextual fire detection algorithm for MODIS,”, Remote Sensing of the Environment, 2003, 87, 273-282.
[26]Roy, D.P., Lewis, P.E., Justice, C.O. “Burned area mapping using multi-temporal moderate spatial resolution data - a bi-directional reflectance model-based expectation approach**”,** Remote Sensing Of Environment, 2002, 83 (1-2): 263-286,
[27]Prins, E. M., Feltz, J. M., Menzel W. P., and Ward, D. E. “An overview of GOES-8 diurnal fire and smoke results for SCAR-B and 1995 fire season in South America,”, Journal of Geophysical Research, 1998, 103(D24), 31821–31835,.
[28]Reid, J. S., Prins, E. M., Westphal, D. L., Schmidt, C. C., Richardson, K. A., Christopher, S. A., Eck, T. F., Reid, E. A., Curtis, C. A., and Hoffman, J.P., “Real-time monitoring of South American smoke particle emissions and transport using a coupled remote sensing/box-model approach,”, Geophysical Research Letter, 2004, 31, L06107, DOI: 10.1029/2003GL018845.
[29]Ito, A., Penner, J. E. “Global estimates of biomass burning emissions based on satellite imagery for the year 2000,”, Journal of Geophysical Research, 2004, 109, D14S05.
[30]Korontzi, S., Roy, D. P., Justice, C. O., and Ward, D. E., “Modeling and sensitivity analysis of fire emissions in southern Africa during SAFARI 2000,”, Remote Sens. Environ., 2004, 92: 255–275,
[31]Myneni, R.B., Hoffman, S., Knyazikhin, Y., Privette, J.L., Glassy, J., Tian, Y., Wang, Y., Song, X., Zhang, Y., Smith, G.R., Lotsch, A., Friedl, M., Morisette, J.T., Votava, P., Nemani, R.R., Running, S.W. “Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data**”,** Remote Sens. Environ., 2002, 83, 214-231.
[32]Hansen, M. C., R. S. DeFries, J. R. G. Townshend, M. Carroll, C. Dimiceli, and R.A Sohlberg, “Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS vegetation continuous fields algorithm,”, Earth Interactions, 2003, *7*, 1-15.
[33]Friedl, M. A, McIver, D. K, Hodges, J. C., Zhang, X. Y., Muchoney, D., Strahler, A. H., Woodcock, C. E., Gopal, S., Schnieder, A., Cooper, A., Baccini, A., Gao, F., and Schaaf, C. B. “Global land cover mapping from MODIS: algorithms and early results,”, Remote Sensing of Environment, 2002, 83(1-2), 287-302
[34]Heinsch, F. A., et al., *User’s Guide GPP and NPP (MOD17A2/A3) Products NASA MODIS Land Algorithm*, 2003, available at http://www.ntsg.umt.edu/modis/MOD17UsersGuide.pdf.
[35]White, M. A., Thornton, P. E., Runing, S. W., and Nemani R. R. “Parameterization and sensitivity analysis of the BIOME_BGC Terrestrial Ecosystem Model: Net Primary production controls,”, Earth Interactions, 2002, *4*, 1-85.

[36]Cruz, M.G., Alexander, M.E., Wakimoto, R.H. "Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America", International Journal of Wildland Fire, 2003, 12 (1): 39-50.
[37]Zhang, x., Kondragunta, S. "Estimating Forest Biomass in the USA Using Generalized Allometric Model and MODIS Land Data,", Geographical Research Letter, 2006, in press.
[38]Sah, J.P., Ross, M.S., Koptur, S., and Snyder, J.R., "Estimating aboveground biomass of broadleaved woody plants in the understory of Florida Keys pine forests,", Forest Ecology and Management, 2004, 203: 319-329.
[39]Michell, J.E., Bartling, P.N.S., O'Brien, R.O., *Understory cover-biomass relationshipd in the Front Range ponderosa pine zone*. Research Notie RM-471. US department of Agriculture. Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 5pp; 1987, available at www.fs.fed.us/rm/main/pubs/inventories/rm_rn.pdf.
[40]Brown, J.K., and Marsden, M.A., "Estimating fuel weights of grasses, forbs, and small woody plants. Research Note INT-210. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah", 1976, 11pp; available at www.fs.fed.us/rm/main/pubs/inventories/int_rn/pdf.
[41]Chojnacky, D. C., Mickler, R. A., Meath, L. S., Woodall C. W. "Estimates of Down woody materials in eastern US forests,", *Environmental Management*, 2004, 33, S44-S55.
[42]Harmon M.E., Franklin J.F., Swanson F.J., Sollins P., Gregory S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Cummins, K.W. "Ecology of coarse woody debris in temperate ecosystem,", Ecology Of Coarse Woody Debris In Temperate Ecosystems,1986, 15: 133-302.
[43]Matthews E. "Global vegetation and land use: New high-resolution data bases for climate studies,", J. Clim. Appl. Meteorol., 1983, 22:474-487
[44]Matthews E. "Global litter production, pool, and turnover times: estimates from measurement data and regression models,", Journal of Geophysical Research, 1997, 102: d15, 18,7771-18,800.
[45]Weaver, J. F., Dan Lindsey, and Dan Bikos, Chris C. Schmidt, Elaine Prins , "Fire Detection Using GOES Rapid Scan Imagery,", Weather and Forecasting, 2004, 19: 496–510.
[46]Anderson, G.K., Sandberg D. V., and Norheim, R. A. *Fire Emission Production Simulator (FEPS) User's Guide (version 1.0)*, 2004, http://www.fs.fed.us/pnw/fera/publications/fulltext/FEPS_User_Guide.pdf.
[47]Koggan, F.N. "Application of vegetation index and brightness temperature for drought detection,", Natural Hazards: Monitoring And Assessment Using Remote Sensing Technique Advances In Space Research, 1995,15 (11), 91-100
[48]Kogan F.N., Global drought watch from space, Bulletin of the American Meteorological Society 1997, 78 (4): 621-636.
[49]WRAP, *Inter-RPO National 2002 Wildfire Emissions Inventory-Final Work Plan*, Air Sciences &EC/R, Project No. 178-7, 2005.

Table 1. Moisture category factor (mcf) (from Anderson et al., 2004).

Moisture condition	Canopy	Shrub	Grass	Duff	CWD
Very dry	0.33	0.25	0.125	0.33	0.08
Dry	0.5	0.33	0.25	0.5	0.12
Moderate	1	0.5	1	1	0.15
Moist	2	1	2	2	0.22
Wet	4	2	4	4	0.31
Very wet	5	4	5	5	0.75

Table 2. PM2.5 emission factors (fraction) (from FOFEM).

Moisture condition	Litter	Canopy	Shrub and Grass	Duff	CWD
Dry	0.00395	0.01065	0.01065	0.01290	0.00810
Moderate	0.00395	0.01065	0.01065	0.01290	0.00915
Wet	0.00395	0.01065	0.01065	0.01195	0.01125

Table 3. Statistical comparisons in daily emissions derived from different fuel loading data. NFDRS, FCCS, and NESDIS donate the emissions calculated using these three fuel datasets, respectively.

	2002			2003			2004		
	NFDRS	FCCS	MVPFS	NFDRS	FCCS	MVPFS	NFDRS	FCCS	MVPFS
R^2									
NFDRS	1.00	0.787	0.884	1.000	0.701	0.931	1.000	0.718	0.813
FCCS	0.787	1.000	0.930	0.701	1.000	0.773	0.718	1.000	0.781
MVPFS	0.884	0.930	1.000	0.931	0.773	1.000	0.813	0.781	1.000
RMS									
NFDRS	0.00	769.66	958.76	0.00	879.04	683.21	0.00	331.60	379.36
FCCS	769.66	0.00	447.60	879.04	0.00	297.87	331.60	0.00	191.55
MVPFS	958.76	447.60	0.00	683.21	297.87	0.00	379.36	191.55	0.00
Percent of systematic RMS									
NFDRS	0.00	46.89	72.05	0.00	63.83	74.15	0.00	47.35	66.92
FCCS	46.89	0.00	62.93	63.83	0.00	31.70	47.35	0.00	44.46
MVPFS	72.05	62.93	0.00	74.15	31.70	0.00	66.92	44.46	0.00

Figure 1. The variation in fuel moisture category and VCI in 2002.

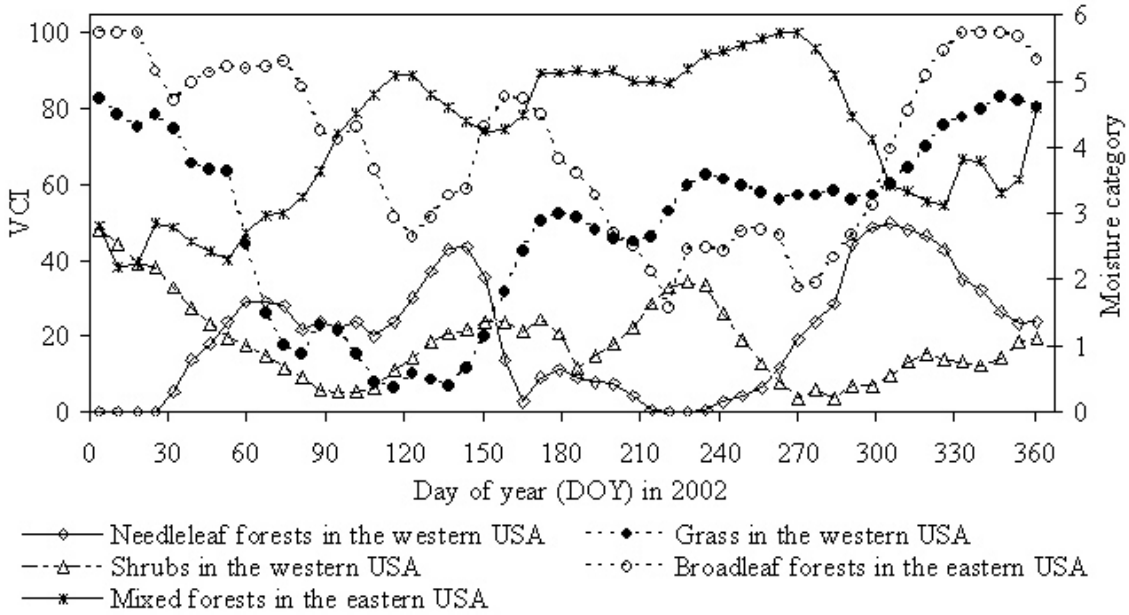

Figure 2. Fuel loadings across the CONUS (ton/ha). (A) Forest foliage, (B) forest branch, (C) shrub, (D) grass, (E) litter, (F) coarse woody detritus.

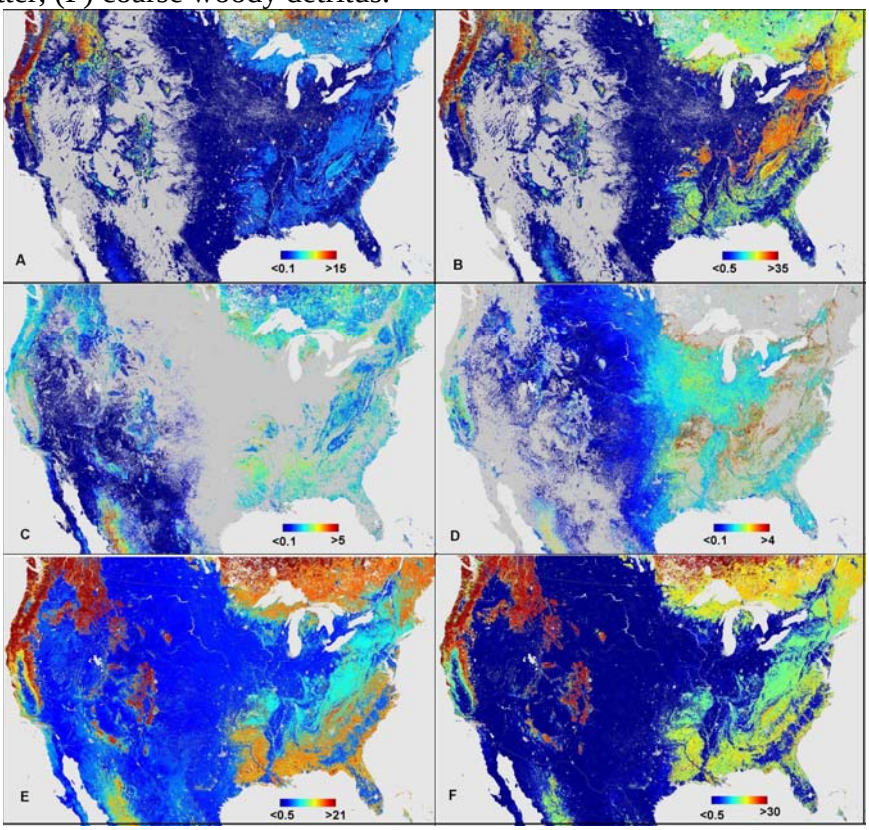

Figure 3. Spatial patterns of annual PM2.5 emissions for 2002 (a), 2003 (b), and 2004 (c), respectively.

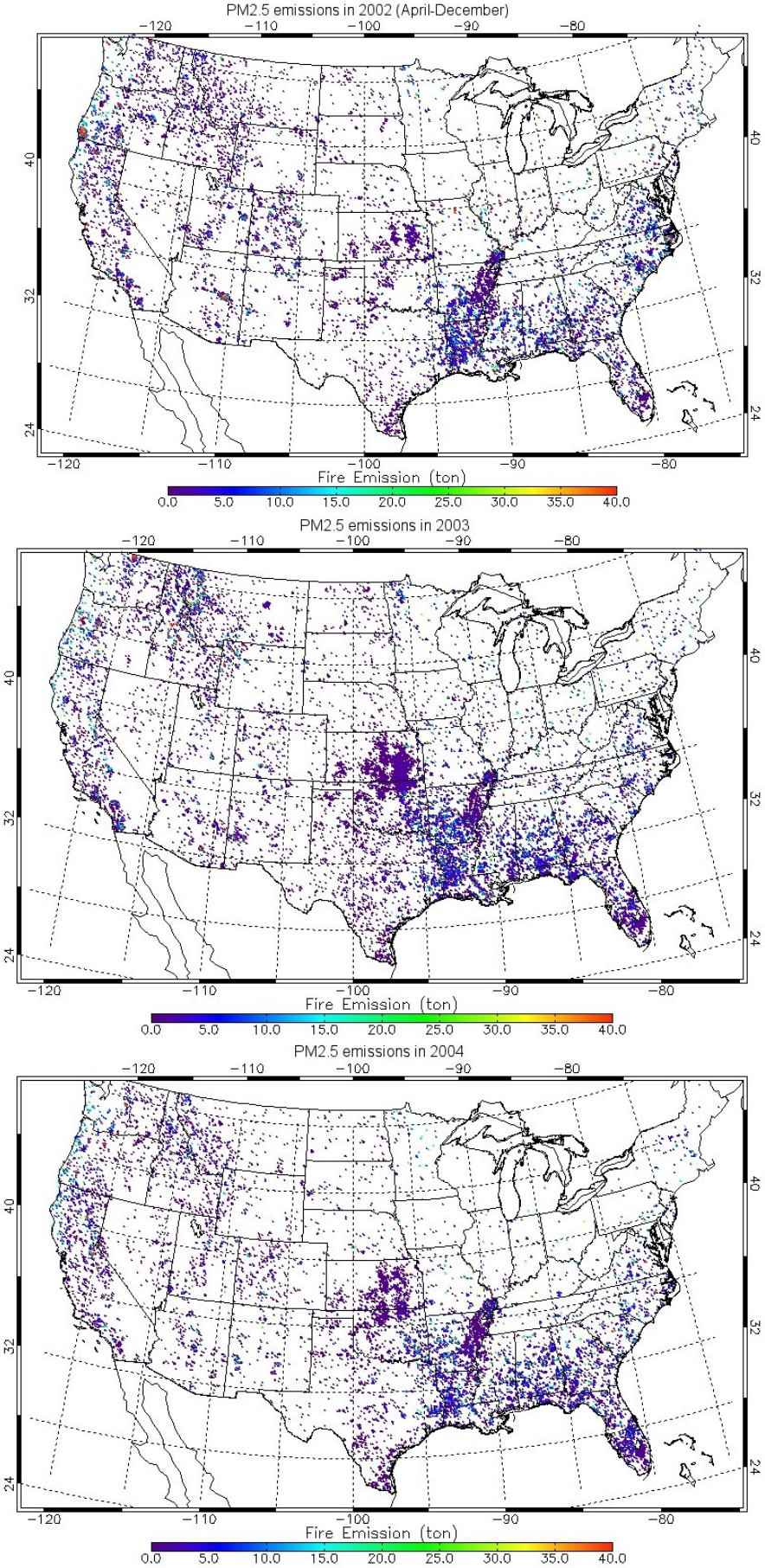

Figure 4. Emission for different states.

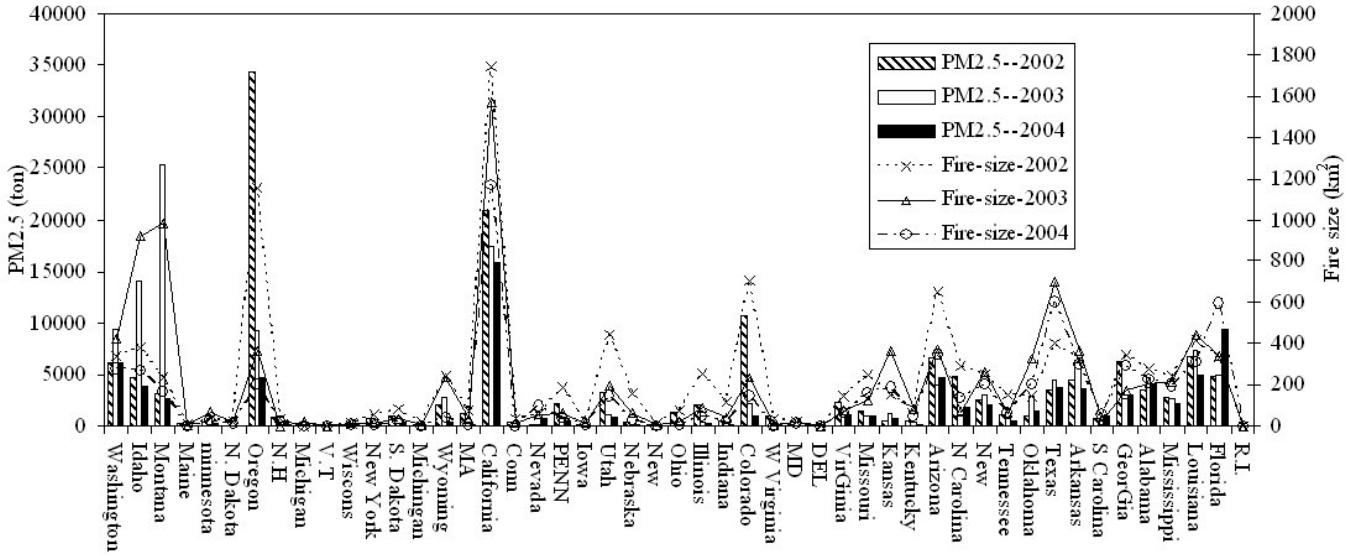

Figure 5. Temporal variation in PM2.5 emissions cumulated from half hourly biomass burning emissions.

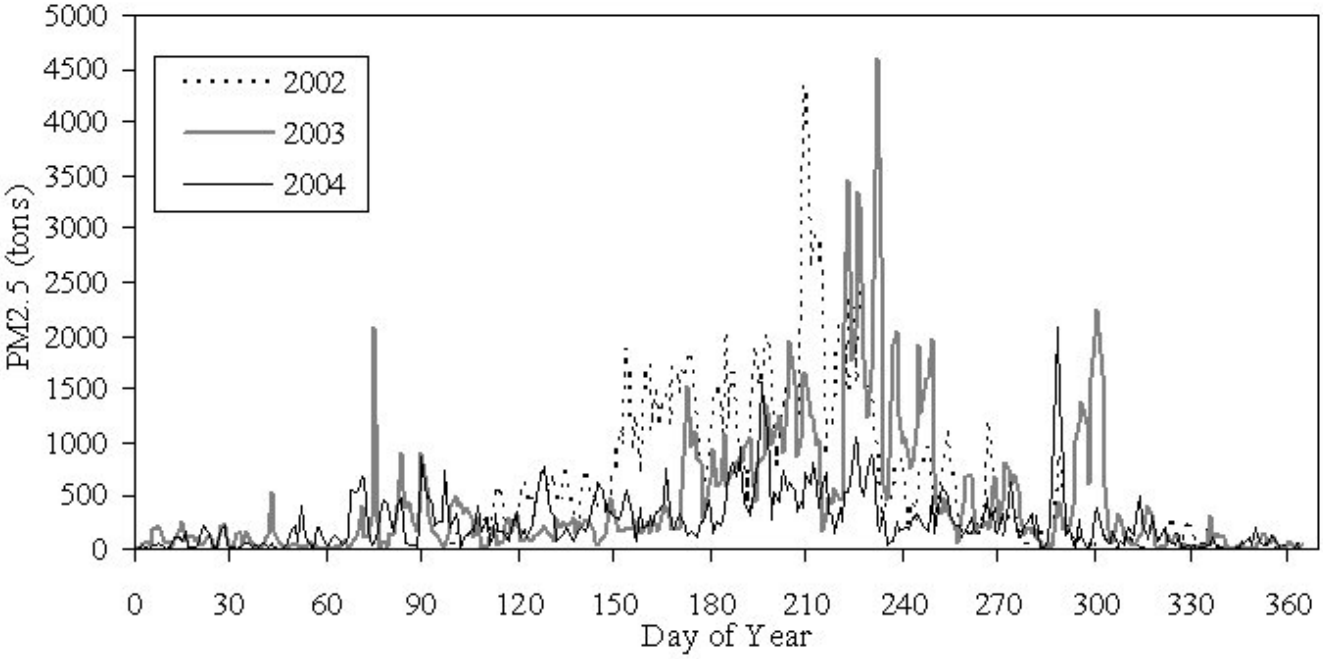

Figure 6. Daily cumulative GOES WF_ABBA fire size (km^2).

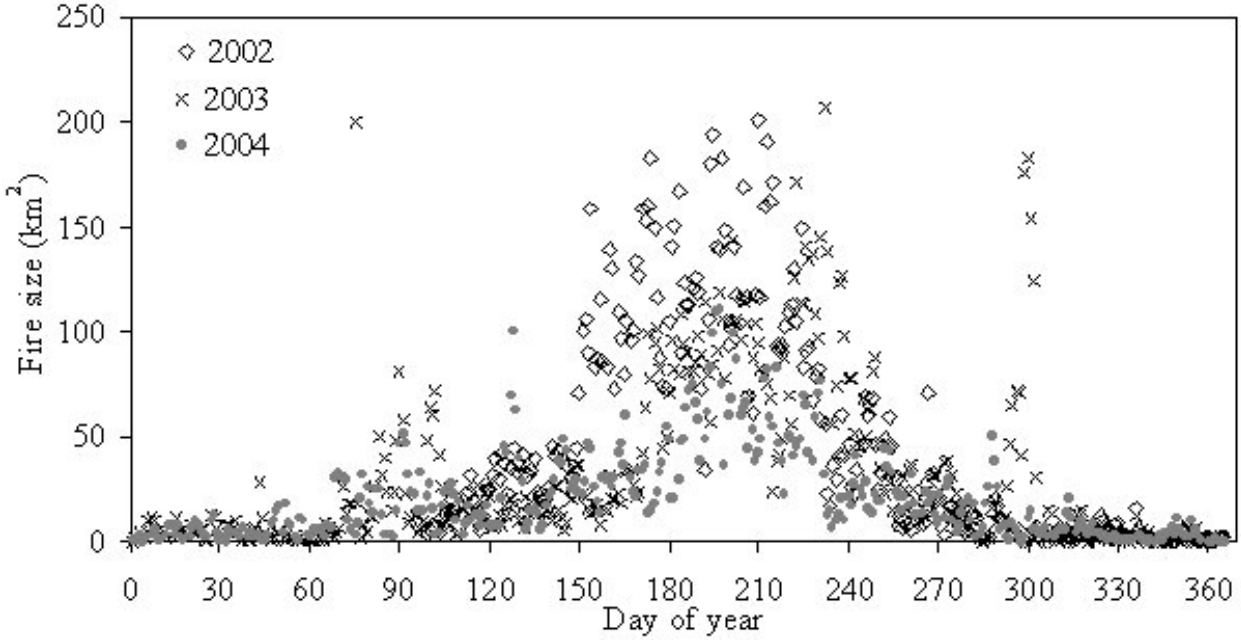

Figure 7. PM2.5 emissions for different land cover types.

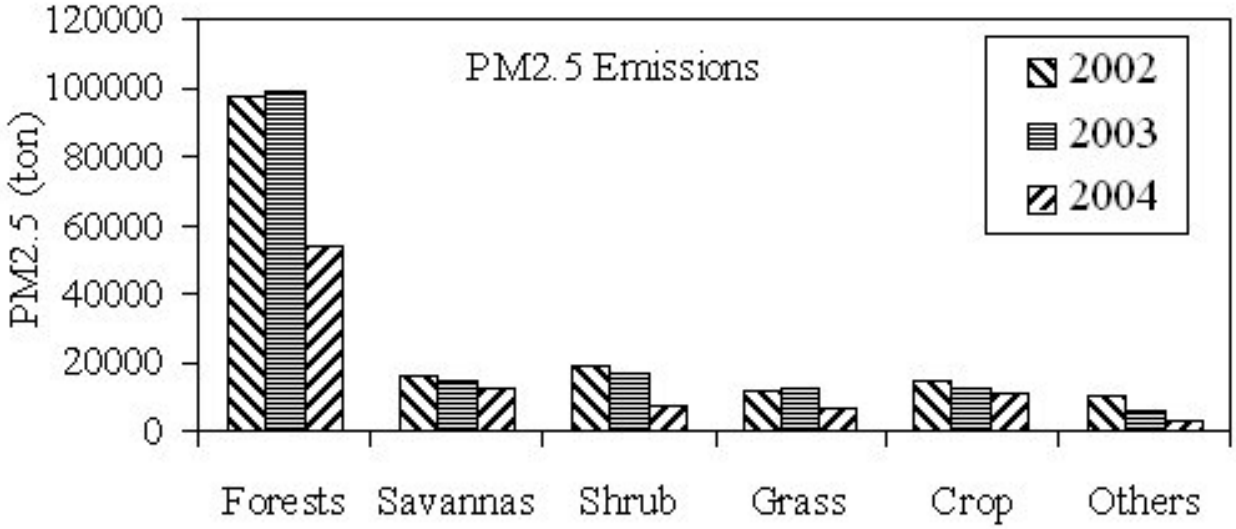

Figure 8. Cumulative GOES fire sizes for different land cover types.

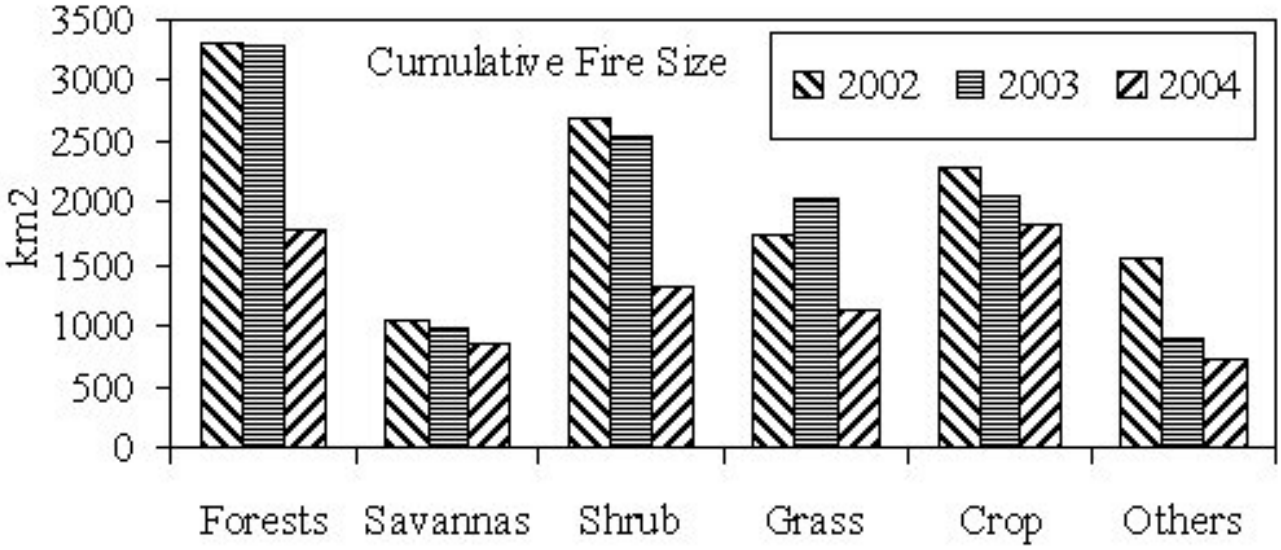
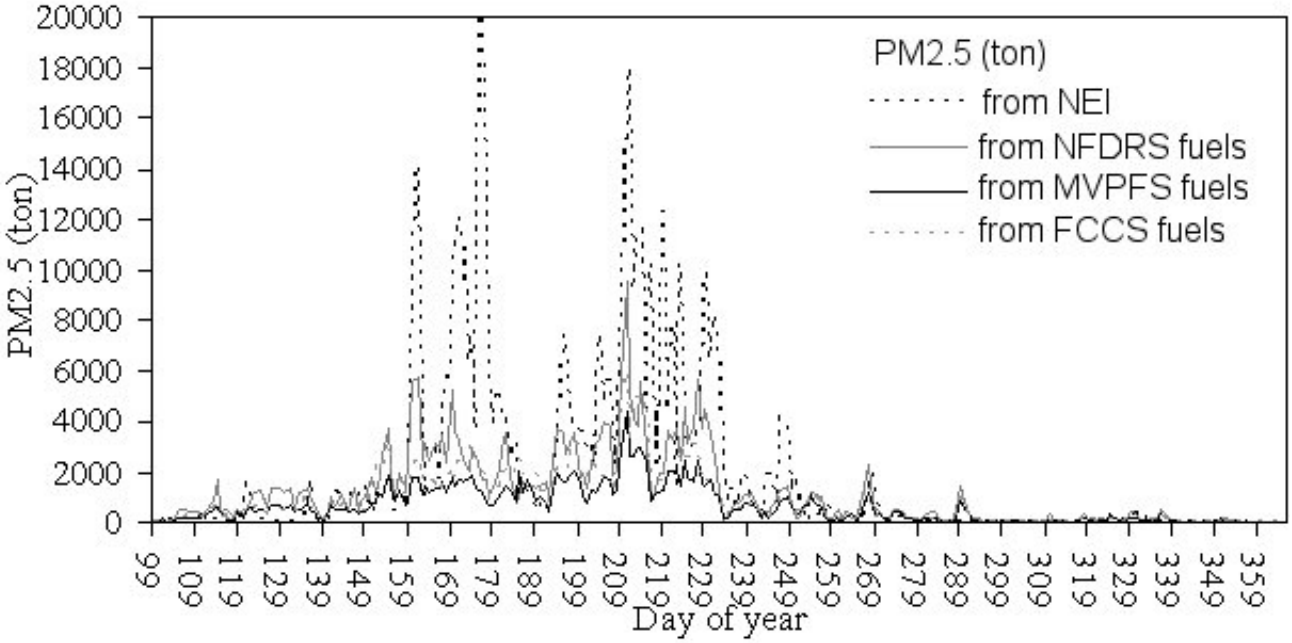
Figure 9. Daily PM2.5 emissions from different estimates in 2002.