SPATIOTEMPORAL VARIATIONS IN BURNED AREAS AND BIOMASS BURNING EMISSIONS DERIVED FROM MULTIPLE SATELLITE-BASED ACTIVE FIRES ACROSS THE USA

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ABSTRACT

Biomass burning releases a significant amount of trace gases and aerosols into the atmosphere. These emissions significantly affect air quality and carbon budget. To qualify the emissions, this study first estimates the burned areas from multiple satellite-based active fires provided through Hazard Mapping System (HMS) which was developed at NOAA. The HMS is an operational system that consolidates the automated fire detections from Geostationary Operational Environmental Satellite (GOES) Imager, Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), and the fires manually checked by experts. Specifically, the burned areas are derived from the diurnal pattern of fire size and fire duration. The fire size is obtained from the GOES fire product and the fire duration is determined using active fire observations from all the satellite instruments. These burned areas, combined with fuel loadings developed from MODIS land products and fuel moisture retrieved from AVHRR data, are then used to calculate emissions of PM2.5 (particulate mass for particles with diameter < 2.5 μm), CH4, CO, N2O, NH3, NOX, SO2, and TNMHC every half hour from 2004-2007. The results show that burned areas and biomass burning emissions present significant spatial and temporal patterns across Continuous United States.

INTRODUCTION

Biomass burning releases significant amount of trace gases and aerosols. It contributes 32% of CO and 40% of CO_2 released to the atmosphere globally[1]. These emissions play a significant role in climate change and air polution[2,3,4,5]. As a result, a great number of research efforts have focused on the investigations of biomass burning emissions at regional and global scales using in *situ* and satellite data[6,7,8].

Emissions from biomass burning are generally modeled from fuel loading, burned area, combustion factor, and emission factor. The commonly used fuel loadings include static values in large scales[9,10], field measurements in local areas, ecoregions-based representatives in regional areas[7]. The most widely used fuel data in Continuous United States (CONUS) are derived from the National Fire Danger Rating System (NFDRS)[11] and the Fuel Characteristic Classification System (FCCS)[12]. These two datasets similarly classifies CONUS lands into various fuel models (or ecosystem regions). In each fuel model, fuel loadings are obtained from a lookup table. More recently, a MODIS (Moderate Resolution Imaging Spectroradiometer) Vegetation Property-based Fuel System (MVPFS) has been developed[8], which determines fuel loadings using MODIS land products at a spatial resolution of 1 km.

Burned area is the major component in the estimates of biomass burning emissions. It is generally derived from local and national fire services or agencies[13]. Recently, satellite data are used to monitor burned areas at regional and global coverage. Particularly, burned areas are derived from active fire-counts observed from one of the Along Track Scanning Radiometer (ATSR), the SPOT (Systeme Pour l'Observation de la Terre) VEGETATION (VGT), the Advanced Very High Resolution Radiometer (AVHRR), and the Moderate Resolution Imaging Spectroradiometer (MODIS)[14,15]. However, the fire pixel counts are difficult to be converted to the burned areas accurately. It is due to the fact that one active fire count could correspond with a wide range of surface fire sizes and that the instantaneous observations from a satellite generally miss the detections of many small fire events[8]. On the other hand, burn scars detected from the time series of satellite reflectance demonstrate great potential for emission calculations for the past fire events[16], but they can not be applied to calculate real (near-real) time burning emissions. Moreover, the satellites with the moderate resolution can reasonably detect the burn scar with a size larger than 2 km^2 but poorly for smaller burn scars[17].

This study estimates burned areas from multiple satellite-based active fires provided through Hazard Mapping System (HMS) developed at NOAA. Specifically, the burned areas are derived from the diurnal pattern of fire size and fire duration from the active fire hotspots which are detected from NOAA AVHRR, TERRA+AQUA MODIS, and GOES (Geostationary Operational Environmental Satellite) Imager. These burned areas, combined with fuel loadings and fuel moisture, are used to quantify emissions of PM2.5 (particulate mass for particles with diameter < 2.5 μm), CH4, CO2, N2O, NH3, NOX, and TNMHC every half hour from 2004-2007.

METHODOLOGY

CALCULATING BURNED AREA USING ACTIVE FIRES FROM MULTIPLE INSTRUMENTS

Active fire data from HMS

We estimates burned areas using the active fire hotspots detected from the Hazard Mapping System (HMS). HMS is an operational system for detecting fires and analyzing smokes. It was developed in 2001 by the NOAA NESDIS (National Environmental Satellite and Data Information Service). This system consolidates fire data from two geostationary and five polar orbiting environmental satellites[18].

Geostationary data are obtained from Imagers on GOES-11 and GOES-12. GOES data offer a nominal spatial resolution of 4 km at satellite subpoint and a high temporal resolution of 30 minutes. The GOES-12 Imager scans surface at 15 and 45 minutes in each hour while GOES-11 at 0 and 30 minutes. Using GOES Imager data, the WF_ABBA (Wildfire Automated Biomass Burning Algorithm) derives fire characteristics in near real time[19]. The GOES fire product contains the time of fire detection, fire location in latitude and longitude, instantaneous subpixel fire size, corresponding ecosystem type, and quality flag. The quality flag represents the confidence of fire detections with six different levels.

HMS also integrates fire detections from five polar orbiting environmental satellites. Polar orbiting data are currently provided by the MODIS instruments on both the NASA Terra and Aqua spacecrafts and the AVHRR on NOAA-15/17/18. These data provide a spatial resolution of 1 km. Each instrument scans surface twice per day in low-middle latitudes while its observations could be as many as six times in higher latitudes. The Terra and NOAA-17 spacecrafts cross equator near 10:30 AM/PM local standard time (however, the NOAA-17 3.9μm band does not operate during daylight) while Aqua and NOAA-18 do near 1:30 AM/PM. NOAA-15 provides coverage near 6:00 AM/PM. The instruments on these satellites automatically detect fire hotspots using 3.9μm band based on threshold methods[18,20].

The HMS system allows satellite analysts to manually integrate fire data from all these satellite detections[18]. The analysts inspect fires detected from all instruments, delete detections appeared to be false alarms, and add fires undetected in the automated routines. Thus, these data are believed to be controlled with high quality. The HMS data are available at NOAA/NESDIS (http://gp16.ssd.nesdis.noaa.gov/FIRE/fire.html).

Simulating burned area

Burned area is assumed to be a function of fire size and fire duration[21]. It can be described as:

$$A = \alpha \int_{t_s}^{t_e} F_t \tag{1}$$

where
A -- area burned within a specified time period (km^2)
F_t -- subpixel fire size (km^2)
t_s and t_e -- starting and ending time of a fire, where the time step is set to half hours to match the temporal resolution of GOES satellite fire detection
α -- coefficient of conversion, which is defined as 1 which is described in the reference[21]

The diurnal variation in fire characteristics for a given fire pixel is reconstructed from multiple satellite instruments. Fire size in every half hour (0-29 minutes and 30-59 minutes) is determined from GOES instantaneous fire size. The time of the instantaneous fire is recorded from all fire detections including MODIS and AVHRR within a GOES pixel size. The fire size for the MODIS and AVHRR fire observation is treated in two different ways. If there are GOES fire detections in a given GOES pixel footprint, MODIS and AVHRR fire detections only contribute the time of fire observation to improve the quality of fire duration. Otherwise, the fire size in MODIS and AVHRR observations is replaced using the rate of burned area calculated from regression model between ETM+ burn scars and MODIS and AVHRR fire counts[22].

The diurnal pattern of fire size is simulated using the recorded half-hourly fire sizes and fire duration[21]. In brief, representative patterns in half-hourly GOES fire sizes are generated for different ecosystem types[21]. Assuming that the shape of the diurnal pattern in the same ecosystem is similar, the diurnal curve of fire sizes in a given pixel is then generated by imposing the corresponding representative diurnal curve on the detected fire sizes. This process provides fire sizes for the detected fires with saturations and cloudy contaminations, and the temporally missed detections.

Some of the fire detections are not considered for the estimates of burned area. First, a fire pixel is only observed from GOES Imagers and the fire observations are all with low probability (quality assurance flag 5) and they are less than three times within a day. Second, a fire event within a GOES pixel footprint is only observed once in a day by MODIS, AVHRR and GOES Imagers. This fire could be either a false detection or a very small fire.

MODELING BIOMASS BURNING EMISSIONS

Biomass burning emissions are generally modeled by integrating four fundamental parameters. These parameters are burned area, fuel loading (biomass density), the fraction of combustion, and the factor of emission for trace gases and aerosol. The model of biomass burning emission is described using the following formula[8, 23]:

$$E = \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{j=1}^{J}\sum_{i=1}^{I} A_{ijk} B_{ijl} C_{ijkl} F_{ijkl} \tag{2}$$

where
E -- emission from biomass burning (ton)
A -- burned area (ha), which is calculated using the method described in above section
B – fuel loading or biomass density (ton/ha)
C -- fraction of biomass consumed during a fire event
F -- factor of the consumed biomass released as trace gases and smoke particulates
i and j --- fire geo-location (or pixel column and row)
l -- fuel type
k – fire time period

Fuel loading type 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. The fuel loading for each pixel is obtained from a MODIS Vegetation Property-based Fuel System (MVPFS)[8,24]. This dataset was primarily calculated from MODIS land product including percent vegetation cover in MODIS continuous field product, leave area index (LAI), and land cover types at a spatial resolution of 1 km.

The factors of fuel combustions are controlled by fuel moisture condition. The moisture is divided into six categories, which are very dry, dry, moderate, moist, wet, and very wet, using AVHRR vegetation health index. These moisture conditions were applied to modify combustion factors for various fuel types[8].

The factors of emissions also vary with moisture conditions and fuel types. In investigating emission factors, the moisture is stratified as wet, moderate, and dry conditions. The fuel type is classified into litter, coarse wood, grass and shrub, duff, and tree canopy. This study obtains emission factors from the First Order Fire Effects Model (FOFEM)[25] for PM2.5, CH4, CO, N2O, NH3, NOX, SO2, and TNMHC.

RESULTS

SPATIOTEMPORAL PATTERN IN BURNED AREAS

Figure 1 presents the spatial pattern of the burned area in each GOES fire pixel. Large fire events are mainly distributed in the western US, where the burned areas in many fire events cover entire pixels. The number of fire events are large in southeastern US and along central and southern Mississippi Valley, while the burned area in each event is relative small. This spatial pattern is consistent during the four years.

Figure 2 reveals the burned area in different states across CONUS. The top ten states with large burned area are California (5214 km^2), Arizona (3156 km^2), Idaho (2979 km^2), Texas (2902 km^2), Montana (1601 km^2), Florida (1539 km^2), Kansas (1362 km^2), Oregon (1256 km^2), Oklahoma (1240 km^2), Washington (1232 km^2). In these states, the burned area is mainly caused by shrubland fires in California and Arizona, by grassland fires in Texas, and by forest fires in Idaho. Among the total burned area during the four years, the area burned in forests and shrublands is about 25%, respectively, and it accounts for 21% in grasslands and croplands, respectively.

Figure 3 shows the proportion of monthly burned area in various ecosystems. The average proportion from 2004-2007 indicates that the burned areas from forest fires are larger than those in other ecosystems during autumn and winter. Majority of the burned areas during summer are caused by shrubland fires, which account for 35%. In contrast, the burned areas in spring are mainly caused by agricultural fires and grassland fires.

The annual burned area across CONUS is $3.4\text{x}10^4 \pm 0.7\text{x}10^4$ km^2 from 2004-2007, which accounts for about 0.4% of total land. The inter-annual burned area varies considerably (Table 1). The area in 2004 is about 40% smaller than that in 2006. The coefficient of variation is 20% during the four years.

VARIATIONS IN BIOMASS BURNING EMISSIONS

Annual biomass burning emission varies significantly. The emission in 2007 is about 42% smaller than that in 2006. On average, the annual emission is $3579\times10^6\pm876\times10^6$ kg of CO, $342\times10^6\pm82\times10^6$ kg of PM2.5, $251\times10^6\pm61\times10^6$ kg of TNMHC, $188\times10^6\pm44\times10^6$ kg of NOX, $142\times10^6\pm35\times10^6$ kg of CH4, $58\times10^6\pm14\times10^6$ kg of SO2, $36\times10^6\pm9\times10^6$ kg of NH3, and $11\times10^6\pm3\times10^6$ kg of N2O.

Figure 4 exhibits diurnal variation in emissions released from biomass burning. During noon, annual emission is larger than $550\text{x}10^6$ kg per hour of CO and $50\text{x}10^6$ kg per hour of PM2.5. In contrast, it is generally less than $80\text{x}10^6$ kg per hour of CO and $7\text{x}10^6$ kg per hour of PM2.5 during night. The emissions of other species also show the same diurnal pattern although the magnitude varies with the emission factors.

Figure 5 presents monthly variation in biomass burning emissions. The monthly patterns are the same for emissions of various species because they are mainly dependent on burned areas. In generally, the emissions are mainly released during summer season, particularly, with a proportion of 32% in July and August. In contrast, the emissions from November to next February only account for about 15%.

Figure 6 illustrates the variation in monthly emission with ecosystem. The emissions released from forest fires are consistently larger than those from other ecosystems. The monthly forest fire emission accounts for more than 46% of the monthly total emissions, except for that in June. The largest proportion is 65% which occurs in August. The monthly emission proportion in shrubland fires presents a distinctive seasonal pattern, which is larger during summer (June and July) while it is much smaller during winter and spring. Emission proportion in croplands (croplands + croplands and natural vegetation mosaics) is noticeably high during spring (20% in April and 27% May) while it ranges from 8-16% during the period from July to December. Annually, the proportion of fire emission is 55% in forests, 14% in savannas, 8% in shrublands, 10% in grasslands, and 13% from croplands.

Trace gases and aerosols released from wildland fires are distinguishable geographically. The 20 states with large emissions are distributed in western, southern, and southeastern US (Figure 7). The emission in California and Idaho are particularly large with a proportion of 14% and 11% against total emission in CONUS, separately. Following them are states of Georgia, Louisiana, Washington, Florida, Oregon, and Montana, where the emission ranges from 5-7%. The emission in each state along northeast is less than 0.5%.

DISCUSSION AND CONCLUSIONS

Burned area can be effectively estimated using fire size and fire duration observed from multiple satellites. Instantaneous fires observed from MODIS+AVHRR+GOES in HMS enhance greatly the quality of fire duration determined for a GOES fire pixel, and compensate the limitation in single satellite observations. Thus, the fire observations from multiple satellites significantly improve the inventory of burned area every half hour.

The burned area estimated from MODIS+AVHRR+GOES provides detailed spatiotemporal patterns from 2004-2007. Geographically, the burned area is dominantly distributed in California, Arizona, Idaho, and Texas, which is followed by the sates in southeast region and along Mississippi Valley. Further, fire occurrences appear distinctively seasonal variation in different ecosystems. During spring, agriculture fires and grassland fires are dominant, which is likely associated with agricultural activities before crop plantation. Shrubland fires mainly occur during summer and forest fires mainly appear in autumn and winter. These wildland fire events are likely due to the impact of dry weather condition.

Biomass burning emissions are further estimated from burned areas and fuel loadings. The emission value in various species (PM2.5, CH4, CO, N2O, NH3, NOX, SO2, and TNMHC) present similar spatial and temporal pattern because their differences are only caused by emission factors. In general, seasonal emission pattern is comparable to that in burned area, where the large emissions occur in July and August with a proportion of 32%. However, the emission amount does not follow well the burned area in different ecosystems. Particularly, the monthly emission released from forest fires accounts for 35-63% (52% annually) while the corresponding burned areas is 16-41% (26% annually). In contrast, monthly emission from shrublands and grasslands is 9-38% (21%) but the burned area is 16-61% (44% annually). Evidently, fuel loadings also play a significant role in the emission calculations.

The emissions derived from multiple satellite data also highlights the regions with heavy fire emissions. Particularly, fires in California and Idaho produce one quarter of total emissions in CONUS. These results are significant for air quality modeling and policy making.

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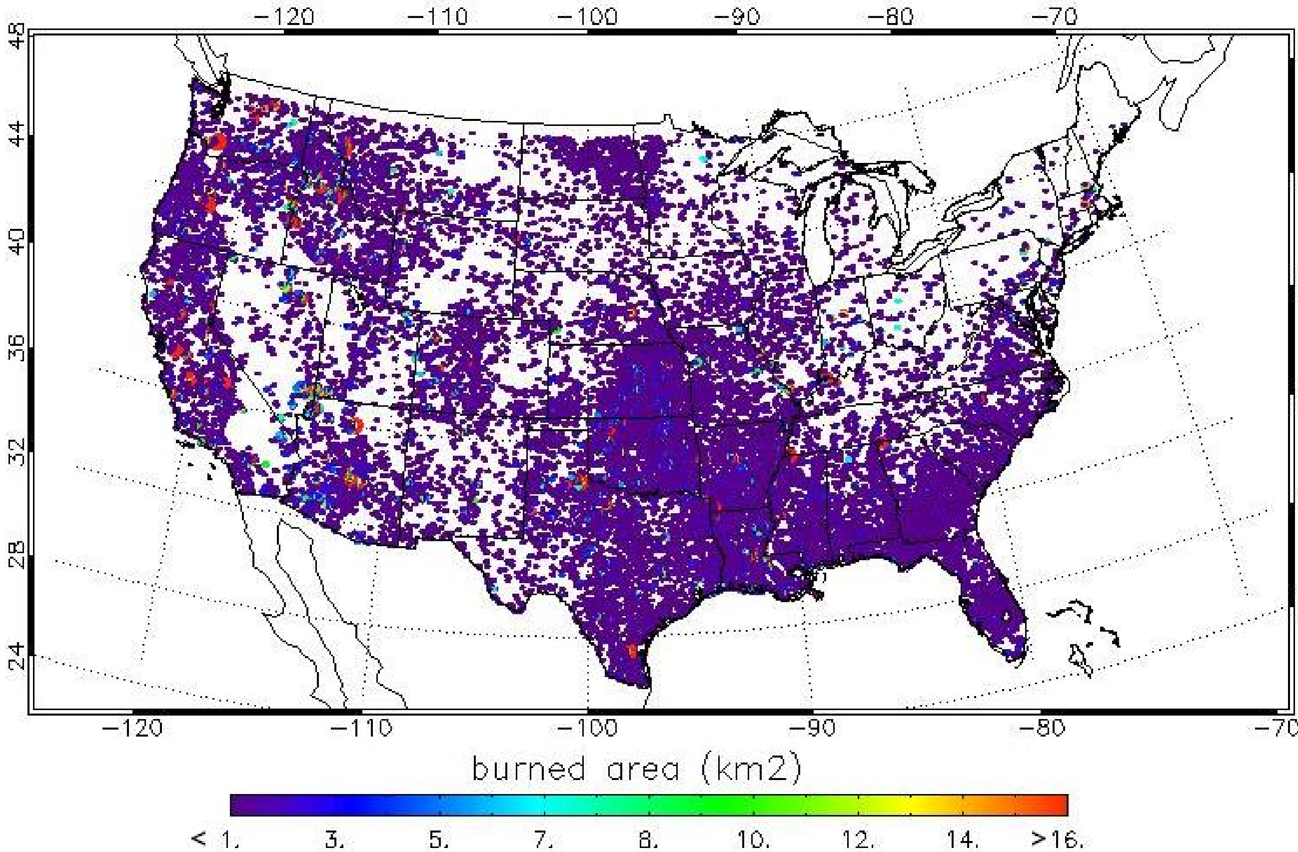
Table 1: Monthly burned area (km^2) from 2004-2007.

Year	2004	2005	2006	2007	Average
January	699	730	1021	123	643
February	1008	810	970	442	807
March	2760	2161	2133	733	1947
April	2020	3273	2968	1413	2418
May	1778	2491	2649	2807	2431
June	2278	4289	4108	3968	3661
July	5893	6967	10608	10355	8456
August	3858	7363	8496	8123	6960
September	2263	3247	5236	1932	3170
October	1575	2008	2024	1304	1728
November	838	1505	1015	395	938
December	593	783	824	184	596
Total	25565	35625	42053	31778	33755

Figure 1: Spatial pattern of burned areas in the footprint of GOES pixel (~4km) derived from MODIS+AVHRR+GOES active fire observations in 2005.



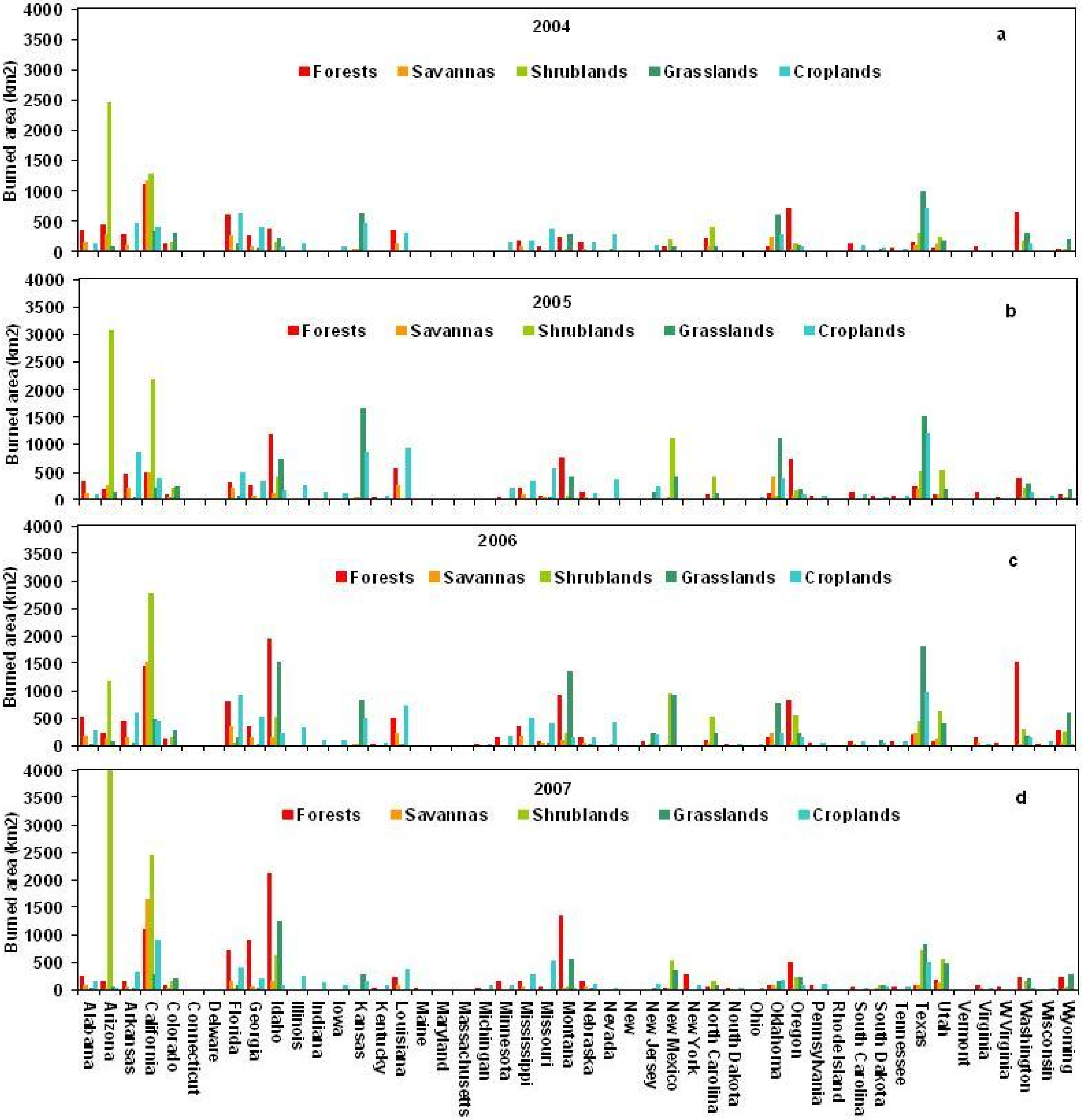


Figure 2: Variation in burned area in various states and ecosystems from 2004-2007.

Figure 3: The average proportion of monthly burned area in different ecosystems from 2004-2007.

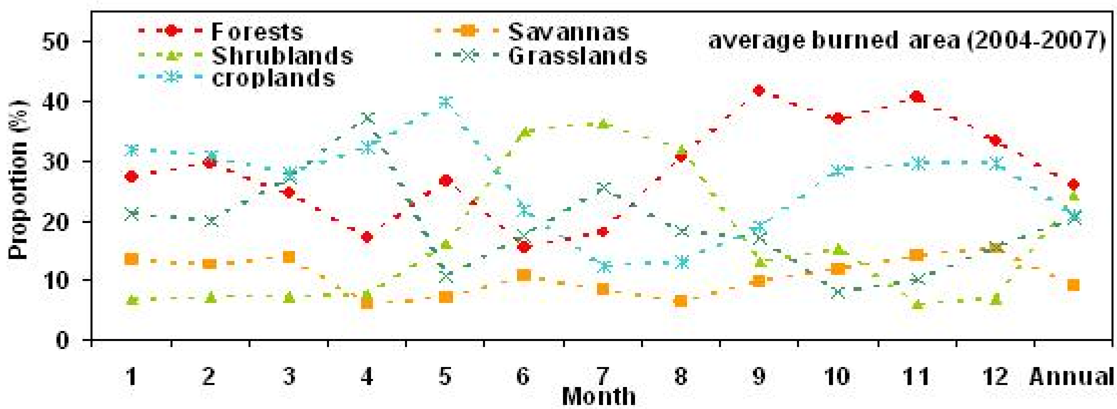


Figure 4: Hourly annual biomass burning emissions averaged from 2004-2007. (a) Hourly PM2.5 emissions and (b) hourly PM2.5 emissions.

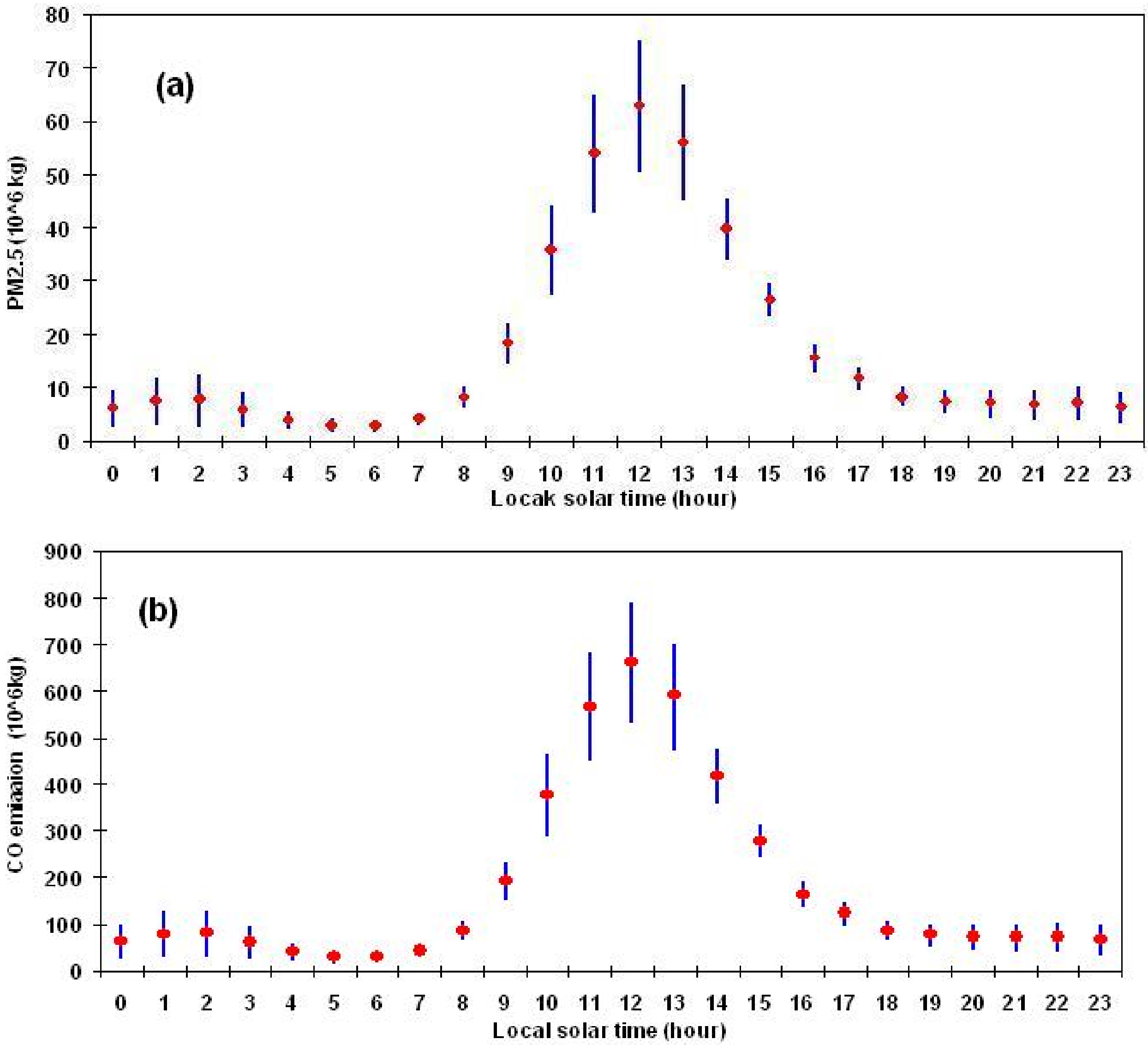


Figure 5: Monthly variation in emissions averaged from 2004-2007.

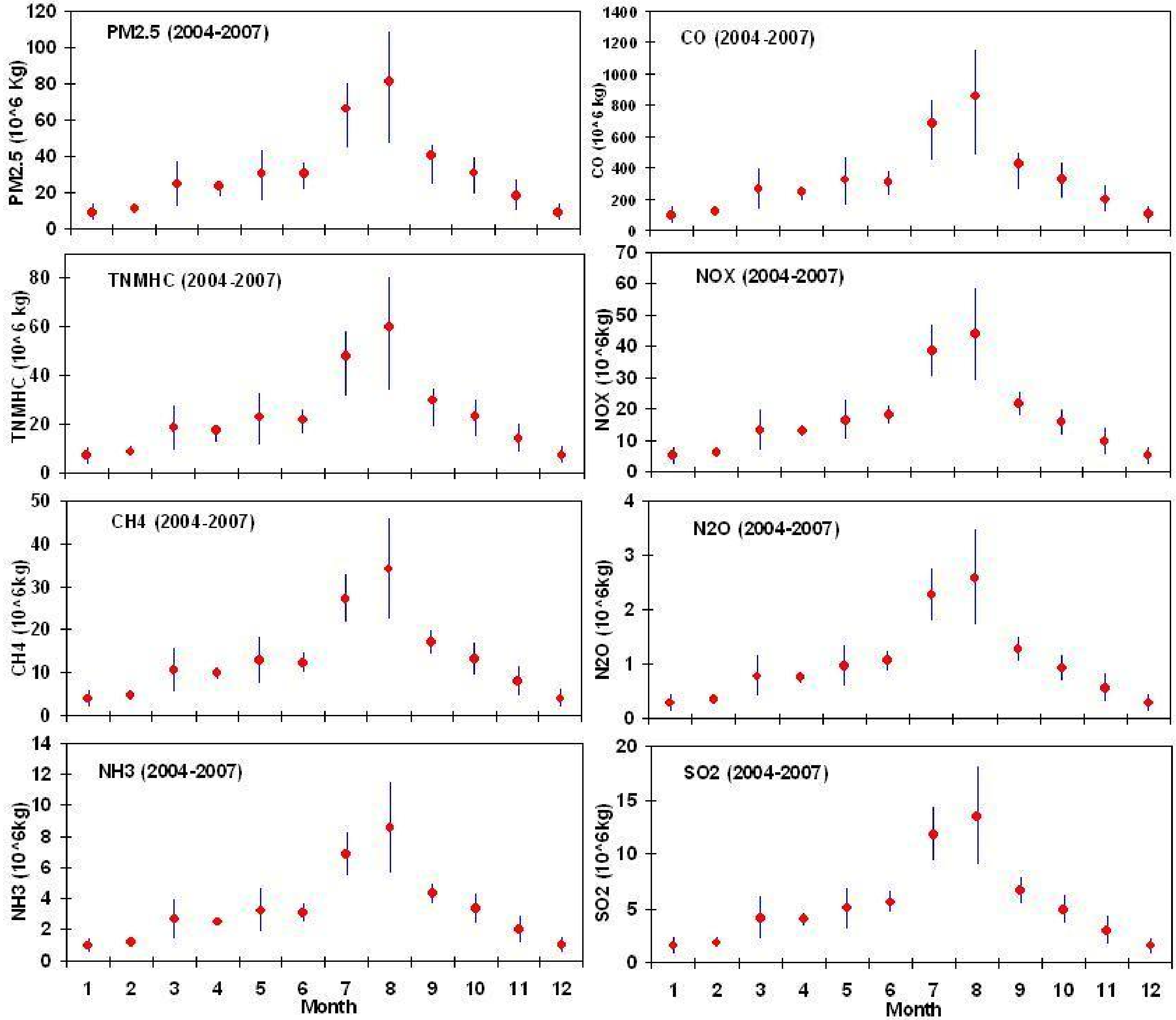


Figure 6: Proportion of monthly emissions (averaged from 2004-2007) in different ecosystems.

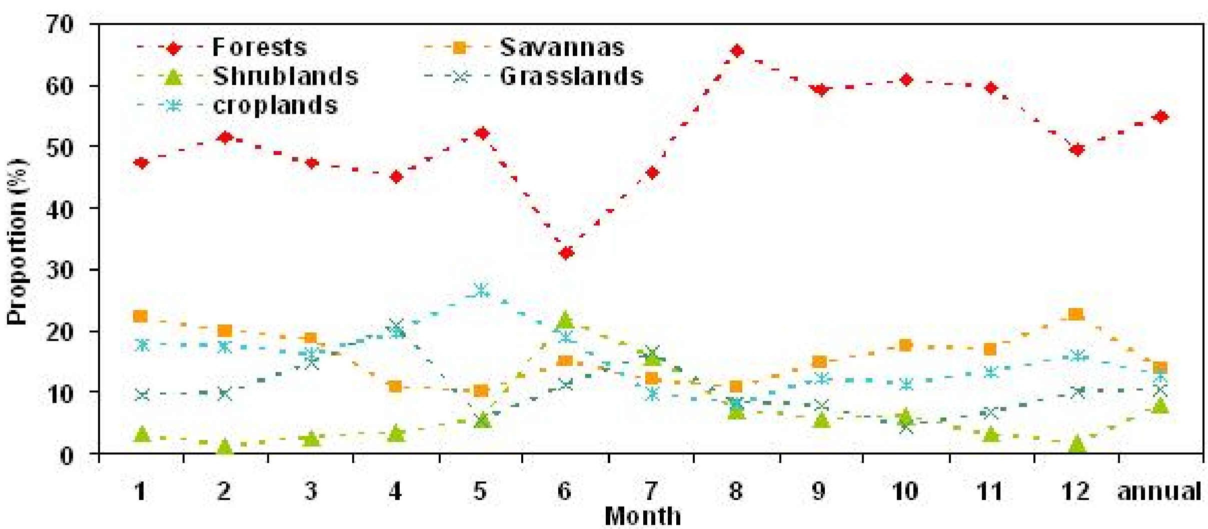


Figure 7: Annual biomass burning emissions averaged from 2004-2007 in the top 20 states.