Development and Sensitivity Analysis of Wildland Fire Emission Inventories for 2002-2006

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ABSTRACT

The BlueSky smoke modeling framework and the Satellite Mapping Automatic Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE) were applied to facilitate the development of day-specific wildland fire emission inventories for the continental U.S. SMARTFIRE was used to generate activity data (acres burned). The FCCS, CONSUME 3.0, and FEPS models were used within the BlueSky framework to model vegetation distribution, fuel consumption, and emission rates, respectively. Emission inventories have been prepared with satellite data only and with human-observed fires only for comparison to the inventories prepared using SMARTFIRE (i.e., satellite data reconciled with human observations). Different fire information sources can have significant impacts on the resulting estimated emissions. Uncertainty in the emission inventories is currently being explored by evaluating the sensitivity of the results to the fire information inputs.

INTRODUCTION

Globally, wildland fire (wildfire and prescribed burning of forests and rangelands) contributes significantly to atmospheric pollution. Pollutants emitted from fires include particulate matter, carbon monoxide, nitrogen oxides, and acrolein (a regulated hazardous air pollutant [HAP]) (Andreae and Merlet, 2001). In the United States, the U.S. Environmental Protection Agency (EPA) estimates that 22% of the primary emissions of non-dust particulate matter less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$) came from non-residential fires in 2001 [970,000 tons, source: AirData web site, http://www.epa.gov/air/data/]. Exposure to wildfire smoke has been associated with increased eye and respiratory symptoms, medication use, physician visits, and exacerbated asthma (Kuenzli et al., 2006). Emissions of carbon monoxide and nitrogen oxides from fires contribute ozone formation in the troposphere (the key component of photochemical smog). Estimates of the magnitude of tropospheric ozone from biomass burning range from less than 15% to 40% of the global total (Levine et al., 1995; Galanter et al., 2000). Carbon particles from fires also contribute to climate forcing, both

directly by increasing atmospheric reflectance, and indirectly by influencing the formation of clouds (Kaufman and Fraser, 1997).

Accurately modeling wildland fire emissions requires many pieces of information, including fire location, ignition time and growth rate, fire intensity, and final size. This information is needed at a daily or better temporal resolution to be useful for air quality modeling of smoke impacts. Emissions from wildland fires can be modeled using the formula in Equation 1.

Equation (1) $E_s = A * F * c * EF_s$

where

E_s = emissions of species s
A = area burned
F = fuel available for consumption
c = fraction of available fuel consumed
EF_s = emission factor (mass of species s emitted per mass of fuel consumed)

There is uncertainty in each of the terms on the right-hand side used to predict emissions. Constraining the area burned is one of the most important uncertainties that can be constrained using available observations.

Historically, for national scale emission inventories in the United States, area burned estimates have come from compilations of fire reporting systems from federal, state, tribal, and local agencies. Given that data are originally collected in a variety of formats, compilation is costly. Some fire reporting systems do not track individual fires, keeping only monthly statistics. To create a fire emission inventory with daily resolution in a timely matter requires a different data source.

Satellites have been used to detect fires globally for several decades (Dozier, 1981). The global climate community routinely uses satellite-based data to derive estimates of area burned (van der Werf et al., 2006). Satellite data offer several advantages over ground reporting systems for estimating area burned over a large area (such as nationally). Satellite data sets are available with global coverage in a single format, making them easy to work with. Also, satellites detect fires that are often too small or too remote to be reported by human observation.

There are, however, limitations in the use of satellite data for emission inventories. Satellite instruments that provide global daily coverage of fires do not yet routinely provide an estimate of area burned for each fire. Instead, a thermal anomaly or “hot spot” is detected and reported. The smallest fire that can be detected is instrument-, algorithm-, and condition-specific. Large fires will be detected as a cluster of several “hot spot” pixels. To use this type of data in Equation 1, one must estimate the area burned per pixel. Though algorithms exist for estimating total burned area (Li et al., 2004) directly from satellite observations of burn scars, these algorithms are not routinely available. Also, burn scar algorithms may have trouble detecting burns that occur below the forest canopy (understory burns). Understory burns are

very common in the southeastern United States, where millions of acres of prescribed burning occur annually.

Though satellites are able to detect many fires, they do not detect all fires. Fires that are too small or too cold, are not burning during the satellite overpass, or are obscured by clouds go undetected. Satellite fire detections have not been used previously to estimate area burned for the National Emission Inventory.

Using data from ground reporting systems in concert with satellite fire detects can help improve fire area burned estimates. The Satellite Mapping Automatic Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE) is an algorithm and database system designed to reconcile these disparate fire information sources to produce daily fire location and size information (Sullivan et al., 2008).

Using SMARTFIRE as the fire activity source, we prepared four years (2003-2006) of daily emission estimates for wildland fires for the lower 48 United States, including wildfire, wildland fire use (WFU), and prescribed burns. The inventory was then reproduced twice using different fire information sources: Incident Command Summary reports (known as ICS-209 reports) and the Moderate Resolution Imaging Spectroradiometer (MODIS) anomalies. The resulting intercomparison is presented below. While agricultural fires were included in the inventory, they are excluded from the analyses in this paper.

BODY

Methods

Fire Information Sources

ICS-209s

For large wildfires and WFU fires for which there is a federal response, ICS-209 reports are created on a near-daily basis. ICS-209 reports contain useful information about particular fires or fire complexes from the incident command team on the ground, such as descriptions of the fuel loading, growth potential, and type of fire. However, ICS-209 reports have several limitations as a data source for predicting daily emissions. Daily estimates of actively burning areas are required, but ICS-209 reports provide only the ignition point of the fire and an estimate of the total area burned over the lifetime of the fire. Also, ICS-209 reports are only created for a small subset of fires. Fires that are not tracked with ICS-209 reports include prescribed burns, agricultural burns, and wildfires for which there is no federal response.

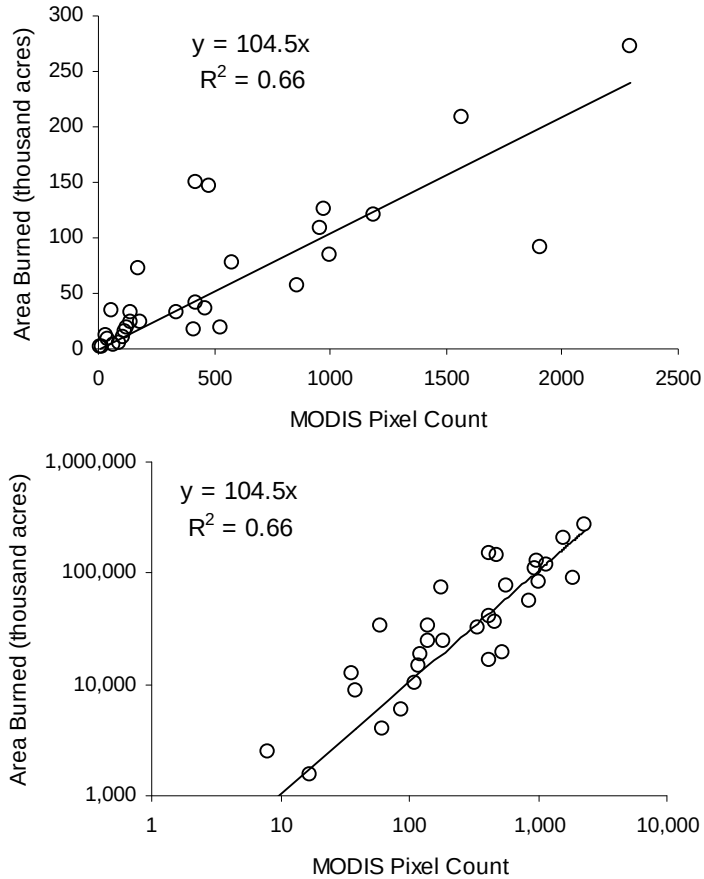
To estimate daily area burned from ICS-209 cumulative area burned, we subtracted the previous day's reported area from the current day. Fires were modeled as a single point source located at the reported ignition point of the fire. Historical ICS-209 reports are available at the Fire and Aviation Management Web Applications (FAMWEB) web site (http://fam.nwcg.gov/fam-web/famweb/index$.startup).

MODIS

The MODIS instrument is onboard both the NASA Terra and Aqua satellites. Each instrument provides daily global coverage, with Terra passing over the conterminous United States in the late morning and Aqua passing over in the mid afternoon. One of the products available from MODIS is thermal anomalies, or "hot spots" (Justice et al., 2002). MODIS hot spots are widely used to track actively burning fires globally. Historical MODIS hot-spot data are available from the USDA Forest Service's Remote Sensing Applications Center (RSAC; http://activefiremaps.fs.fed.us/).

MODIS hot spots detect when a given area is actively burning, but they do not directly provide an estimate of the area burned. The MODIS hot-spot product (also known as MOD14) has a nominal pixel resolution of 1 square kilometer (about 450 acres). However, MODIS can detect fires that are much smaller than that. To estimate daily area burned using MODIS requires an estimate of the area burned that each hot-spot pixel represents. We compared MODIS total pixel counts with final area burned for 30 fires ranging from 2,000 to 300,000 acres in size (Figure 1). The area burned was derived from final helicopter-flown burn scar perimeters. Total pixel count includes all hot-spot pixels within the burn scar over the entire life of the fire. We used a final value of 100 acres per MODIS pixel.

Figure 1. Relationship between total MODIS pixel count and final burn perimeter area in linear (top) and logarithmic units (bottom).



SMARTFIRE

SMARTFIRE uses both satellite-detected and ground-reported fires to produce daily fire information (locations and area burned). SMARTFIRE currently reconciles ICS-209 ground reports and hot spots from the National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping System (HMS) (Ruminski et al., 2006). HMS data consist of compiled fire detection information from three different instruments onboard seven satellite platforms coupled with human quality control. Individual detections are inspected by a trained analyst for false detects and inaccurate geolocation. The HMS product relies on data from the MODIS, Advanced Very High Resolution Radiometer (AVHRR), and Geostationary Earth Observing Satellite (GOES) instruments.

Emissions Modeling Pathway

The emissions for all three fire information cases were processed in the same way using the BlueSky smoke modeling framework (Larkin et al., 2008). The BlueSky framework is designed to facilitate the operation of predictive models that simulate cumulative smoke impacts, air quality, and emissions from forest, agricultural, and range fires. The BlueSky framework

allows users to combine state-of-the-science emissions, and meteorological and dispersion models to generate results based on the best available models. In other words, the BlueSky framework connects models that provide values for the terms in Equation 1. BlueSky allows the user to choose one of several models at each step in the smoke modeling process. The models used for this study are shown in Table 1.

Table 1. Model chain within the BlueSky Framework used to estimate emissions.

Process	Model Used
Fuel Loading	Fuel Characteristic Classification System (FCCS)
Fuel Consumption	Consume 3.0
Emissions	Fire Emission Production Simulator (FEPS)

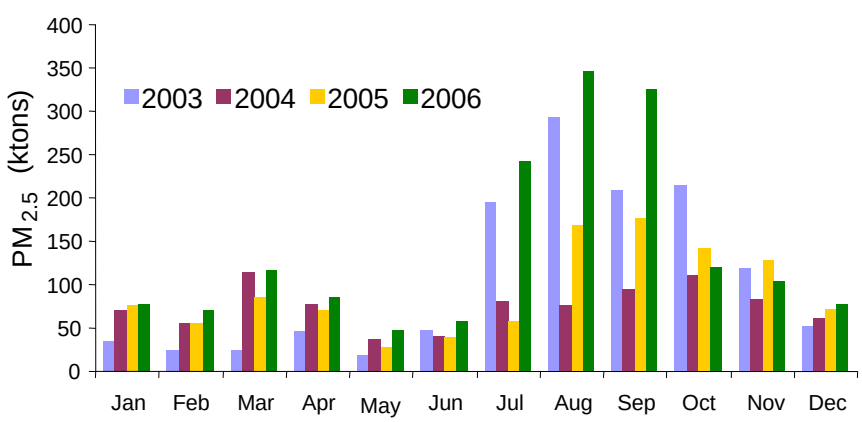
In addition to the standard emission products produced by FEPS ($PM_{2.5}$, CO, etc.), 29 HAP species emissions were estimated based on emission factors provided by Tom Pace of EPA. Fires were assigned fuel moisture values based on the nearest weather station from the USDA-FS Wildland Fire Assessment System.

Results

Emissions from SMARTFIRE

Though emission estimates were calculated for many species, this paper focuses on the primary $PM_{2.5}$ results. All other pollutants were modeled with similar spatiotemporal patterns. Aerosol formed secondarily in the atmosphere was not estimated. Figure 2 shows the estimated primary $PM_{2.5}$ emissions by month for each modeled year. Wildland fire emissions in the lower 48 states exhibit a bimodal yearly pattern, with peaks in the spring and late summer/early fall. Over the four years modeled, emissions in the spring season were fairly consistent year to year. The summer/fall season, however, showed much more variability.

Figure 2. Modeled yearly primary $PM_{2.5}$ wildland fire emissions by month for the lower 48 states.



The bulk of emissions come from two regions: the West and the Southeast. This concentration can be seen in the emissions density plot shown in Figure 3A, which shows the average annual tons of $PM_{2.5}$ emitted per square mile, smoothed for display clarity. The national spatiotemporal pattern is shown in more detail in Figure 3B, which depicts the monthly average $PM_{2.5}$ emissions for each state. The springtime emissions are mostly from the southeastern states, where prescribed burning is a common management practice in spring. The summer/fall emissions are driven by the West, particularly the northwest and California. The largest single state monthly contribution is Idaho in August.

Figure 4 shows the modeled daily area burned and $PM_{2.5}$ emitted for the entire modeled time period (August 2002 through December 2006). Note that the area burned in the spring is similar in quantity to the area burned in the summer/fall, but the $PM_{2.5}$ emitted is greater in the summer/fall. The summer/fall burning is dominated by large wildfires in the West, while the spring burning is largely prescribed burning in the Southeast, which results in less $PM_{2.5}$ per area burned than the western wildfires. Note also the relatively calm wildfire season in 2004.

Figure 3. (A) Average yearly $PM_{2.5}$ emission density. (B) Average monthly $PM_{2.5}$ emissions by state.

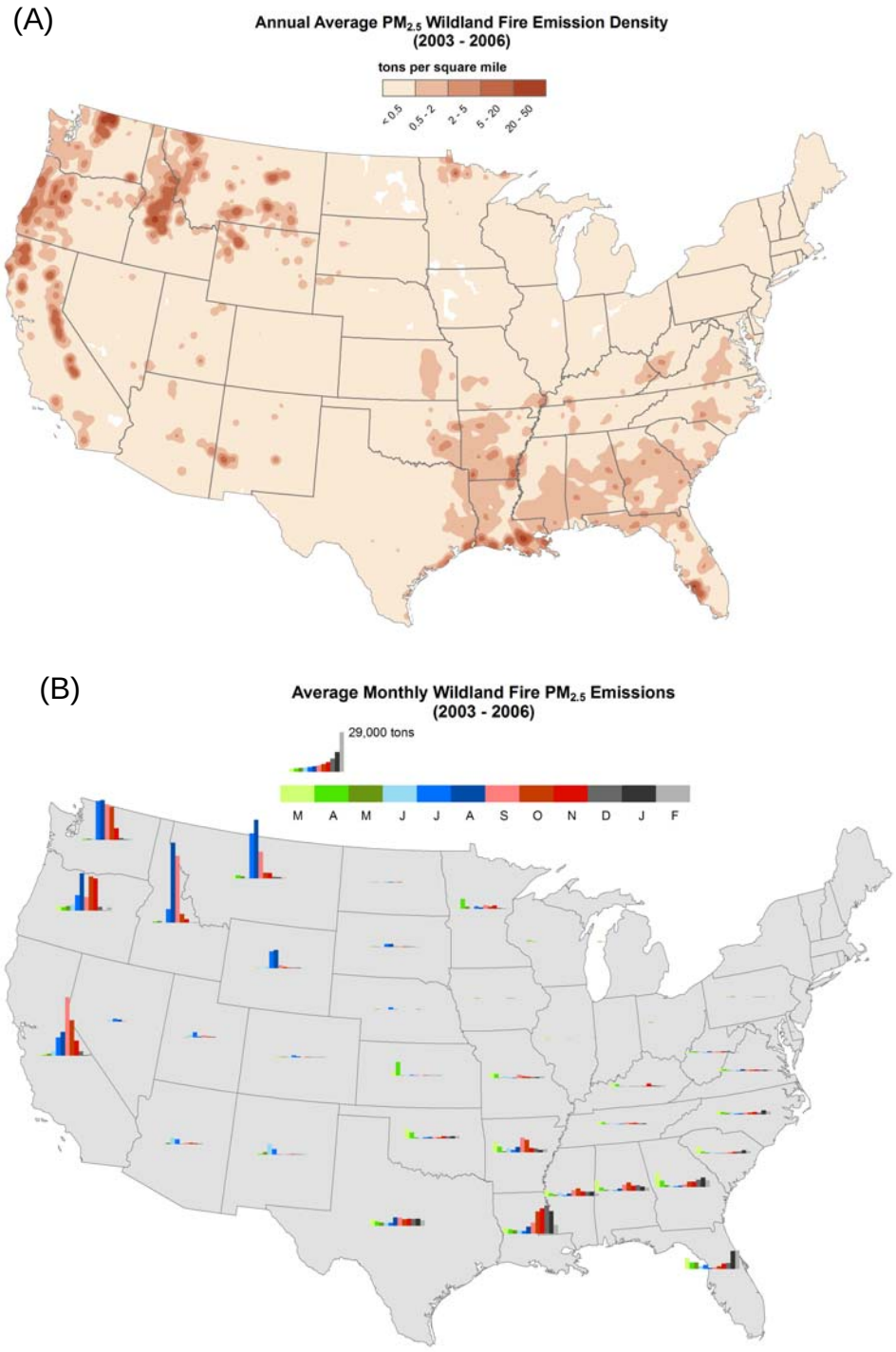
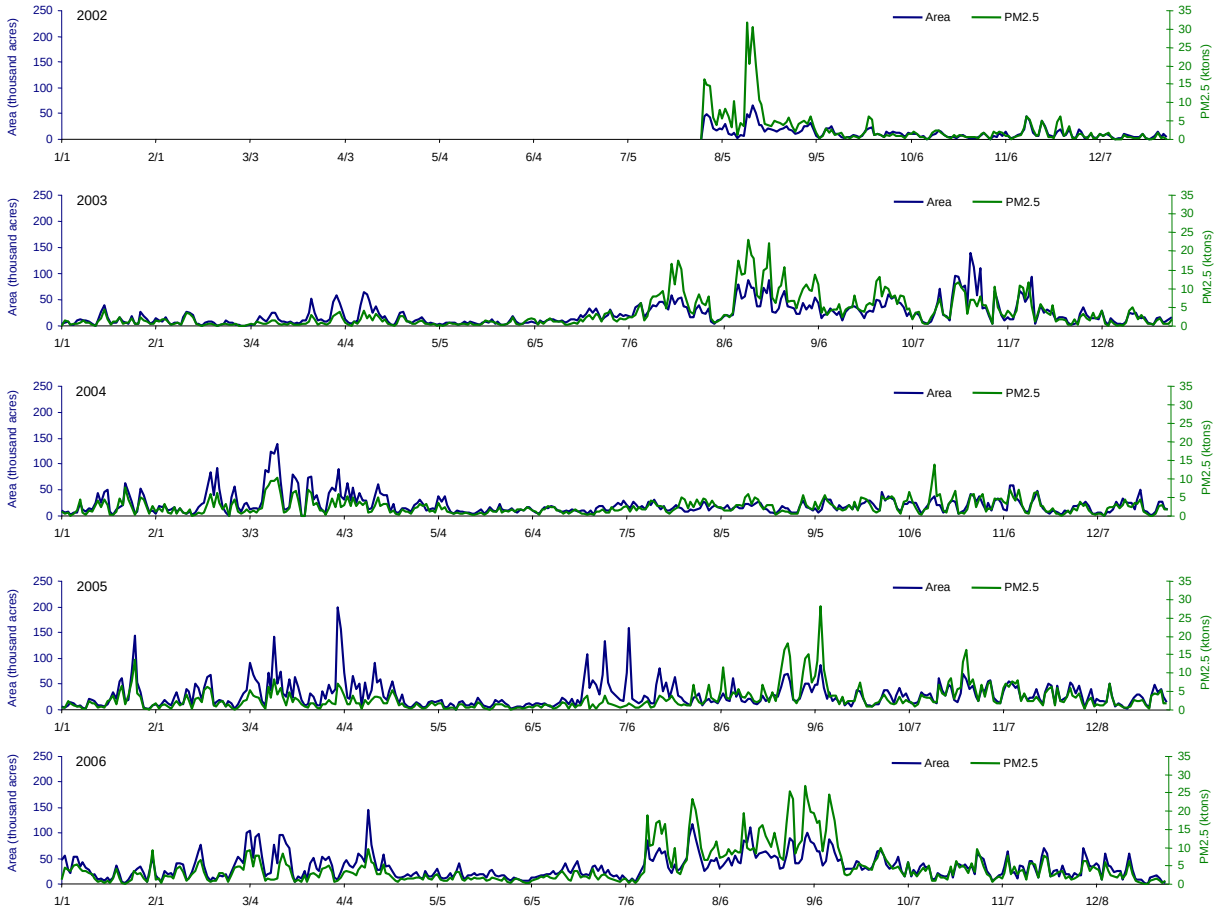


Figure 4. Daily area burned and $PM_{2.5}$ emitted (August 2002 through December 2006).



Fire Information Source Comparison

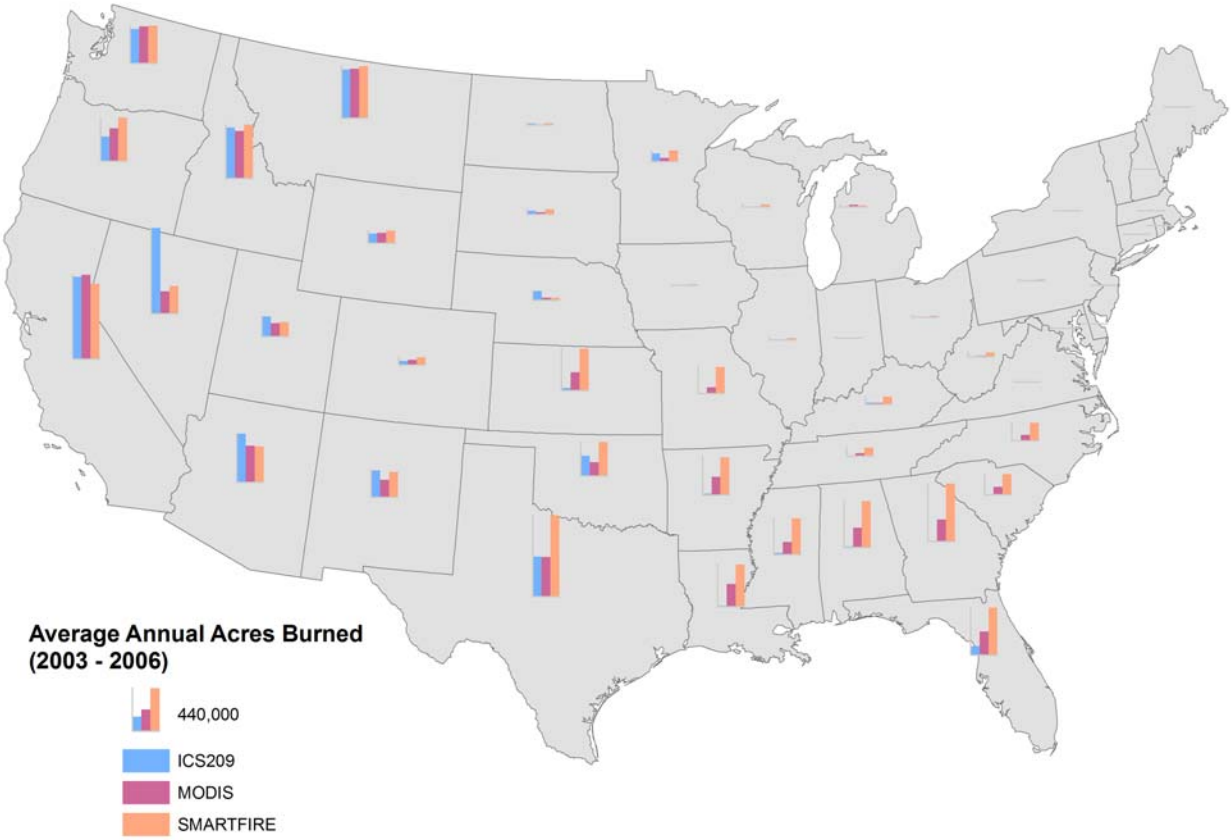
Emissions for 2003-2006 were modeled using two other information sources to compare with SMARTFIRE, ICS-209 reports, and MODIS fire detects. Neither of these data sets is independent from SMARTFIRE because both are used as inputs to the SMARTFIRE algorithm, so this is not a validation. Rather, it is an intercomparison.

Figure 5 shows the annual average area burned by state for the three fire information sources. In the West, the totals are similar for all three data sources, with the exception of Nevada, where the ICS-209 value is much larger than the others. The large ICS-209 value is caused by a typographical error in a single daily report: an extra zero was added to the area of a large wildfire. The error was corrected on subsequent daily reports, but highlights the type of errors that occur in the ICS-209 data, which are created by human data entry.

Note that total burned area in the West is dominated by wildfires, which is captured well both by ground reports (ICS-209s) and satellite (MODIS). SMARTFIRE combines both ground reports and satellite data, but seems to be successfully avoiding double counting. The fires in the southeastern United States are largely prescribed burning. ICS-209 reports are not created for the vast majority of prescribed burns, so that data set reports little acreage in the southeastern

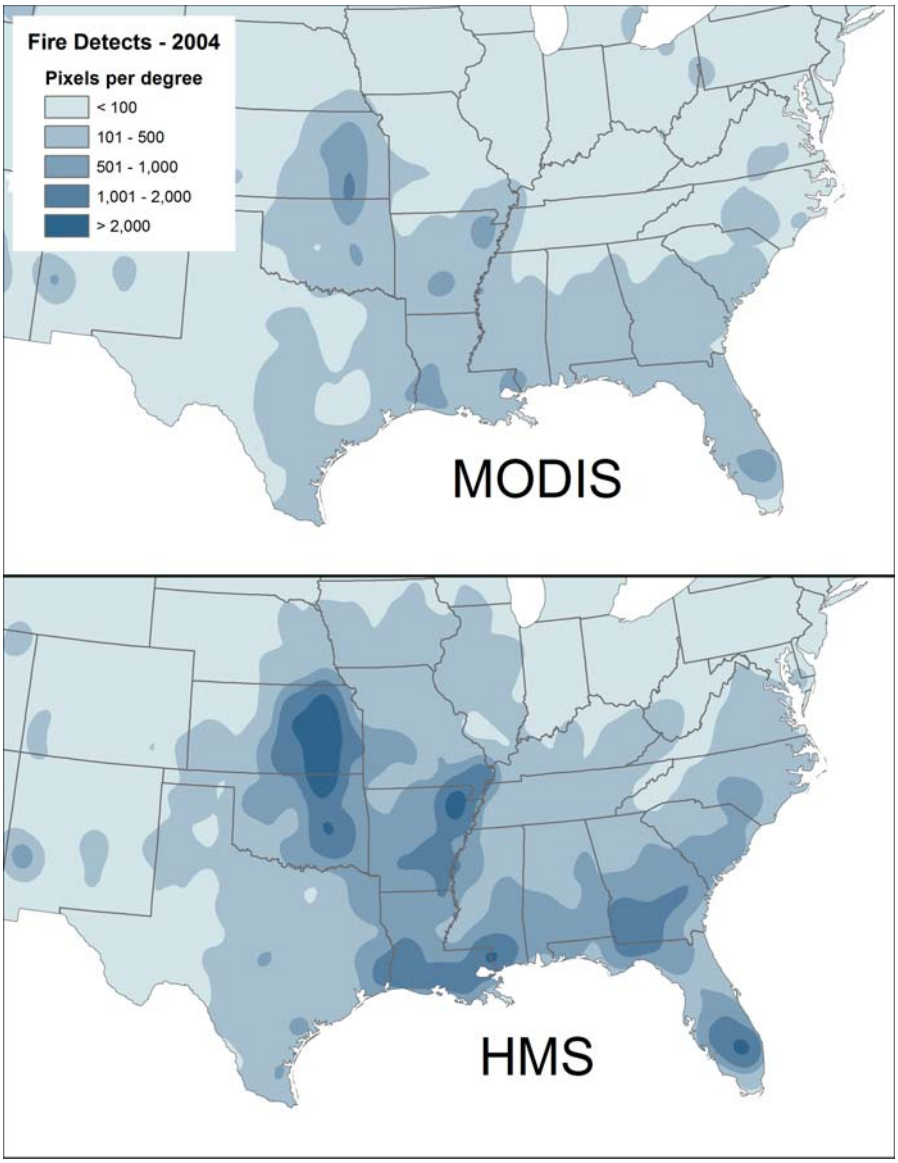
states. Both MODIS and SMARTFIRE report area burned for the Southeast, but SMARTFIRE estimates over twice the total area throughout the region.

Figure 5. Annual average area burned by state for ICS-209 reports, MODIS fire detects, and SMARTFIRE.



The primary reason for the differences between MODIS and SMARTFIRE in the Southeast is shown in Figure 6. SMARTFIRE uses NOAA HMS as its source of satellite-derived fire detects. HMS gathers fire detects from several instruments, including MODIS. Although MODIS is the most sensitive and sophisticated instrument that HMS relies on for fire information, MODIS data are typically only available twice per day over the lower 48 states. Thus, small, short-lived fires, burning during cloudy conditions (such as many prescribed fires in the southeastern US) are easily missed by the MODIS instrument. HMS incorporates fire detects from GOES and AVHRR in addition to MODIS. GOES in particular is useful for detecting these short-lived fires because, as a geostationary instrument, it detects fire every 30 minutes. Figure 6 shows the density of fire hot-spot pixels detected by MODIS and HMS for 2004 in the Southeast.

Figure 6. Fire pixel hot-spot density for MODIS and HMS for 2004.

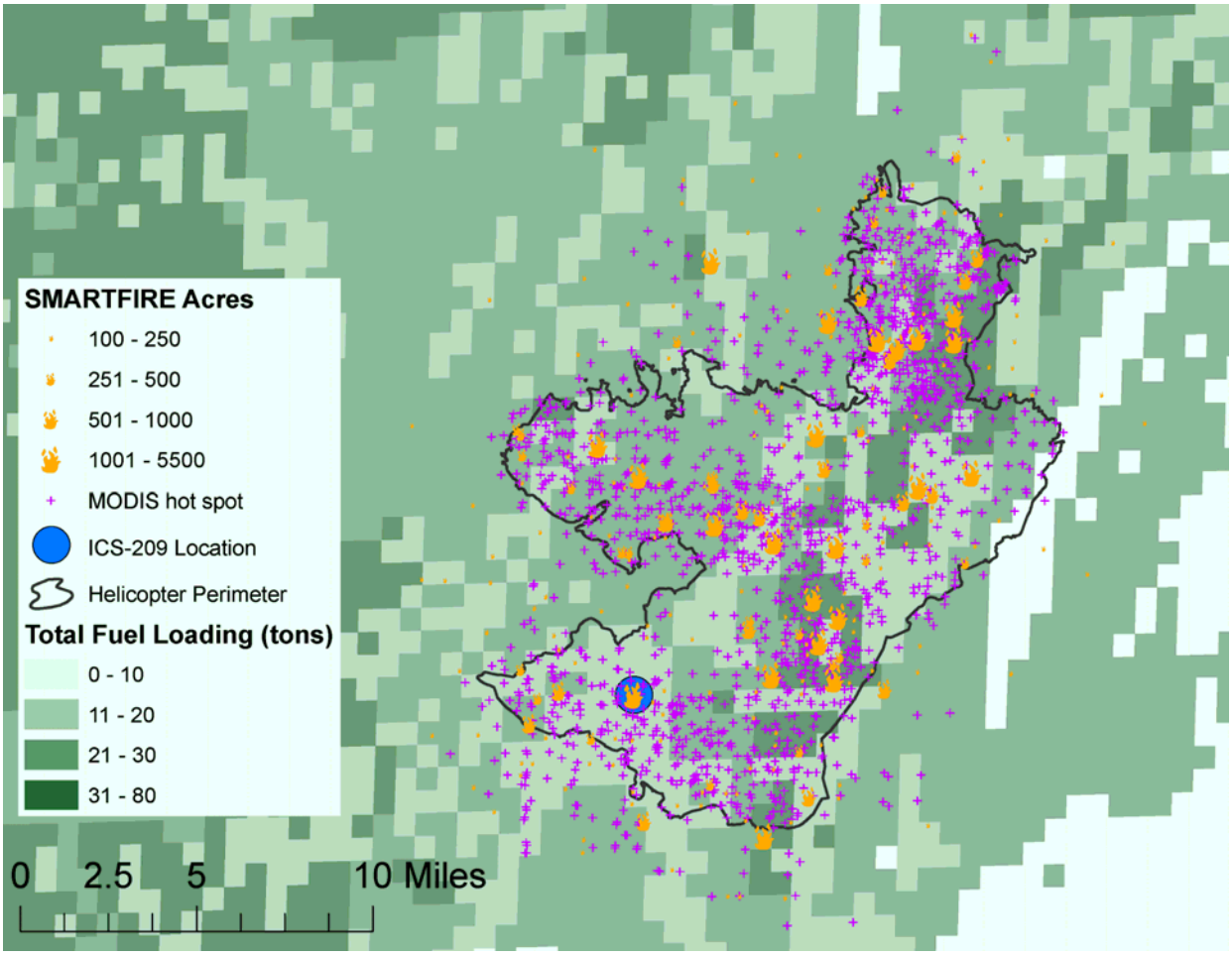


Another key advantage of HMS over other satellite-derived data products is the human quality control that is applied to the data set. The results of this can be seen in Figure 6. Certain very hot industrial sources often result in false positives in fire detection algorithms. The standard MODIS product, for example, often shows fires in Detroit, Michigan; Cleveland, Ohio; and the northern tip of West Virginia, which are known industrial sources. These false fires are not as common in the HMS data.

For large fires, the spatial resolution of satellite data is finer than most ground reporting systems. For example, an ICS-209 report describes the location of a fire of any size by a single latitude/longitude pair that represents the ignition point of the fire. Large fires are often detected as a large number of satellite pixels, which can lead to more refined emission estimates. Figure 7 shows the B&B Complex fire, which burned in Oregon in 2003, as detected by several sources.

The black outline is the final perimeter of the fire as determined by helicopter over-flights after the fire had stopped growing. The MODIS hot-spot fire pixels and SMARTFIRE fire points for the entire time period of the fire are plotted along with the ICS-209 report location. Although the final fire perimeter is over 20 miles wide, the ICS-209 location is only reported as the ignition point. For modeling emissions, this means that the fuel loading, and subsequent consumption and emissions, does not vary throughout the life of the fire. The background of Figure 7 shows the total fuel loading from the FCCS fuel map. The fire ignited in a region of relatively low fuel loading, but then spread to areas with heavier fuel loadings. The satellite-based data are able to capture and model that difference. In the case of the B&B Complex fire, the modeled emissions from SMARTFIRE are about four times greater than the emissions using ICS-209s only, despite a similar estimate in the total area burned.

Figure 7. B&B Complex fire, Oregon, 2003.



CONCLUSIONS

The BlueSky framework was used to produce wildland fire emission inventories for the conterminous United States for August 2002 to December 2006 using SMARTFIRE as the fire

information source and the most recent models for emission processing (FCCS, Consume 3.0, and FEPS). The emission inventory processing for 2003-2006 was repeated using ICS-209 reports as the fire information source and repeated again using MODIS fire detection hot spots.

All fire information sources produce similar estimates of area burned in the wildfire-driven western United States. In the southeastern United States, which has significant prescribed burning, ICS-209 reports provide little information on area burned. SMARTFIRE reports more burning than MODIS because it incorporates information from more satellite instruments, particularly the GOES satellites, which are able to detect many short-lived fires that MODIS may miss. Previous emission inventory work has treated prescribed burning as an area source, with county-level spatial resolution and monthly temporal resolution. Satellite data may provide a more accurate spatio-temporal pattern, but more analysis of the detection rates for different instruments is warranted.

For specific fires, emission estimates may be very different between the different fire information sources even if the area burned estimates are similar. This is because ICS-209 reports only report the ignition point of the fire and the fuel loading at that point may be very different from the areas that the fire eventually burns into. Individual fire burned area estimates are still difficult to pin down, but SMARTFIRE appears better than ICS-209 reports or MODIS fire detects alone.

There is significant spatio-temporal variability in wildland fire emissions, and especially wildfires. An annual emission inventory needs to be year-, day-, and location-specific to accurately account for these emissions. Using one year's emissions for another year may result in poor emission estimates for modeling purposes.

REFERENCES

Andreae M.O. and Merlet P. (2001) Emission of trace gases and aerosols from biomass burning. *Global Biogeochem. Cycles* **15** (4), 955-966.

Dozier J. (1981) A method for satellite identification of surface temperature fields of subpixel resolution. *Remote Sensing of Environment* **11** (3), 221-229.

Galanter M., Levy H., and Carmichael G.R. (2000) Impacts of biomass burning on tropospheric CO, NO_x, and O_3. *J. Geophys. Res.* **105**, 6633-6654 (D5).

Justice C.O., Giglio L., Korontzi S., Owens J., Morisette J.T., Roy D.P., Descloitres J., Alleaume S., Petitcolin F., and Kaufman Y. (2002) The MODIS fire products. *Remote Sensing of Environment* **83**, 244-262.

Kaufman Y.J. and Fraser R.S. (1997) The effect of smoke particles on clouds and climate forcing. *Science* **277**, 1636 (5332).

Kuenzli N., Avol E., Wu J., Gauderman W.J., Rappaport E., Millstein J., Bennion J., McConnell R., Gilliland F.D., and Berhane K. (2006) Health effects of the 2003 southern California wildfire on children. *Am. J. Resp. Crit. Care Med.*, 200604.

Larkin N.K., O'Neill S.M., Solomon R., Krull C., Raffuse S.M., Rorig M., Peterson J., and Ferguson S.A. (2008) The BlueSky smoke modeling framework. *Int. J. Wildland Fire* (in review).

Levine J.S., Cofer W.R., Cahoon D.R., and Winstead E.L. (1995) Biomass burning: a driver for global change. *Environ. Sci. Technol.* **29**, 120A-125A (3).

Li R., Kaufman Y., Hao W., Salmon M., and Gao B. (2004) A technique for detecting burn scars using MODIS data. *IEEE Transactions on Geoscience and Remote Sensing* **42** (6), 1300-1308.

Ruminski M., Kondragunta S., Draxler R.R., and Zeng J. (2006) Recent changes to the Hazard Mapping System. *15th International Emission Inventory Conference, New Orleans, LA.* Available on the Internet at <http://www.epa.gov/ttn/chief/conferences.html>.

Sullivan D.C., Raffuse S.M., Pryden D.A., Craig K.J., Reid S.B., Wheeler N.J.M., Chinkin L.R., Larkin N.K., Solomon R., and Strand T. (2008): Development and applications of systems for modeling emissions and smoke from fires: the BlueSky smoke modeling framework and SMARTFIRE: *17th International Emissions Inventory Conference, Portland, OR, June 2-5*.

van der Werf G.R., Randerson J.T., Giglio L., Collatz G.J., Kasibhatla P.S., and Arellano Jr A.F. (2006) Interannual variability in global biomass burning emissions from 1997 to 2004. *Atmos. Chem. Phys* **6**, 3423–3441.

KEY WORDS

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Wildfire
Prescribed fire
Emission inventory
ICS-209
HMS
MODIS