Estimation of Biomass Burning PM2.5 Emissions Using GOES WFABBA Fire Characterization Data

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The WildFire Automated Biomass Burning Algorithm

The need to systematically and reliably generate diurnal biomass burning information led to the development of the Wildfire Automated Biomass Burning Algorithm (WF_ABBA) processing system. With inputs consisting of geostationary satellite data, total precipitable water from numerical forecast models, and an ecosystem map, the WF_ABBA is able to detect and characterize fires in near real-time, providing users such as the National Oceanic and Atmospheric Administration and the hazards community with high temporal and spatial resolution fire data. Current Geostationary Operational Environmental Satellite (GOES) data allows for fire detection at a spatial resolution of 4 km, and the WF_ABBA runs every half-hour for both GOES-12 and GOES-10, detecting fires within a satellite zenith angle of 80° (covering the better part of the visible hemisphere). The WF_ABBA algorithm can be extended to any geostationary satellite platform that possesses 3.9 µm and ~11 µm bands which meet certain requirements (ex: high saturation temperatures, good band-to-band co-registration, etc…).

A Brief Primer on Satellite Fire Detection

IR fire detection from satellites takes advantage of the fact that as target temperature increases radiance increases faster at the shortwave end of the spectrum as opposed to the longwave end. By using two windows such as the 3.9 µm and 11 µm fire locations and even characteristics can be determined. Algorithms can determine the radiance due to the fire itself, within limits determined by viewing conditions and satellite characteristics. That fire radiance can be split into instantaneous size and temperature via the Dozier method or converted into fire radiated power (FRP). The key to successfully estimating any of those quantities is to have good radiance information, which requires correcting for atmospheric attentuation, accurately estimating the background temperature, and having good instrument performance (such as low NEDT at high temperatures and a sufficiently high saturation temperature). Every recent and currently planned geostationary satellite has the IR bands necessary for fire detection, though some have limited capabilities due to low saturation temperatures and/or Level 1 data processing which distorts point sources such as fires.

Calculating Fire Radiated Power and Fire Radiated Energy (FRE)

(and why we want to know them)

FRE and its time derivative FRP are by definition related to the temperature and size of a fire:

$$FRP = A\,s\,T^4$$

where A is the area burning, s is the Stephan-Boltzman Constant, and T is the temperature of the fire. The typical unit of FRP is Watts (J/s) and FRE is Joules. For a given material one may assert that the total FRE of a fire is directly related to mass consumed by that material's heat of combustion, which can then be related to PM2.5 and other emissions. Geostationary satellites allow for observations of sufficient frequency to calculate upwardly emitted FRE from satellite-derived FRP. There are two approaches to calculate FRP: use the above definition with the Dozier-estimated instantaneous A and T, or use an approximation such as the relationship:

$$L_4 = aT^4$$

where L_4 is the radiance at ~4 µm, a is a curve-fitting constant, and T is the fire temperature. This relationship is only valid for 600K < T < 1400 K and fires are assumed to emit as gray-bodies. The "radiance method" FRP looks like:

$$FRP = A_{pixel}\,s\,(L_{4,fire} - L_{4,background})/a$$

Which utilizes the aforementioned difference between the fire pixel and the background radiances. A_{pixel} is the area of the satellite pixel.

Typically emissions from fires for an individual species (i) is calculated through the relationship:

$$Emission_i = A_{burned} * B * CE * EF_i$$

where A_{burned} is the area burned, B is the fuel loading in biomass per unit area, CE is the fraction of fuel burned, and EF_i is the emission factor for species i. Combined the terms A_{burned}, B, and CE equal biomass burned (BB):

$$Emission_i = BB * EF_i$$

and BB is proportional to FRE, thus:

$$Emission_{i,k} = ß_k * FRE * Ef_{i,k}$$

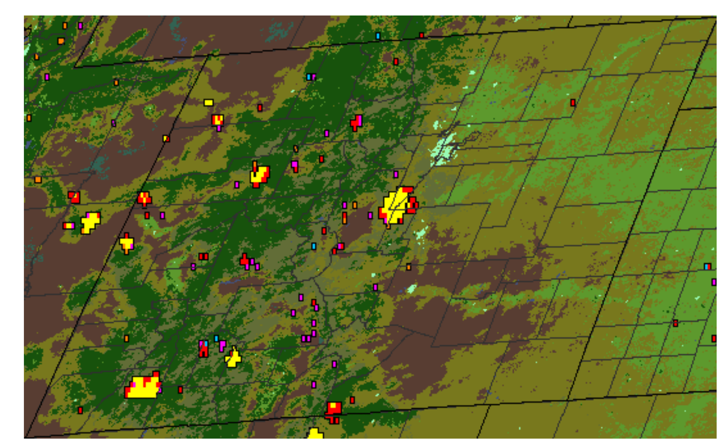
Where $ß_k$ is the constant relating *satellite-detectable* FRE to the heat of combustion of a specific material k. Wooster et al. determined $ß_k$ to be 0.368 for *Miscanthus* and found no evidence to suppose that $ß_k$ varies significantly with vegetation type.

Wooster, M. J., G. Roberts, and G. L. W. Perry, 2005: Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. J. Geo. Res., Vol. 110, D24311, doi:10.1029/2005JD006318

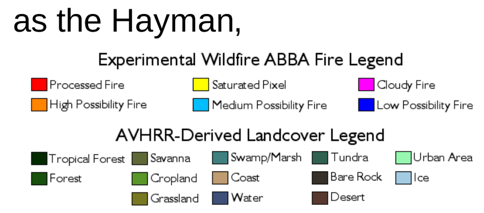
The Hayman Fire: WF_ABBA-derived PM2.5 emissions case study

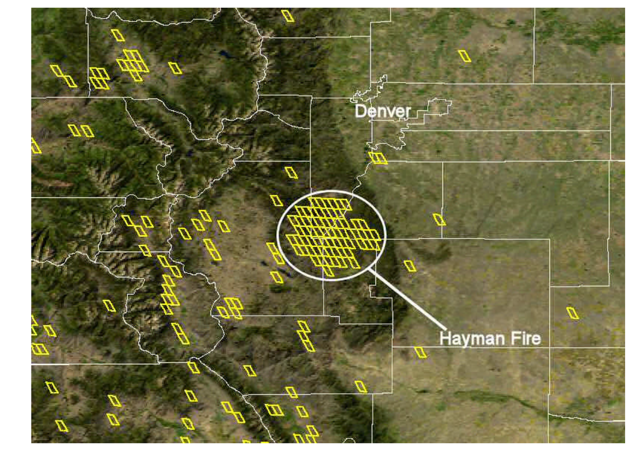
What GOES-8 Saw:

GOES-8 captured the Hayman Fire from within minutes of its reported start time and monitored the entire cycle of the fire. The Hayman was an extreme event both in its costs and the energy output. It saturated the GOES-8 sensor for 43% of the 519 Hayman Fire-related pixels detected between 8 June 2002 and 28 June 2002.



Composite of WF_ABBA pixels for the Hayman Fire 8 June 2002 through 28 June 2002. Processed fires have associated size and temperature estimates. The other fires in the region occurred during the same time period as the Hayman,





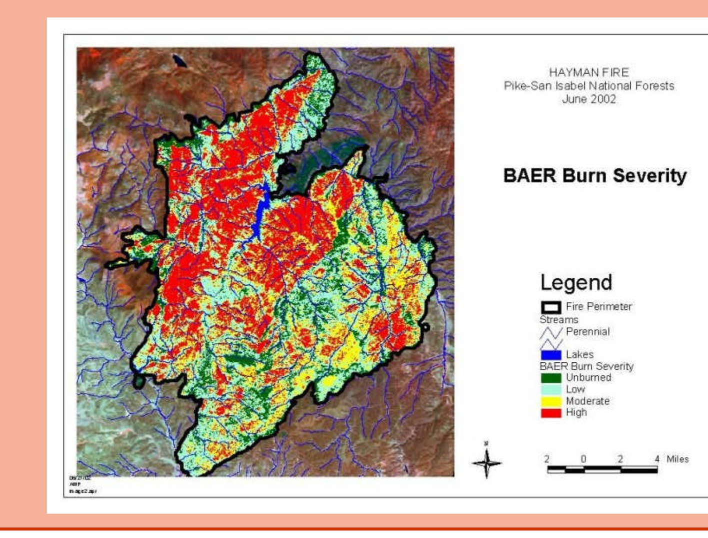
Outlines of fields-of-view for all GOES-8 WF_ABBA pixels during study period. GOES pixels are relatively large at these viewing angles (approx. 35 km² and 55° satellite zenith angle)

Background: MODIS Blue Marble.

Quick Facts on the Hayman Fire

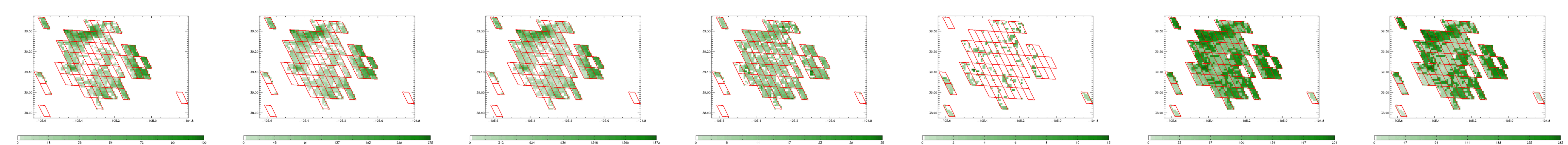
(data and image credit: http://www.fs.fed.us/r2/psicc/hayres/index.htm)

Location: North of Lake George (Park, Jefferson, Douglas and Teller Counties)
Date of Origin: 6/8/02, reported at 4 PM MDT
Human Caused
Size: 137,760 acres; **Contained**: 7/2/2002;
Controlled: 7/18/2002
Cost to Date: $39,100,000



Fuel Loads Within the Hayman Fire Region: A Challenge for Emissions Estimates

The MODIS LAI fuel load database from NESDIS contains fuel loads for 7 different fuel types at 1 km resolution. A methodology of identifying fuel load values within the GOES fields-of-view was applied to the Hayman Fire region. Each pixel shows variation in fuel loading (some of which is due to the Hayman itself as the database includes MODIS LAI data from after the fire). Since emissions and fuel loading are linearly related choosing the wrong loading can be a large source of error.

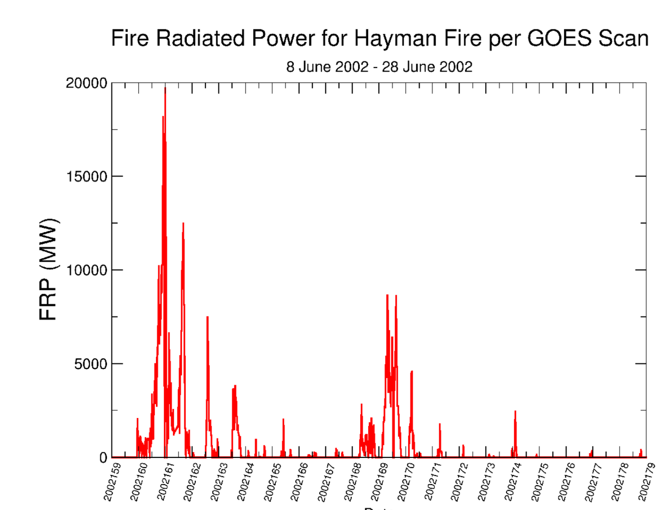


Tree leaf biomass (g/m²) | Tree branch (wood and bark) (g/m²) | Above ground tree mass (g/m²) | Total shrub mass (g/m²) | Grass mass (g/m²) | Litter (g/m²) | Coarse woody debris (g/m²)

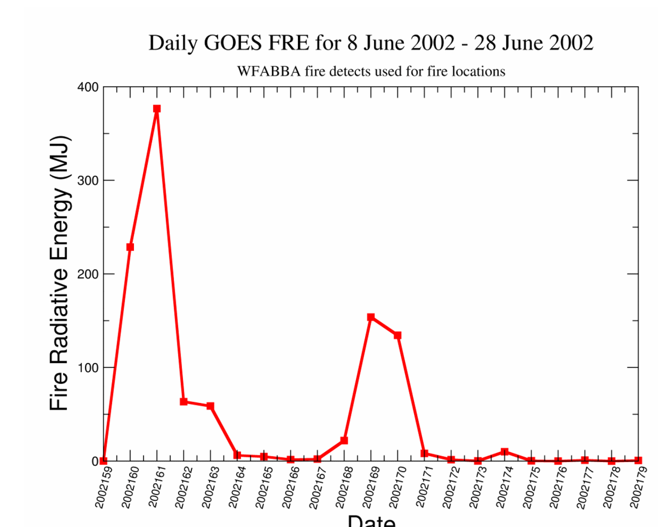
Emissions with FRP/FRE

Calculating FRP with WF_ABBA data

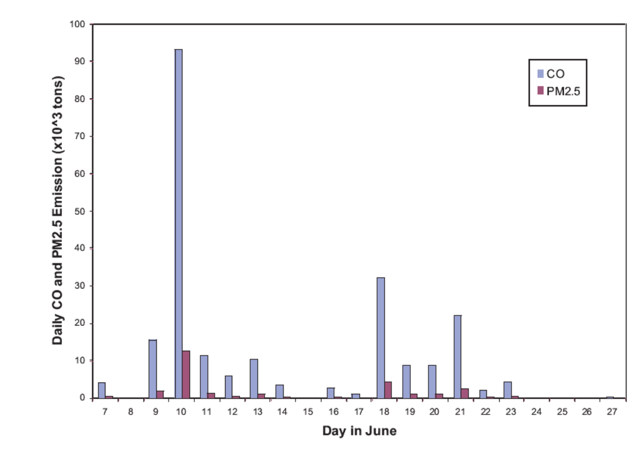
The data and metadata from WF_ABBA runs dating back to 1 January 2000 allow the calculation of FRP using both equations presented to the left. The radiance method can be applied to every fire, whereas the definition of FRP only works for processed fires (28% of the Hayman fire pixels). To fill in the gaps the cases without Dozier characteristics were handled with the radiance method. For saturated fires this meant that the FRP would likely be underestimated, perhaps quite substantially. As evidenced below, saturated pixels were abundant during this fire episode.



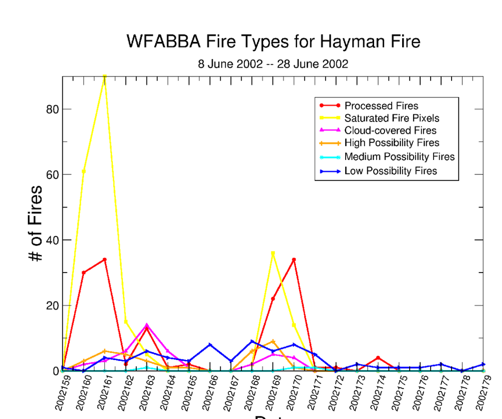
Estimated GOES WF_ABBA FRP for each GOES scan (half-hourly, 48 per day).



Daily FRE (time-integrated FRP)
FRE trend generally matches emissions trend from BAER report



BAER report emissions data (USFS Gen. Tech. Rep. RMRS-GTR-114.2003, p. 147, image credit Wei Min Hao). Derived from MODIS burned area maps and additional data.



Total PM2.5 Emissions Estimates:	
GOES WF_ABBA FRE (assumed ß=0.368, EF_i=16 g/kg):	**7,400 tons**
BAER Report:	**29,400 tons**

Potential Error Sources:
1) Large number of saturated pixels guaranteed an underestimate
2) Adjustments for atmosphere and background can have errors
3) Some fires missed due to clouds
4) Incorrect assumptions on ß and Ef_i

Future work:
FRP shows promise for emissions estimates, however much validation needs to be done. Requirements for future platforms should aim to minimize the number of saturated pixels as they make fire characterization, and therefore emissions work, more difficult.

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