AOS274, 'Atmospheric Chemistry, Radiation and Climate', UCLA, June 4, 2012

Remote Sensing Methods to Estimate Wildfire Emissions

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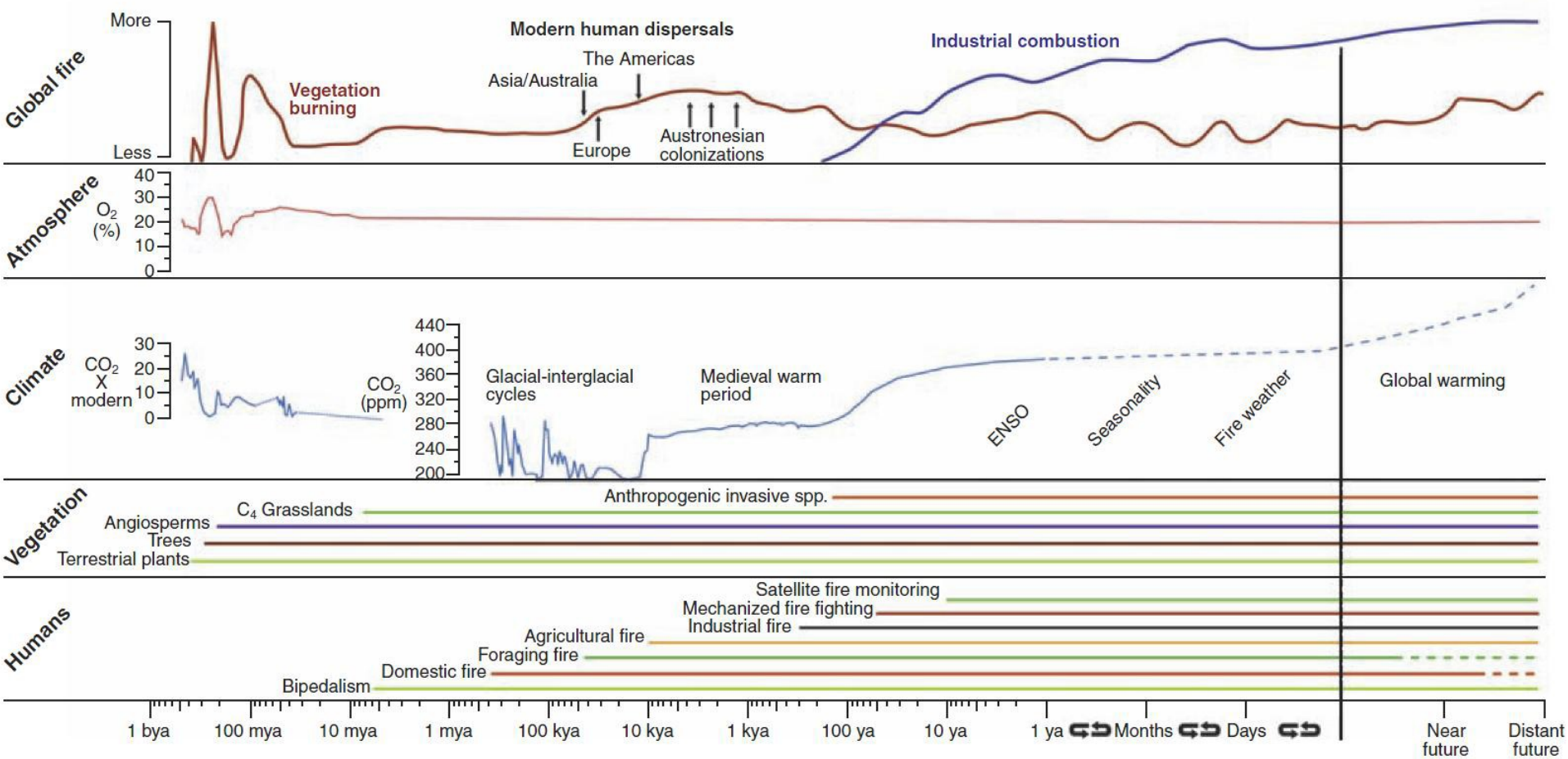
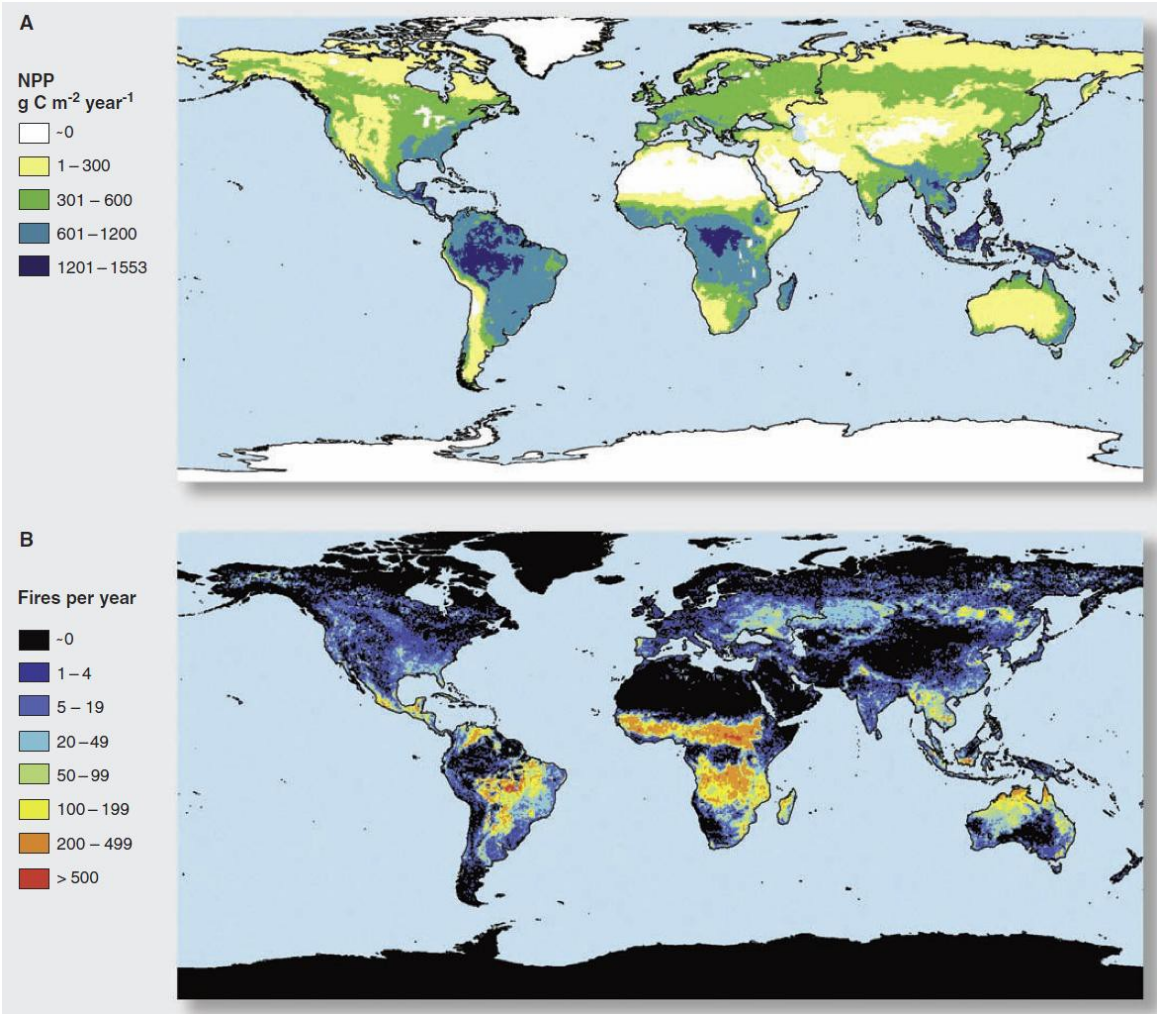
Humans and Fire



(Bowman et al. 2009)

Fire in the Earth System

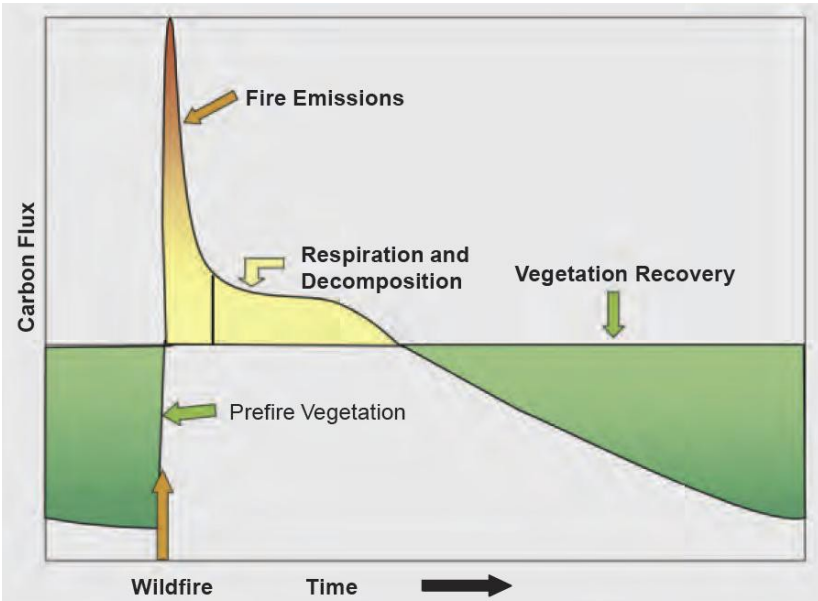


(Bowman et al. 2009)

Carbon emissions from wildfires account for 20-40 % of the total global carbon emissions (van der Werf et al. 2010)

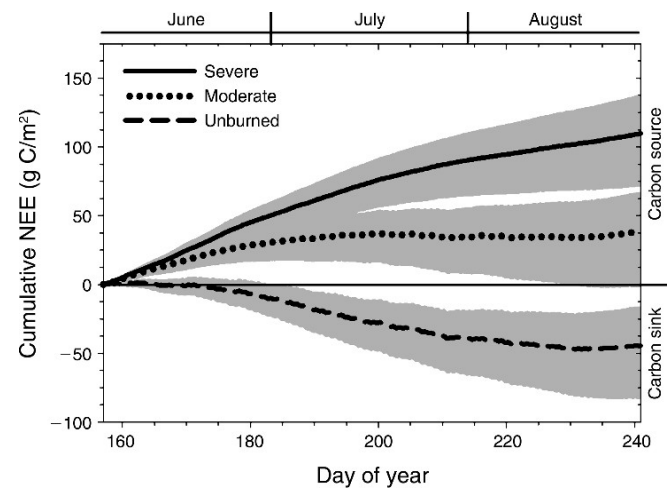
Uncertainties in wildfire emission estimates are large

Net Carbon Balance



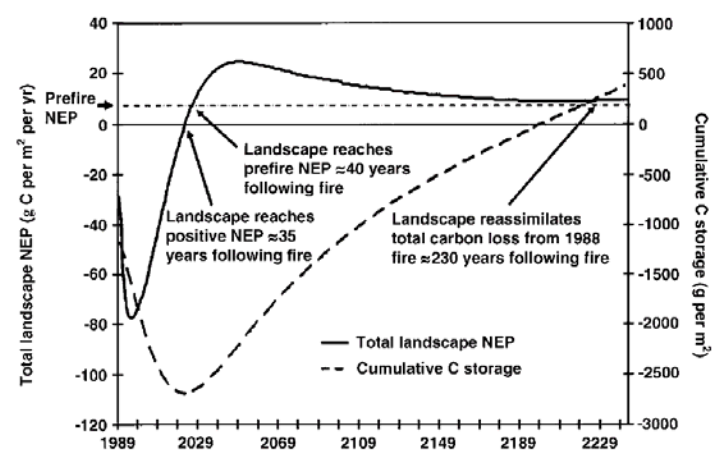
(Conard and Solomon 2009)

Short-term



(Rocha and Shaver 2011)

Long-term



(Conard and Solomon 2009)

Net Effect on Global Warming?

How does the surface albedo change?

(Veraverbeke et al. 2012)

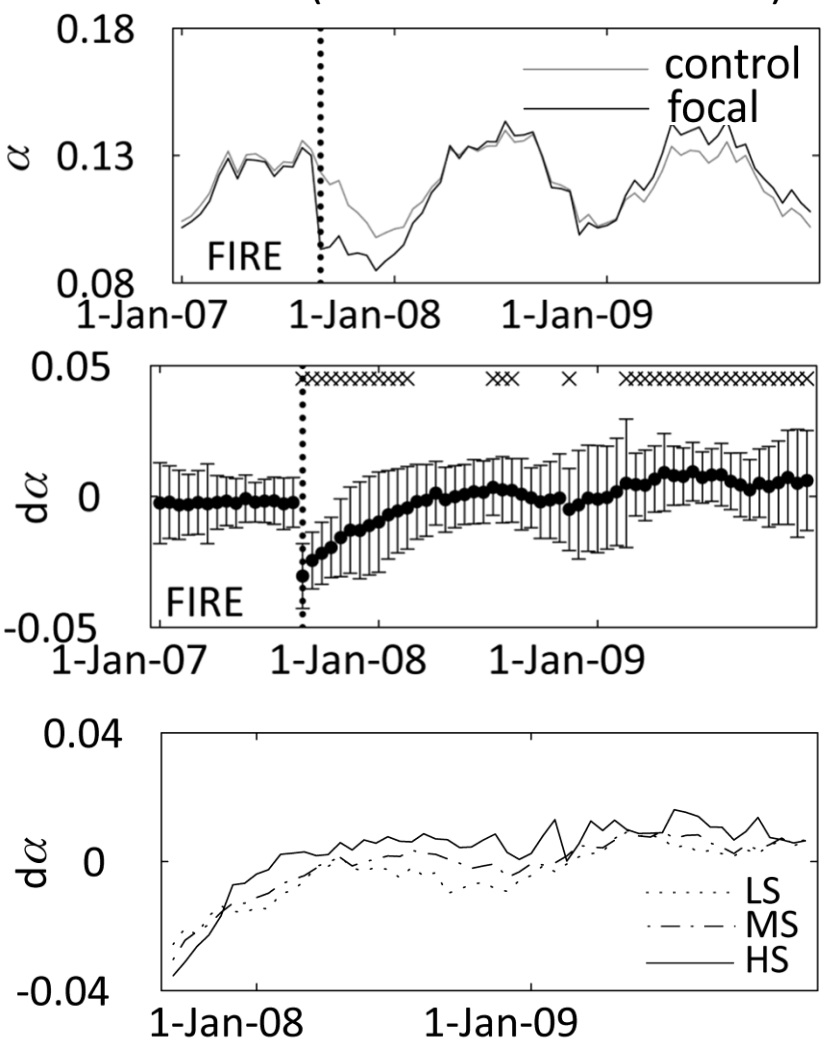
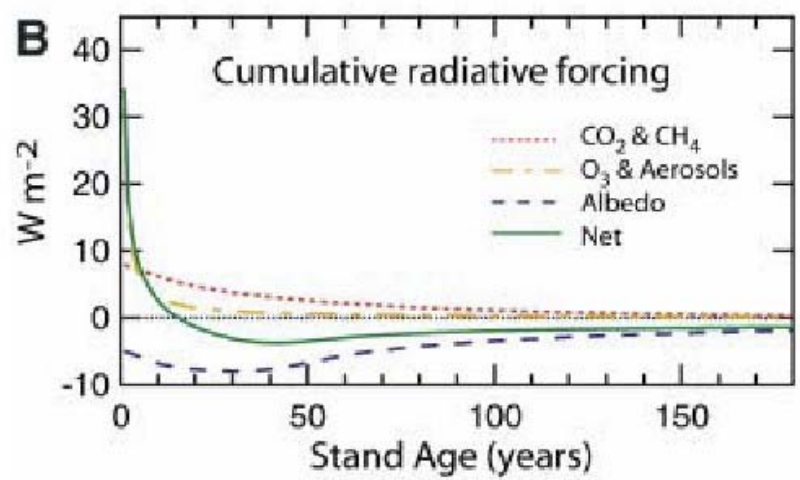


Table 1. Radiative forcing associated with the Donnelly Flats fire.

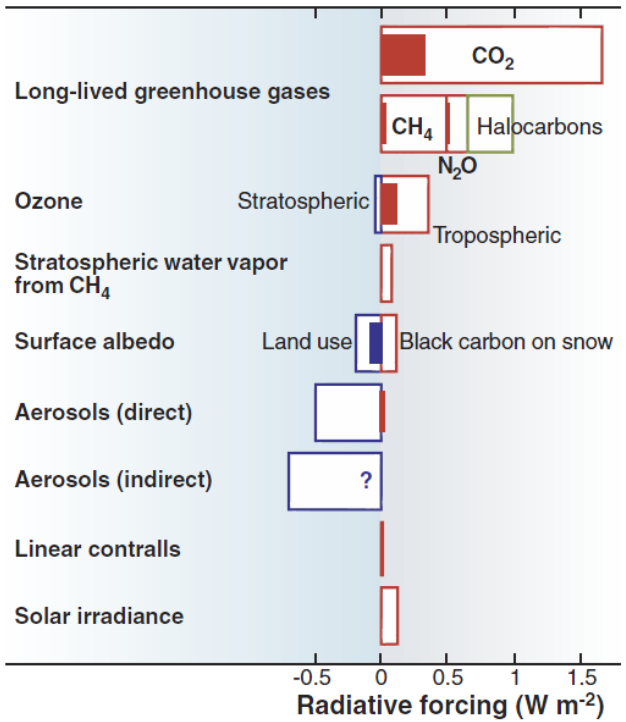
Forcing agent	Radiative forcing* [W (m^2 burned)$^{-1}$]	
	Year 1	Years 0 to 80 (mean)
Long-lived greenhouse gases (CH_4 and CO_2)	8 ± 3	1.6 ± 0.8
Ozone	6 ± 4	0.1 ± 0.1
Black carbon deposition on snow	3 ± 3	0.0 ± 0.0
Black carbon deposition on sea ice	5 ± 4	0.1 ± 0.1
Aerosols (direct radiative forcing)†	17 ± 30	0.2 ± 0.4
Impact at the surface: −90 W ± 35 m^{-2}		
Changes in post-fire surface albedo	−5 ± 2	−4.2 ± 2.0
Total‡	34 ± 31	−2.3 ± 2.2

Short-term ⟷ Long-term

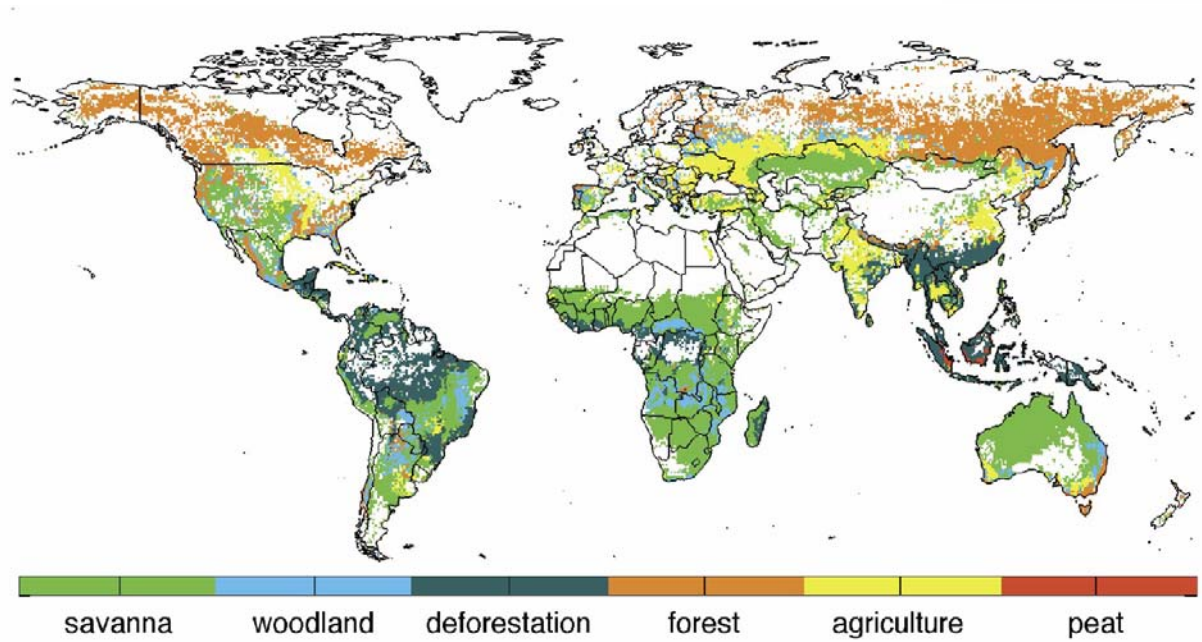
(Randerson et al. 2006)



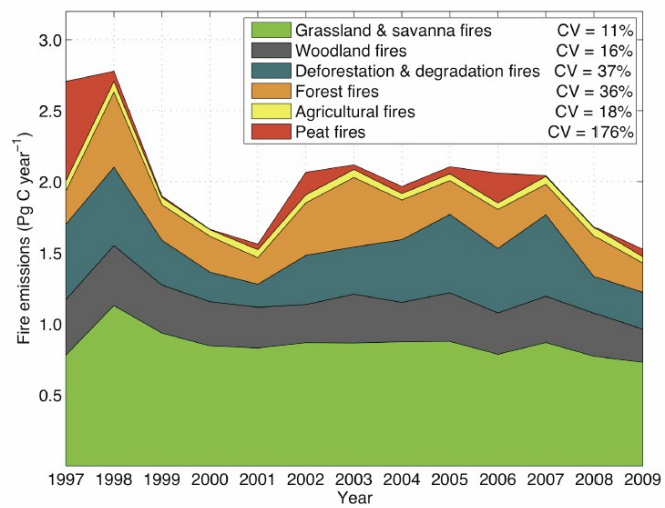
Role of Deforestation Fires



(Bowman et al. 2009)



(van der Werf et al. 2010)



Wildfire Emission Estimates: 2 Approaches

1) Bottom-up approach

Emission = *Burned area X Fuel load X Combustion completeness X Emission factor*

Remote sensing for estimation of burned area, fuel load and combustion factor

Traditional approach (since Seiler and Crutzen 1980), heavily used

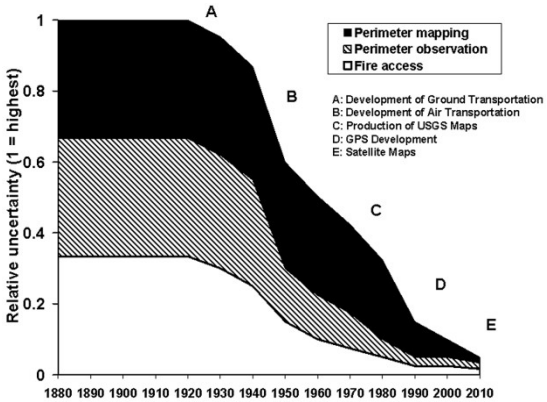
2) Top-down approach

Based on the measurement of the Fire Radiative Power from thermal imagery

More recent method (since Kaufman et al. 1998)

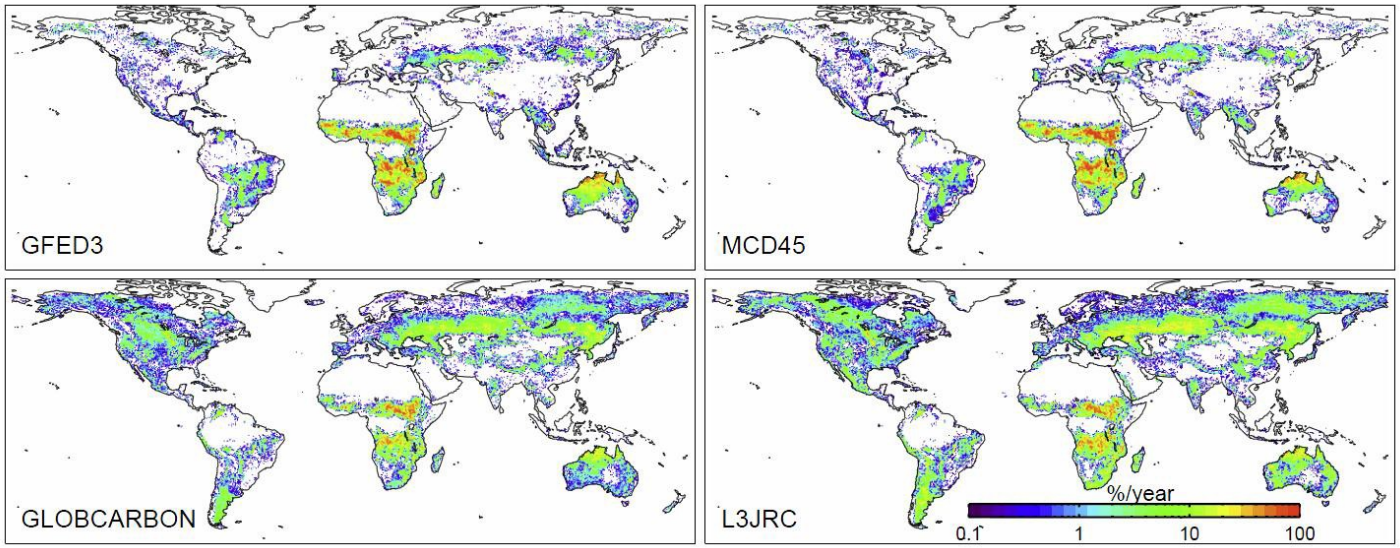
Bottom-up Approach: Burned Area

By far the most accurately mapped factor in the equation



(Kasischke et al. 2011)

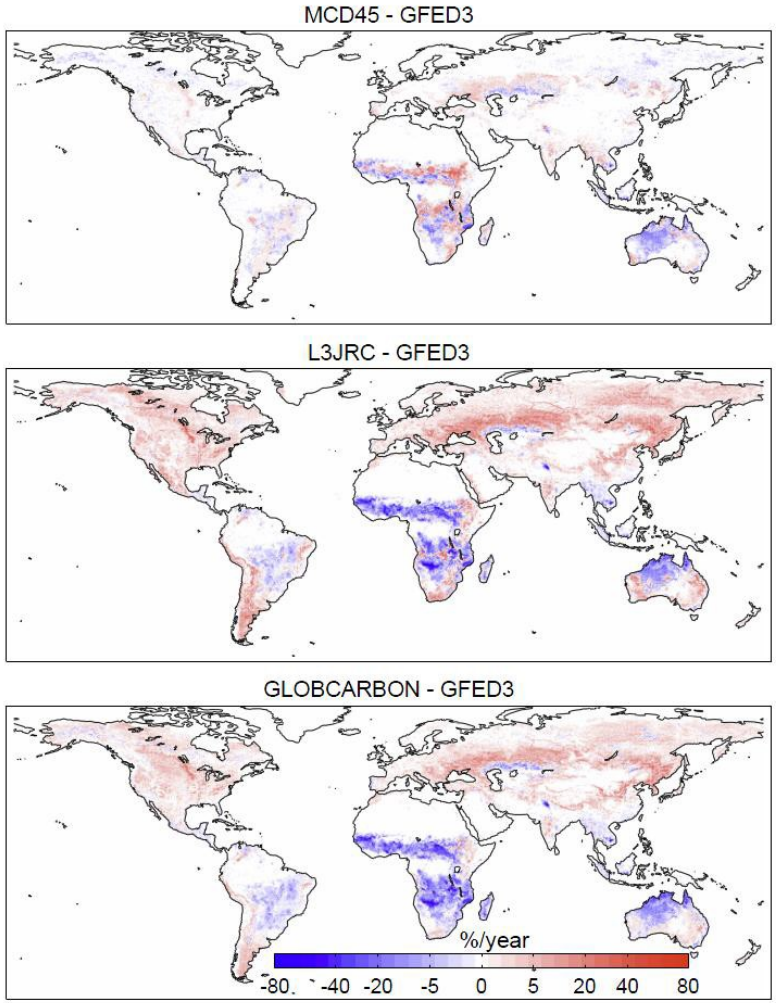
Several global remote sensing products available



(Giglio et al. 2010)

Bottom-up Approach: Burned Area

But still large discrepancies (up to 100 %) between the different products



(Giglio et al. 2010)

Bottom-up Approach: Fuel Load

The biomass or Fuel Load term represents all organic matter present at a site

The total Fuel Load at a given site is the sum of its composing parts

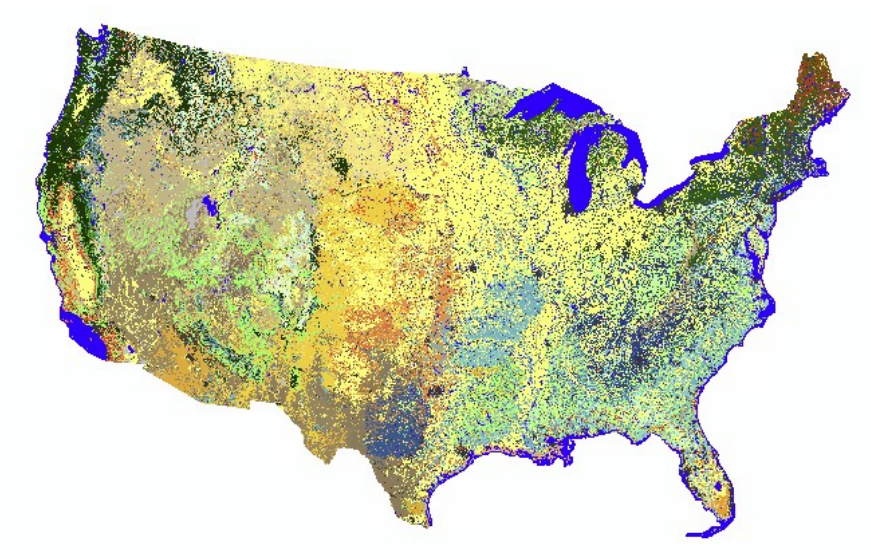
Stratum	Category
CANOPY	Trees, snags, ladder fuels
SHRUBS	Primary and secondary layers
NONWOODY VEGETATION	Primary and secondary layers
WOODY FUELS	All wood, sound wood, rotten wood, stumps, and woody fuel accumulations
LITTER-LICHEN-MOSS	Litter, lichen, and moss layers
GROUND FUELS	Duff, basal accumulations, and squirrel middens

Prichard et al. 2011

Derived from mapped vegetation or process modeling using satellite input

Bottom-up Approach: Fuel Load

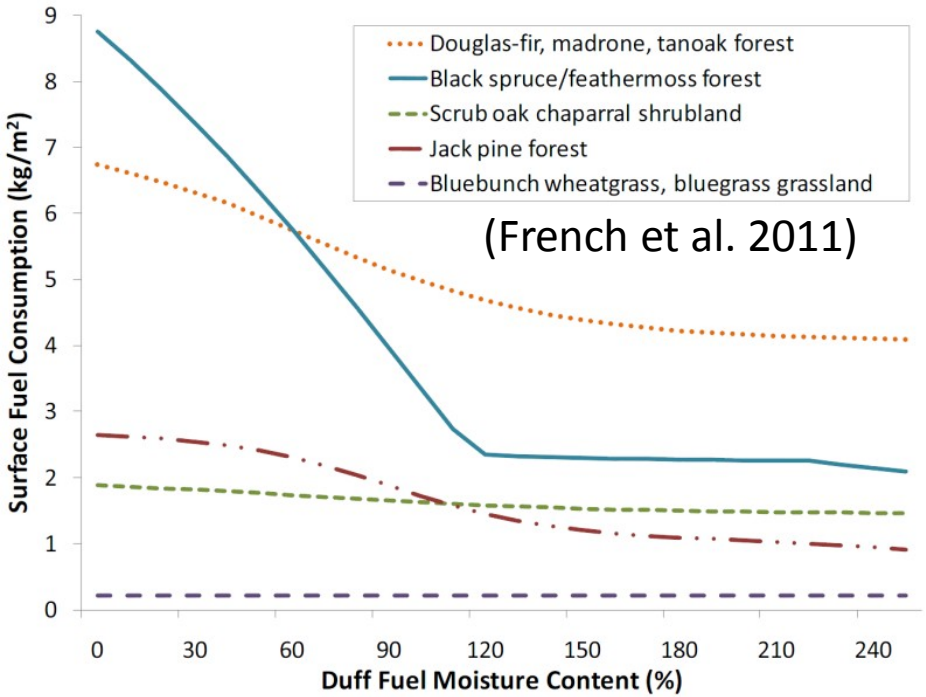
Available for the US: the Fuel Characteristic Classification System (Ottmar et al. 2007)



Bottom-up Approach: Combustion Completeness

Combustion completeness (= combustion factor = biomass consumption) is the amount of biomass consumed by the fire

Modeled based on fuel type and fuel moisture content



Available for the US: Consume, can be linked to the FCCS (Ottmar et al. 2006)

Highly uncertain factor

Bottom-up Approach: Emission factor

Emission factor for C = 0.45-0.5

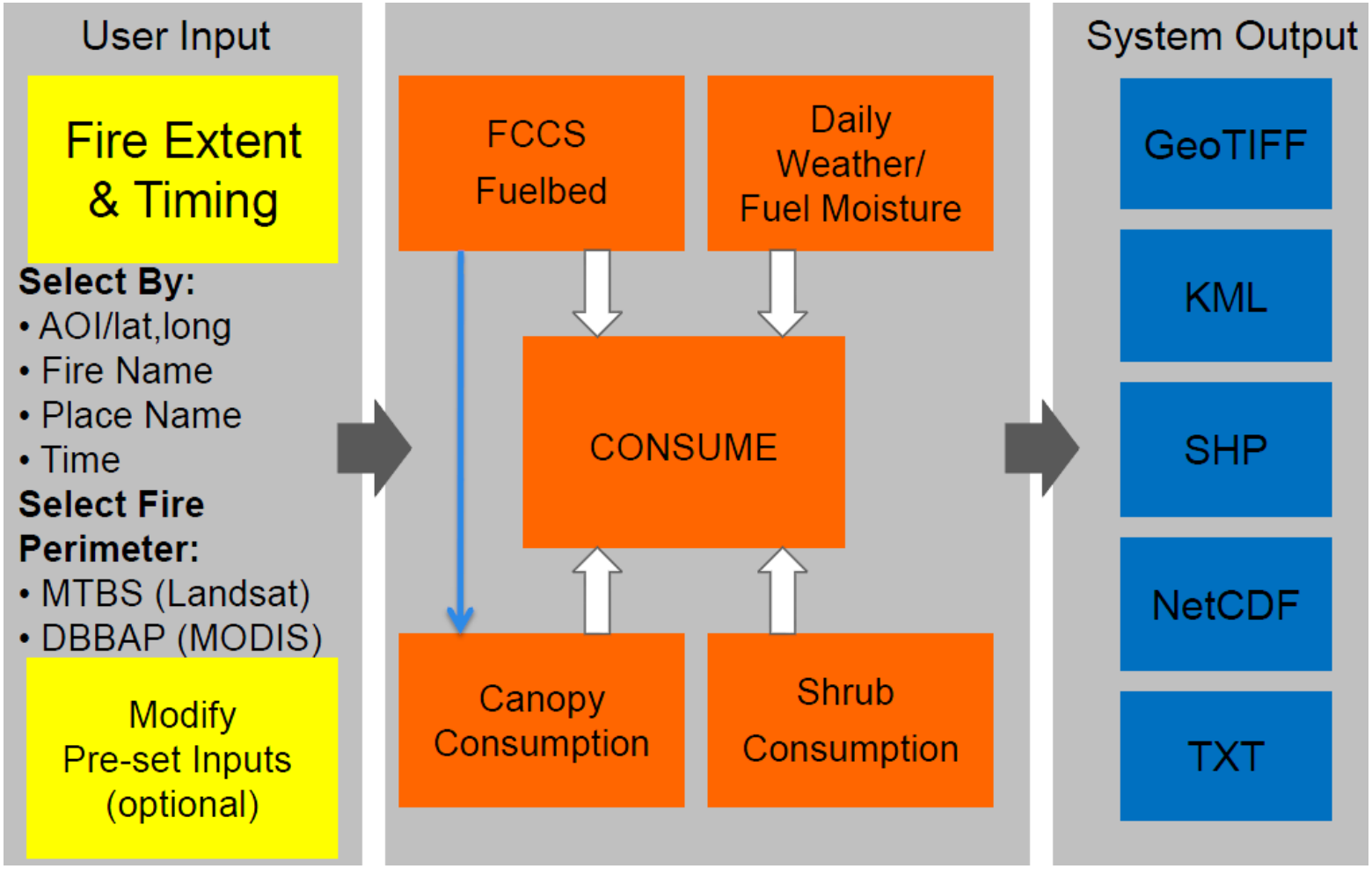
Emission factors of most pyrogenic species are known (Andreae and Merlet 2001)

Table 1. Emission Factors for Pyrogenic Species Emitted From Various Types of Biomass Burning[a]

Species	Savanna and Grassland[b]	Tropical Forest[c]	Extratropical Forest[d]	Biofuel Burning[e]	Charcoal Making[f]	Charcoal Burning[f]	Agricultural Residues[i]
CO_2	1613 ± 95	1580 ± 90	1569 ± 131	1550 ± 95	440	2611 ± 241	1515 ± 177
CO	65 ± 20	104 ± 20	107 ± 37	78 ± 31	70	200 ± 38	92 ± 84
CH_4	2.3 ± 0.9	6.8 ± 2.0	4.7 ± 1.9	6.1 ± 2.2	10.7	6.2 ± 3.3	2.7
Total nonmethane hydrocarbons	3.4 ± 1.0	8.1 ± 3.0	5.7 ± 4.6	7.3 ± 4.7	2.0	2.7 ± 1.9	(7.0)[h]
C_2H_2	0.29 ± 0.27	0.21–0.59	0.27 ± 0.09	0.51–0.90	0.04	0.05–0.13	(0.36)[h]
C_2H_4	0.79 ± 0.56	1.0–2.9	1.12 ± 0.55	1.8 ± 0.6	0.10	0.46 ± 0.33	(1.4)[h]
C_2H_6	0.32 ± 0.16	0.5–1.9	0.60 ± 0.15	1.2 ± 0.6	0.10	0.53 ± 0.48	(0.97)[h]
C_3H_4	0.022 ± 0.014	0.013	0.04–0.06	(0.024)[h]	–	(0.06)[h]	(0.032)[h]
C_3H_6	0.26 ± 0.14	0.55	0.59 ± 0.16	0.5–1.9	0.06	0.13–0.56	(1.0)[h]
C_3H_8	0.09 ± 0.03	0.15	0.25 ± 0.11	0.2–0.8	0.04	0.07–0.30	(0.52)[h]
1-butene	0.09 ± 0.06	0.13	0.09–0.16	0.1–0.5	–	0.02–0.20	(0.13)[h]
i-butene	0.030 ± 0.012	0.11	0.05–0.11	0.1–0.5	–	0.01–0.16	(0.08)[h]
trans-2-butene	0.024 ± 0.014	0.05	0.01–0.05	0.05–0.3	–	0.01–0.06	(0.04)[h]
cis-2-butene	0.021 ± 0.011	0.042	0.008–0.13	0.05–0.18	–	0.01–0.03	(0.05)[h]
Butadiene	0.07 ± 0.05		0.06–0.08	0.11–0.36	–	0.01–0.10	(0.09)[h]
n-butane	0.019 ± 0.09	0.041	0.069 ± 0.038	0.03–0.13	–	0.02–0.10	(0.06)[h]
i-butane	0.006 ± 0.003	0.015	0.022 ± 0.009	0.01–0.05	–	0.006–0.01	(0.015)[h]
1-pentene	0.022 ± 0.010	0.056	0.04–0.07	0.5	–	0.028	0.008
n-pentane	0.005 ± 0.004	0.014	0.05–0.06	0.07	–	0.10	(0.025)[h]
2-methyl-butenes	0.008 ± 0.004	0.074	0.033	0.16	–	0.015	0.007
2-methyl-butane	0.011 ± 0.012	0.008	0.026–0.029	0.08	–	0.07	(0.018)[h]
Isoprene	0.020 ± 0.012	0.016	0.10	0.15–0.42	–	0.017	(0.05)[h]
Cyclopentene	0.012 ± 0.008	(0.02)[h]	0.019	0.61	–	0.035	(0.02)[h]
4-methyl-1-pentene	0.048	0.048	(0.05)[h]	0.015	–	(0.09)[h]	0.016
1-hexene	0.037 ± 0.016	0.063	0.07–0.11	(0.05)[h]	–	(0.13)[h]	0.013
n-hexane	0.039 ± 0.045	(0.05)[h]	0.03–0.06	(0.04)[h]	–	0.063	(0.05)[h]
Isohexanes	0.05	(0.08)[h]	(0.08)[h]	(0.06)[h]	–	(0.15)[h]	(0.08)[h]
Heptane	0.05	(0.08)[h]	(0.08)[h]	(0.06)[h]	–	(0.15)[h]	(0.08)[h]
Octenes	0.003–0.008	0.012	0.005	(0.007)[h]	–	(0.017)[h]	0.004
Terpenes	0.015	(0.15)[j]	0.22	(0.15)[j]	–	0.0	(0.015)[h]
Benzene	0.23 ± 0.11	0.39–0.41	0.49 ± 0.08	1.9 ± 1.0	–	0.3–1.7	0.14
Toluene	0.13 ± 0.06	0.21–0.29	0.40 ± 0.10	1.1 ± 0.7	–	0.08–0.61	0.026
Xylenes	0.045 ± 0.025	0.04–0.08	0.20	0.55 ± 0.44	–	0.04–0.22	0.01
Ethylbenzene	0.013 ± 0.003	0.013–0.035	0.048	0.17 ± 0.12	–	0.01–0.07	0.03
Styrene	0.024	(0.03)[h]	0.13	0.04–0.5	–	0.03–0.22	(0.03)[h]
PAH	0.0024	(0.025)[j]	(0.025)[j]	(0.025)[j]	–	(0.025)[j]	(0.025)[j]
Methanol	(1.3)[h]	(2.0)[h]	2.0 ± 1.4	(1.5)[h]	0.16	(3.8)[h]	(2.0)[h]
Ethanol	(0.011)[h]	(0.018)[h]	0.018	(0.013)[h]	–	(0.03)[h]	(0.018)[h]
1-propanol	0.025	(0.04)[h]	(0.04)[h]	(0.03)[h]	–	(0.08)[h]	(0.04)[h]
Butanols	0.008	0.009	(0.011)[h]	(0.008)[h]	–	(0.02)[h]	0.012
Cyclopentanol	0.032	0.031	(0.04)[h]	(0.03)[h]	–	(0.08)[h]	0.017
Phenol	0.003	0.006	(0.005)[h]	(0.004)[h]	–	(0.01)[h]	0.001
Formaldehyde	0.26–0.44	(1.4)[h]	2.2 ± 0.5	0.13 ± 0.05	–	(2.6)[h]	(1.4)[h]
Acetaldehyde	0.50 ± 0.39	(0.65)[h]	0.48–0.52	0.14 ± 0.05	–	(1.2)[h]	(0.65)[h]
Acrolein, propenal	0.08	(0.18)[h]	0.13–0.35	0.01–0.1	–	(0.35)[h]	(0.18)[h]
Propanal	0.009	(0.08)[h]	0.03–0.25	0.02–0.03	–	(0.15)[h]	(0.08)[h]
Butanals	0.053	0.071	0.21	0.04–0.05	–	(0.20)[h]	0.021
Hexanals	0.002–0.024	0.031	0.02	0.004–0.009	–	(0.04)[h]	0.012
Heptanals	0.003	0.003	(0.004)[h]	(0.003)[h]	–	(0.008)[h]	0.001
Acetone	0.25–0.62	(0.62)[h]	0.52–0.59	0.01–0.04	0.02	(1.2)[h]	(0.63)[h]
2-butanone	0.26	(0.43)[h]	0.17–0.74	0.03–0.06	–	(0.83)[h]	(0.44)[h]
2,3-butanedione	(0.57)[h]	(0.92)[h]	0.35–1.5	(0.68)[h]	–	(1.8)[h]	(0.9)[h]
Pentanones	0.01–0.02	0.028	0.09	(0.04)[h]	–	(0.09)[h]	0.007
Heptanones	0.006	0.002	(0.005)[h]	(0.004)[h]	–	(0.01)[h]	0.002
Octanones	0.015	0.019	(0.02)[h]	(0.016)[h]	–	(0.04)[h]	(0.02)[h]
Benzaldehyde	0.029	0.027	(0.036)[h]	0.02–0.03	–	(0.07)[h]	0.009
Furan	0.095	(0.48)[h]	0.40–0.45	0.65	–	(0.9)[h]	(0.5)[h]
2-methyl-furan	0.044–0.048	0.17	0.47	(0.18)[h]	–	(0.46)[h]	0.012
3-methyl-furan	0.006–0.011	0.029	0.05	(0.023)[h]	–	(0.06)[h]	0.003
2-ethylfuran	0.001	0.003	0.006	(0.003)[h]	–	(0.007)[h]	0.001
2,4-dimethyl-furan	0.008	0.024	(0.019)[h]	(0.014)[h]	–	(0.04)[h]	0.002
2,5-dimethyl-furan	0.002	(0.03)[h]	0.05	(0.021)[h]	–	(0.05)[h]	(0.03)[h]
Tetrahydrofuran	0.016	0.016	(0.02)[h]	(0.015)[h]	–	(0.04)[h]	0.006
2,3-dihydrofuran	0.012	0.013	(0.017)[h]	(0.012)[h]	–	(0.031)[h]	0.005
Benzofuran	0.014	0.015	0.026	(0.016)[h]	–	(0.04)[h]	0.004
Furfural	(0.23)[h]	(0.37)[h]	0.29–0.63	0.22	0.12	(0.72)[h]	(0.37)[h]
Methyl formate	(0.015)[h]	(0.025)[h]	0.025	(0.018)[h]	–	(0.05)[h]	(0.025)[h]

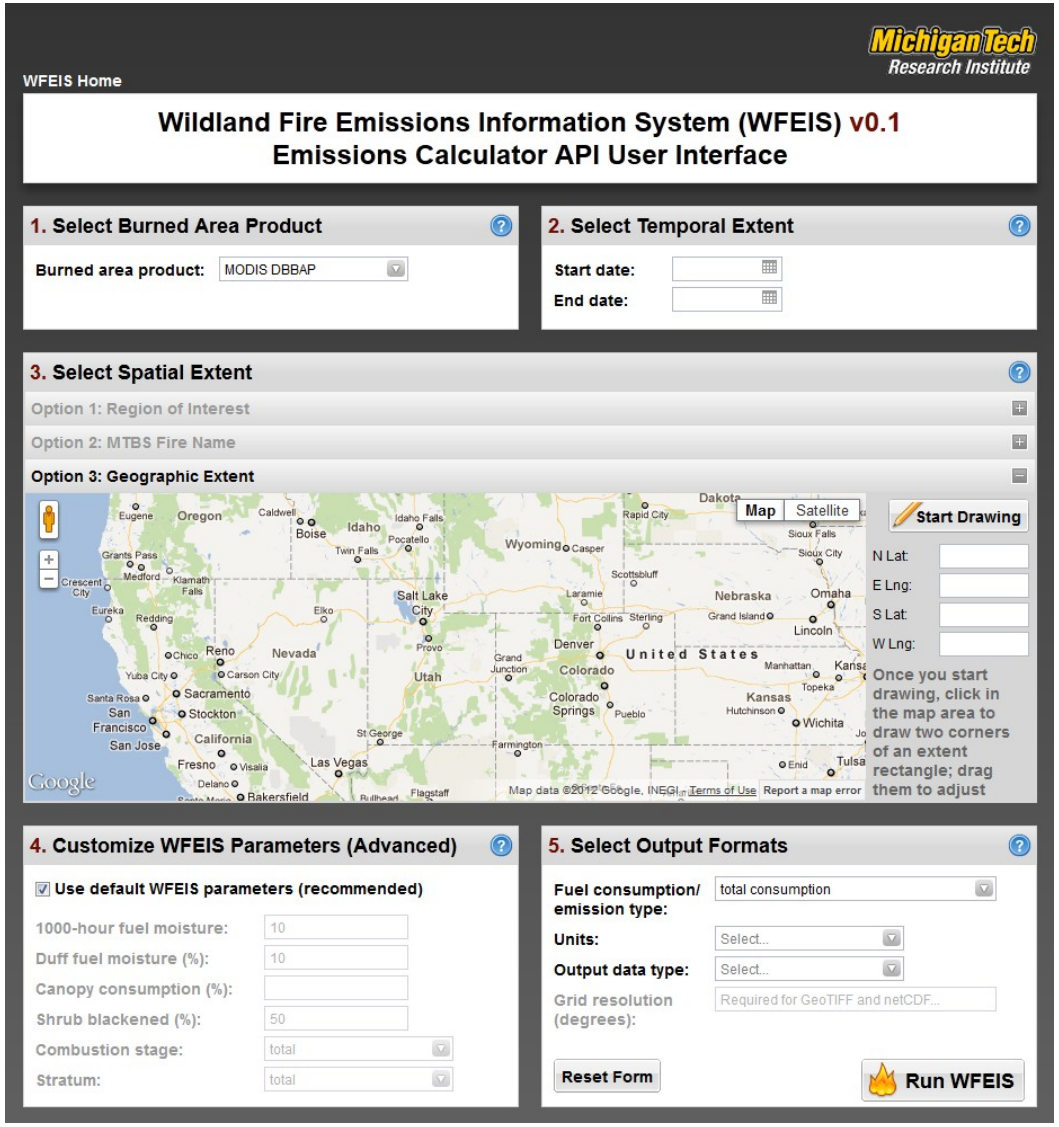
Wildland Fire Emissions Information System (WFEIS)

WFEIS (French et al. 2011): North America, 1 km, C and PM
WFEIS is a spatial application of Consume



WFEIS

http://wfeis.mtri.org
(French et al. 2011)



Global Fire Emission Database (GFED)

GFED (van der Werf et al. 2010)

global, 0.5 degrees, many species

www.globalfiredata.org

Global Fire Data (GFED)

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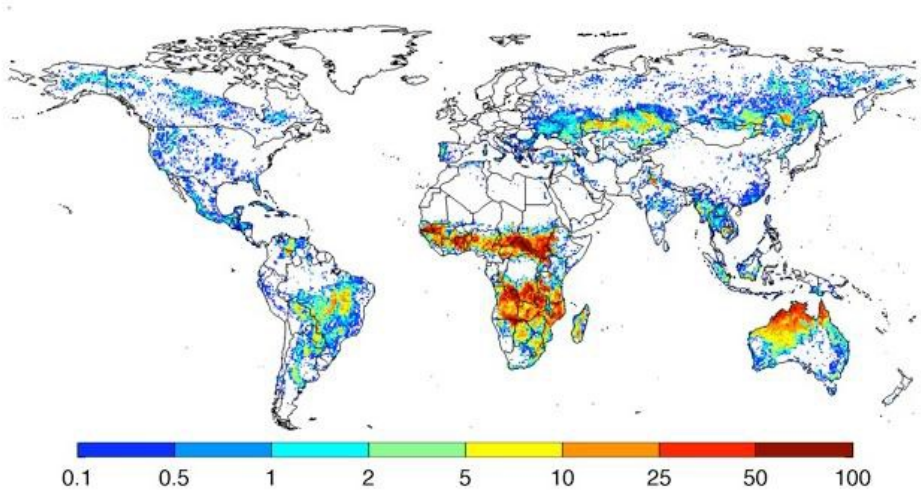
Fires are an important source of atmospheric trace gases and aerosols and are the most important disturbance agent on a global scale. In addition, deforestation and tropical peatland fires and areas that see an increase in the frequency of fires add to the build-up of atmospheric CO_2.

We have combined satellite information on fire activity and vegetation productivity to estimate gridded monthly burned area and fire emissions, as well as scalars that can be used to calculate higher temporal resolution emissions. The resulting datasets are downloadable from this website for use in large-scale atmospheric and biogeochemical studies. The core datasets are monthly burned area, monthly emissions (carbon emissions as well as a suite of trace gas and aerosol emissions), and fields to distribute the monthly emissions to a daily time step, or a 3-hourly time step using a mean diurnal cycle. The current version is 3.

While the data was released initially as the Global Fire Emissions Database (GFED) and will still be released as GFED, it now also includes burned area and other datasets besides the emissions fields



Annual burned area (as percentage of the area of the grid cell), averaged over 1997-2009. For November 2000 onwards it is for 90% based on mapped MODIS burned area using the direct broadcast algorithm, aggregated from the native 500-meter resolution to 0.5 degree. The remaining 10% and burned area for 1997 - October 2000 are based on relations between active fires (ATSR, TRMM-VIRS, and MODIS) and mapped burned area for periods they overlap.

Top-down Approach

$$(C_6H_{10}O_5)_n + O_2 + \textit{ignition temperature} \rightarrow CO_2 + H_2O + \textit{heat}$$

measured by thermal imagery

$$\text{FRP [MW km}^{-2}] = 4.34 \times 10^{-19} (T^8_{MIR} - T^8_{bg,\,MIR})$$

designed for MODIS (Kaufman et al. 1998)

or

$$FRP = \frac{A_{sampl}.\sigma.\varepsilon}{a.\varepsilon_{MIR}}(L_{MIR,fire} - L_{MIR,bg})$$

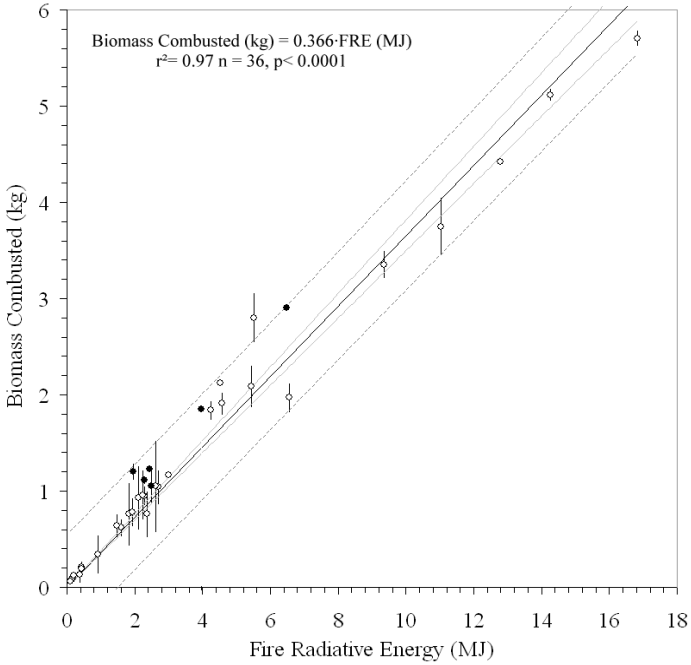
more widely applicable (Wooster et al. 2003)

(Wooster et al. 2005)

Fire Radiative Energy is temporal integration of Fire Radiative Power

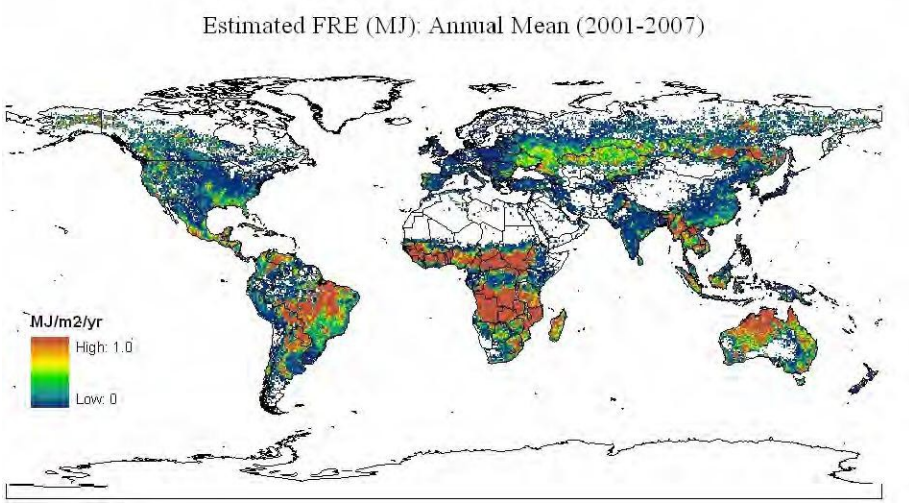
Fuel consumption is linearly related to FRE

Emission = *Fuel consumption X Emission factor*

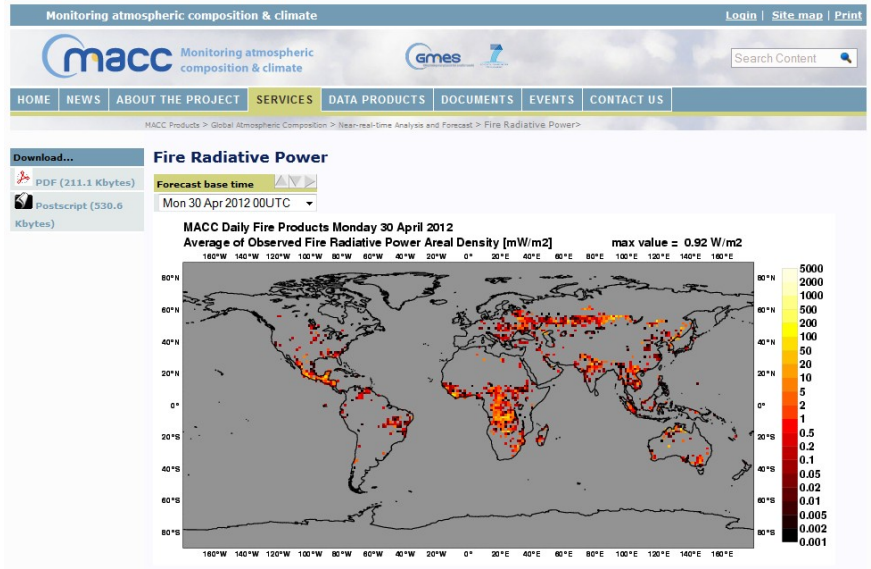


Top-down Approach

Global applications by Ellicott et al. (2009) and the Global Monitoring for Environment and Security



with MODIS



with geostationary satellites
in real-time
www.gmes-atmosphere.eu/service/gac/fire

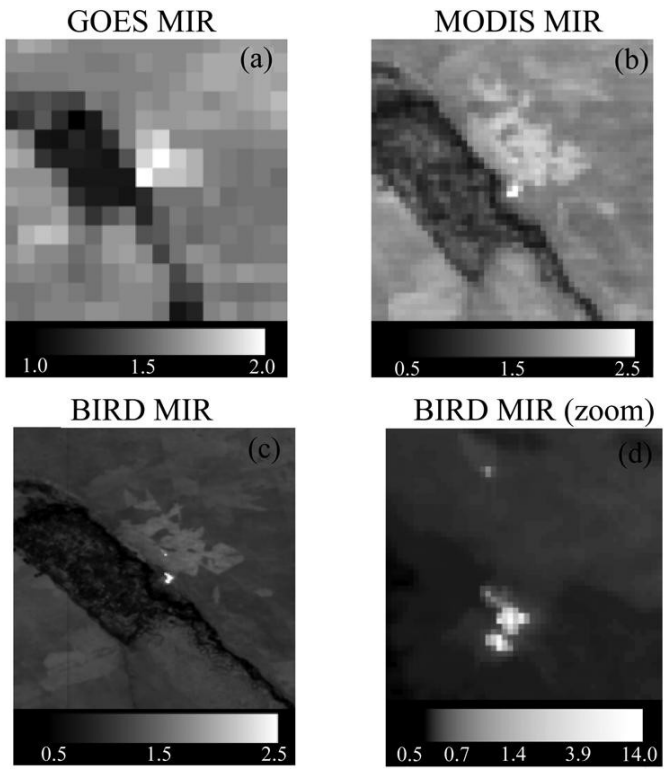
Uncertainties

Bottom-up approach:

+ straightforward, simple and conceptually easy
- uncertainties in each factor propagate into the actual emissions

Top-down approach:

+ no 'uncertain' data needed on fuel load and combustion completeness
- trade-off between spatial and temporal resolution
  - → temporal integral is necessary to derive FRE
  - → small fires might be missed



(Wooster et al. 2005)

Bottom-up Approach: Uncertainties

Uncertainties in wildfire emission estimates are up to 100 %

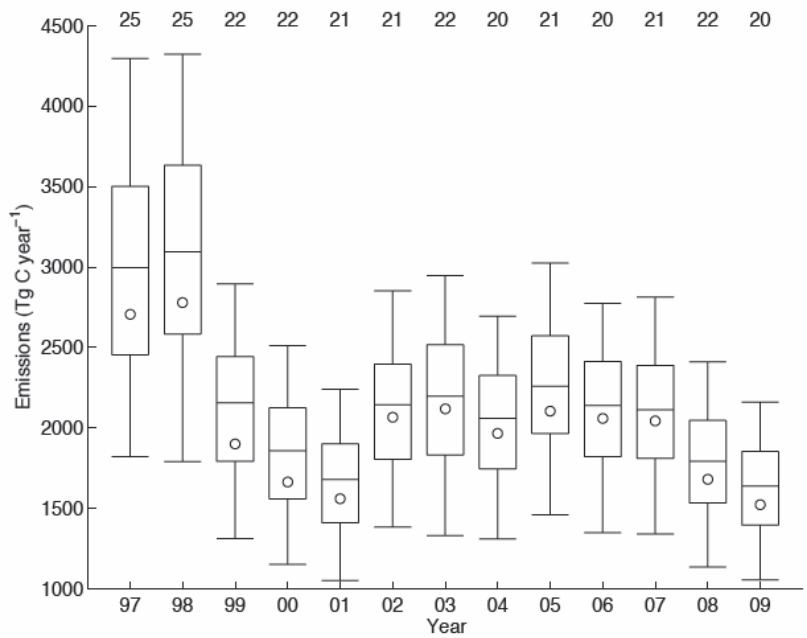
Table 6. Reported and best-guess uncertainties (1σ) for various parameters influencing fire emission estimates.

Parameter	Uncertainty
Burned area	Reported standard deviation (Giglio et al., 2010)
Deforested area	Reported burned area standard deviation $\times 2$
Woody biomass	22%[1]
Herbaceous biomass	44%[2]
Tree mortality	25%
Depth of soil burning	50% of range
Combustion completeness	50% of range

Table 2. Coefficient of Variation (CV) Values Used in Three Uncertainty Model Runs

	"Best Guess" Uncertainty	Low Uncertainty	High Uncertainty
Area burned[a]	0.15	same	same
Aboveground C	0.10	0.05	0.25
Ground-layer C	0.10	0.05	0.25
Aboveground β	0.23	0.05	0.25
Ground-layer β	0.30	0.05	0.25
Emission factor flaming[a,b]	CO_2		
	CO	same	same
	CH_4		
	0.02		
	0.09		
	0.15		
Smoldering	0.03		
	0.06		
	0.08		

(van der Werf et al. 2010)



(French et al. 2004)

Case Study: Uncertainty in Combustion Completeness

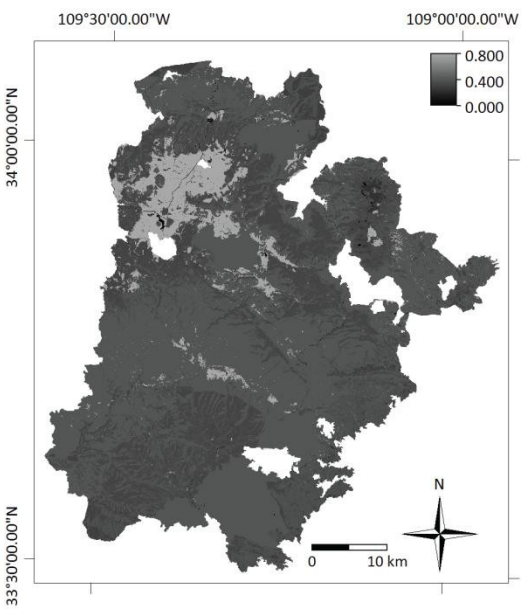
Combustion factor depends on:

- Fuel type
- Fuel moisture
- Fire severity

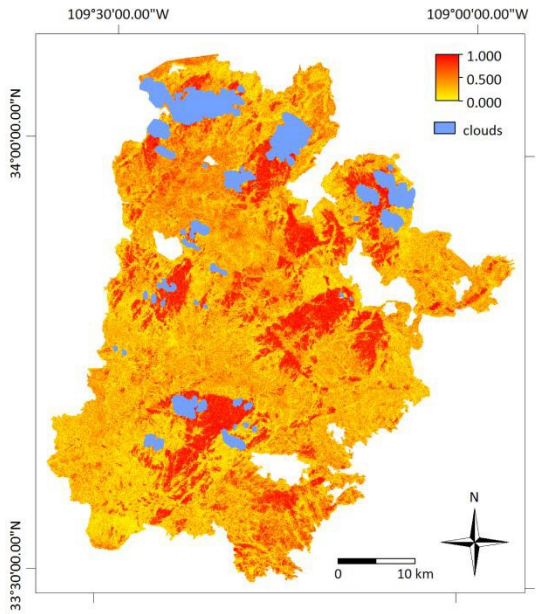
} Modeling

→ Remote sensing

MODELING & FIRE SEVERITY → COMBUSTION



&



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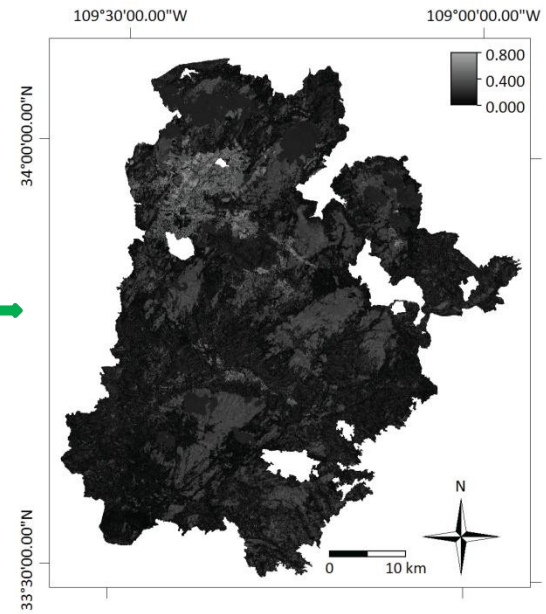
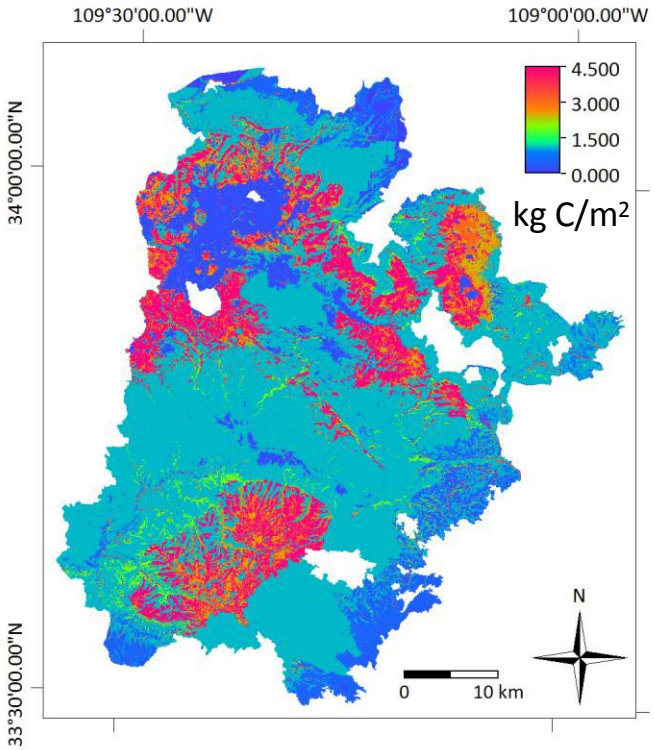


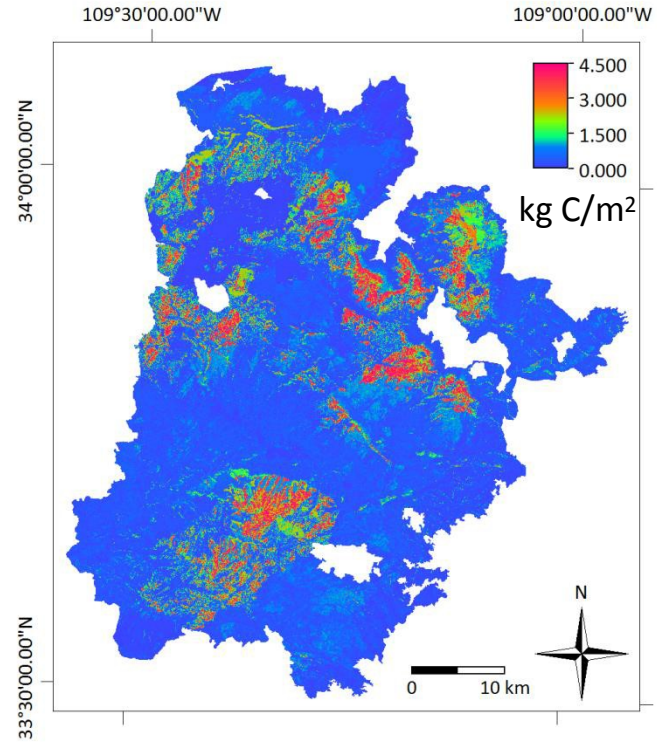
(Veraverbeke an Hook 2012)

Case Study: Uncertainty in Combustion Completeness

C emission from modeling only



C emission from modeling and RS



Fire	Burned area (ha)	CC estimation methodology	Total C emission (Tg)	Area normalized C emission (kg/m²)	% carbon emitted relative to modeling approach
Wallow	218 000	Modeling	3.44	1.57	1
Wallow	218 000	Modeling and RS	1.52	0.70	0.45

(Veraverbeke and Hook 2012)

Top-down Approach: Uncertainties

MODIS small active fire omissions	70 %	(Hawbaker et al. 2008)
Clouds obscuration	11 %	(Shroeder et al. 2008)
Point spread function	75 %	(Schroeder et al. 2010)
Improper characterization of background	80 %	(Schroeder et al. 2010)
MIR-FRP conversion	15 %	(Wooster et al. 2005)
FRP-FRE conversion	5 %	(Ellicott et al. 2009)
FRE-biomass conversion	2 %	(Wooster et al. 2005)
Biomass-C conversion	10 %	(French et al. 2004)

Emissions from the top-down approach are a factor of 3 lower than those of the bottom-up approach!!!

Who is right??

References

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

*Bowman D, Balch J, Artaxo P, Bond W, Carlson J, Cochrane M, D'Antonio C, DeFries R, Doyle J, Harrison S, Johnston F, Keely J, Krawchek M, Kull C, Marston J, Moritz M, Prentice I, Roos C, Scott, A, Swetnam T, van der Werf G, Pyne S (2009) Fire in the earth system. Science **324:** 481-484.*

Conard S, Solomon A (2009) Effects of wildland fire on regional and global carbon stocks in a changing environment. In: 'Wildland fires and air pollution, Developments in Environmental Science Volume 8'. (Eds A Bytnerowicz, M Arbaugh, A Riebau and C Andersen). Elsevier, Amsterdam, the Netherlands, 109–138.

*Ellicott E, Vermote E, Giglio L, Roberts G (2009) Estimating biomass consumed from fire using MODIS FRE. Geophysical Research Letters **36**: L31401.*

*French N, Goovaerts P, Kasischke E (2004) Uncertainty in estimating carbon emissions from boreal forest fires. Journal of Geophysical Research **109**: D14S08*

*French N, de Groot W, Jenkins L, Rogers B, Alvarado E, Amiro B, de Jong B, Goetz S, Hoy E, Hyer E, Keane R, Law B, McKenzie D, McNulty S, Ottmar R, Perez-Salicrup D, Randerson J, Robertson K, Turetsky M (2011) Model comparisons for estimating carbon emissions from North American wildland fire. Journal of Geophysical Research **116**: G00K05.*

*Giglio L, Randerson J, van der Werf G, Kasibhatla P, Collatz G, Morton D, DeFries R (2010) Assessing variability and long-term trends in burned area by merging multiple satellite fire products. Biogeosciences **7:** 1171-1186.*

*Hawbaker T, Radeloff V, Syphard A, Zhu Z, Stewart S (2008) Detection rates of the MODIS active fire product in the United States, Remote Sensing of Environment **112**: 2656-2664.*

*Kaufman Y, Justice C, Flynn L, Kandall J, Prins E, Ward D, Menzel P, Setzer A (1998) Monitoring global fires from EOS-MODIS, Journal of Geophysical Research **103**: 32215-32238.*

*Kasischke E, Loboda T, Giglio L, French N, Hoy E, de Jong B, Riano D (2011) Quantifying burned area for North American forests: Implications for direct reduction of carbon stocks. Journal of Geophysical Research **116**: G04003.*

Ottmar R, Pritchard S, Vihnanek R, Sandberg D (2006) Modification and validation of fuel consumption models for shrub and forested lands in the southwest, Pacific Northwest, Rockies, Midwest, southeast and Alaska. Final Report JFSP 98-1-9-06, pp. 1–97.

*Ottmar R, Sandberg D, Riccardi C, Prichard S (2007) An overview of the Fuel Characteristic Classification. Canadian Journal of Forest Research **37**: 2383-2393.*

Pritchard S, Ottmar R, Sandberg D, Eagle P, Andreu A, Swedin K (2011) FCCS user's guide. pp. 1–121.

*Randerson J, Liu H, Flanner M, Chamber S, Jin Y, Hess P, Pfister G, Mack M, Treseder K, Welp L, Chapin F, Harden J, Goulden M, Lyons E, Neff J, Schuur E, Zender C (2006) The impact of boreal forest fire on climate warming. Science **314**: 1130-1132.*

*Rocha A, Shaver G (2011) Burn severity influences postfire CO_2 exchange in arctic tundra. Ecological Applications **21:** 477-489.*

*Schroeder W, Csiszar I, Morisette J (2008) Quantifying the impact of cloud obscuration on remote sensing of active fires in the Brazilian Amazon, Remote Sensing of Environment **112**: 456-470.*

*Schroeder W, Csiszar I, Giglio L, Schmidt C (2010) On the use of fire radiative power, area, and temperature estimates to characterize biomass burning via moderate to coarse spatial resolution remote sensing data in the Brazilian Amazon, Journal of Geophysical Research **115:** D21121.*

*Seiler W, Crutzen P (1980) Estimates of gross and net fluxes of carbon between the biosphere and atmosphere from biomass burning. Climatic Change **2:** 207-247.*

*van der Werf G, Randerson J, Giglio L, Collatz G, Kasibhatla P, Arellano A (2010) Global fire emissions and the contribution of deforestation, savanna, forest, agricultural and peat fires (1997-2009). Atmospheric Chemistry and Physics **10:** 11707-11735.*

Veraverbeke S, Verstraeten WW, Lhermitte S, Van De Kerchove R, Goossens R (2012) Spaceborne assessment of post-fire changes in vegetation, land surface temperature and surface albedo. International Journal of Wildland Fire, in press.

Veraverbeke S, Hook S (2012) Refining combustion completeness and carbon emissions from wildfires by combining remote sensing and modeling. Geophysical Research Letters, in review.

*Wooster M, Zhukov B, Oertel D (2003) Fire radiative energy for quantitative study of biomass burning: derivation from the BIRD experimental satellite and comparison to MODIS fire products. Remote Sensing of Environment **86**:* 83-107.

*Wooster M, Roberts G, Perry G, Kaufman Y (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. Journal of Geophysical Research **110:** D24311.*

DON'T START FIRES YOU CAN'T STOP
BE FIREWISE
FIREWISE
WILDFIRE
MOVES
QUICKER
THAN YOU