COMPARISON OF WFEIS V0.3 AND GFED3 FIRE EMISSIONS MODELS

June 2014

Michael Billmire CMS-GIS/LIS mgbillmi@mtu.edu
Nancy H. F. French Ph.D nhfrench@mtu.edu
Kimberly Mobley kamobley@mtu.edu

GFED data provided by G. Jim Collatz, Ph.D, NASA's Goddard Space Flight Center

ABSTRACT

Major model components of GFED v3.1 and WFEIS v0.3 are compared by analyzing aggregate results from 2001-2010 for the CONUS region. These components include: burned area, fuel loadings, combustion completeness, and emission factors. Burned area source (MODIS MCD64A1) is identical and so results compare well). GFED fuel loadings are 55% higher than WFEIS and combustion completeness is 15% lower than WFEIS for the study period and region. Carbon emission factors are approximately equivalent but CO_2 emission factors used in GFED are ~80% larger than the aggregate CO_2 emission factor used in WFEIS. These component differences lead to estimates of carbon emissions that are ~50% lower in GFED than in WFEIS and estimates of CO_2 that are ~5% lower in GFED than in WFEIS.

OVERVIEW

For the NASA-CMS project, one task planned in our project is to assess methods of quantifying carbon emissions from wildland fire. Under NASA-CMS Pilot Study, the flux products used the CASA-GFED and NASA-CASA models to assess “bottom-up” fluxes from terrestrial systems to the atmosphere. Under previous and on-going NASA-sponsored projects, our team at MTRI has developed an alternative to GFED for regional to landscape-scale assessments of carbon emissions from fire. For this activity we will be comparing results and input data for estimating carbon emissions from GFED3, the fire emissions module of CASA-GFED, and WFEIS. The two approaches use the same base data set for burned area for 2002 to present (MODIS Product MCD64A1) but different assumptions for the other components of the emissions model.

OVERVIEW OF WFEIS

The Wildland Fire Emissions Information System (WFEIS) is a web-based tool that provides users a simple interface for computing wildland fire emissions across CONUS and Alaska at landscape to regional scales (1-km spatial resolution). WFEIS integrates burned area maps along with corresponding fuel loading data layers and fuel consumption models to compute wildland and cropland fire fuel consumption and emissions for user-specified locations and date ranges. The system currently allows for calculation of emissions from fires within the United States (excluding Hawaii and territories) from 1984 through 2013 depending on the selected burned area product.

OVERVIEW OF GFED

Global Fire Data (GFED) is a global assessment of emissions from fire that combines 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 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.

ASSESSMENT PLAN

The *Seiler and Crutzen* [1980] method for estimation of carbon emissions from wildland fire (also known as biomass burning) requires quantification of three parameters: area burned, fuel loading (biomass per unit area), and the fraction of biomass fuel consumed, represented as fuel combustion factors and also known as the combustion completeness or percent consumed (Figure 1).

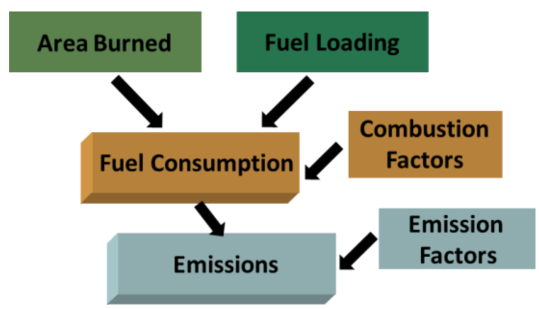


Figure 1. Common approach to bottom-up modeling of emissions from wildland and prescribed fire (a.k.a. biomass burning).

The general equation for computing total carbon emissions (C_t) as interpreted by *French et al.* [2002b] and *Kasischke and Bruhwiler* [2003] is:

$$C_t = A \cdot (B \cdot f_c \cdot \beta) \quad (1)$$

Where:

A is the area burned (hectares, ha or m^2),
B is the biomass density or fuel load ($t\ ha^{-1}$; $kg\ m^{-2}$),
f_c is the fraction of carbon in the biomass (fuel), and
β is the fraction of biomass consumed in the burn.

Here, we analyze the differences between the two systems for these four major model components using aggregate results from 2001-2010 CONUS.

Model component	GFED	WFEIS
Burned area (m^2 or km^2)	MCD64A1 5° of lat (primary source)	MCD64A1 500m
Fuel loading (biomass)	CASA-derived NPP by strata	US Forest Service FCCS by strata
Combustion completeness (fraction of biomass consumed)	Scaled by moisture within strata-specific predefined range	Modeled in Consume
Emission factors	Fire type-specific factors based predominantly on Andreae and Merlet (2001)	Published factors based on fuel type used within Consume model

Table 1. Comparison of major fire emission modeling components by data source.

We also explore yearly patterns and ecoregion-specific results where appropriate to help to further inform the system differences. Figure 2 shows the ecoregions used for the analysis.

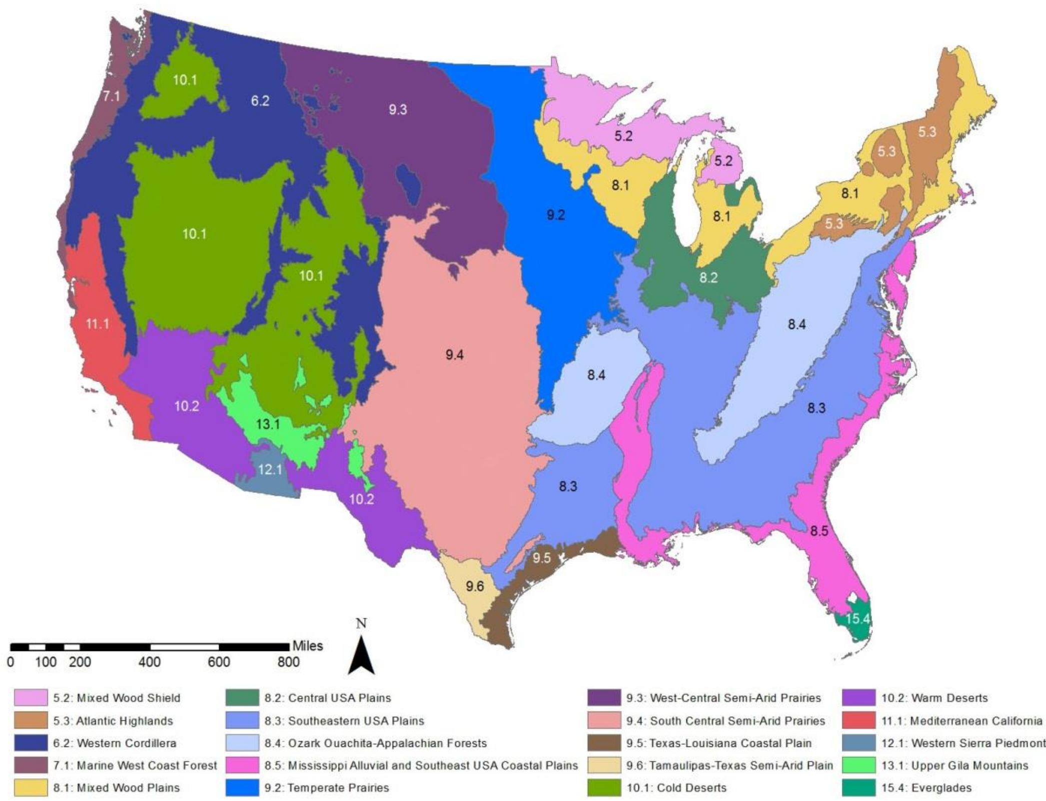


Figure 2. CEC level II ecoregions used throughout this analysis.

ANALYSIS

BURNED AREA

BACKGROUND: WFEIS AND GFED

WFEIS and GFED both use the MODIS MCD64A1 standard data product (Giglio et al. 2009) as their primary burn area data source. WFEIS uses the product at its native 500m resolution, whereas GFED down-scales the burn area to 0.5° of latitude grid scale and augments the MODIS-derived burn area with other information for some years.

COMPARISON RESULTS

As expected given the common source, burned area values are very similar between the two systems (Figure 3). Over the 2001-2010, cumulative GFED burned area is 2% greater than WFEIS burned area. The minor differences observed are not consistent from year to year (i.e. in some years GFED is larger and vica versa) and can be explained by the difference in spatial scales as well as possible differences in MODIS MCD64A1 data version.

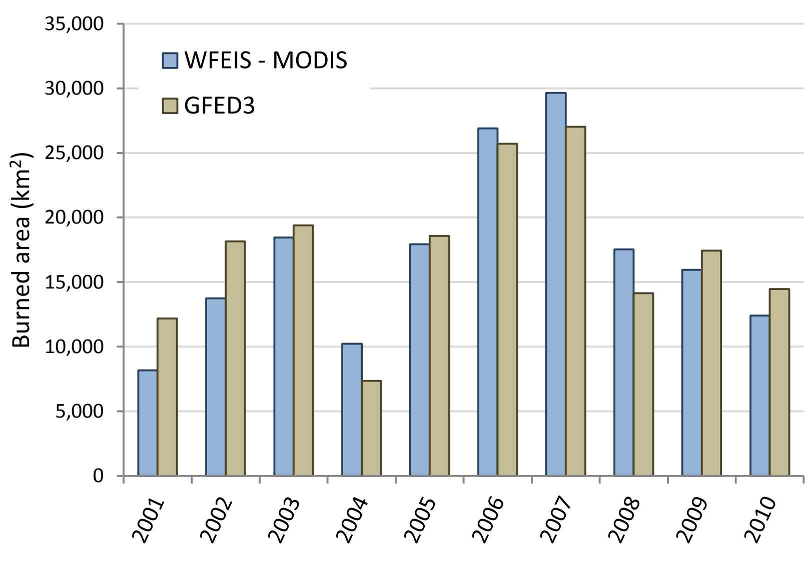


Figure 3. Comparison of annual MCD64A1 burned area used in GFED and WFEIS systems.

There are larger differences between the systems on an ecoregion level (**Figure 4**). This is best explained by the difference in spatial scales; many ecoregion spatial features are not well represented when distributed on a 0.5 degree grid.

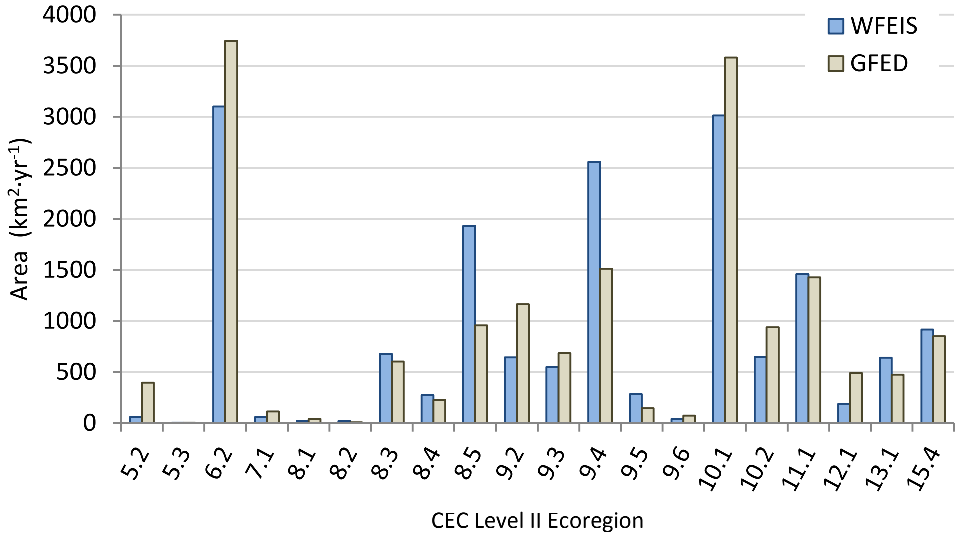


Figure 4. Comparison of burned area by CEC Level II ecoregion by mean annual totals 2001-2010 for CONUS.

FUEL LOADING

Fuels comprise the live and dead biomass at a fire location. Low-intensity fires typically burn only grasses, other non-woody vegetation, and plant litter and small twigs. In contrast, high-intensity fires can consume everything except tree boles, including tree crowns, shrubs, grasses, woody fuels, litter, and organic soils. The estimation of actual fuel amounts is likely the greatest source of uncertainty in calculating carbon release and other emissions from wildfires, particularly large fires that burn multiple vegetation types. The amount of vegetation fuels at a site is called in the fire community "fuel loading"; the carbon modeling community refers to this as "biomass".

Note that for modeling fire emissions, this measure includes only fuel that is available to burn as opposed to total biomass across all strata, and so throughout the analysis of this component it will be referred to as *available fuel*. Tree boles are an example of a fuel that is not available for burning (large live trunks are too moist and large to be effected by fire) but would be included in measures of total biomass.

BACKGROUND: WFEIS

WFEIS uses fuel loading from the USDA Forest Service Fuel Characteristic Classification System (FCCS) that defines a mass per unit area for up to 32 substrata of each fuelbed type described. A set of standard fuelbed types were mapped at a 1-km cell size for use within WFEIS (McKenzie et al. 2012).

BACKGROUND: GFED

Fuel loading in CASA-GFED is distributed among 10 carbon "pools" representing different fuel strata (e.g. woody, herbaceous, litter, soil, etc.). Loading values are based on satellite-driven estimations of net primary productivity (NPP), calculated for each 0.5° grid cell and monthly time step and allocated to carbon pools according to Hui and Jackson (2005). Pool stocks are then modified by various pathways, including transition to litter, decomposition, herbivory, and fuelwood collection. CASA-GFED also applies a mortality fraction to live carbon pools and applies combustion completeness values (described below) only to the fraction of dead fuels. Mortality fraction data was not available for this analysis and so estimates of fuel loadings initially include live unburned fuels that would not technically qualify as available.

COMPARISON RESULTS

CASA-GFED total fuel loadings (without mortality accounted for) are ~13.5% lower than WFEIS fuel loading over the entire time period ("GFED (surface + all" in Table 4 and Figure 5). Accounting for mortality, CASA-GFED fuel loadings would be expected to be lower; a method to estimate these values is described in the Fuel Consumption section. These estimates are shown in Table 4 and Figure 5 under the "GFED (surface + dead)" heading.

The years with the largest discrepancies are 2002, 2003, and 2006.

FUEL CONSUMPTION

Combustion completeness (CC; also referred to as *percent consumed*) is the fraction of the *available* biomass fuel consumed and ranges from 0 (no fuel consumed) to 1 (all fuel consumed). Thus, we again have the complication of not being able to account for mortality fraction in GFED results. WFEIS models and documentation generally use the terms *consumption* and *percent consumed* while CASA-GFED models and documentation refer to the equivalent *combustion* and *combustion completeness*.

BACKGROUND: WFEIS

The WFEIS approach uses the USDA Forest Service FERA Consume model to calculate fuel consumption (mass of combusted material) based on:

- the FCCS fuelbed (strata, type, and loadings),
- fuel moisture derived from RAWS weather data, and
- default inputs for some variables (particularly *shrub blackened* , which defaults to 50%)

Each strata is subject to its own consumption equation. CONSUME consumption equations are often non-linear and include conditionals related to ecoregion and/or fuel moisture inputs and so nominal values of each strata are not easily extracted.

BACKGROUND: GFED

GFED assigns combustion completeness to each grid cell and pool. CC values for each pool fall within the range shown in Table 2. Within these ranges, the exact values used are determined by scaling linearly according to local moisture conditions (described fully in van der Werf et al. 2006).

Pool	CC_{min}	CC_{max}
Leaves	0.8	1.0
Stems	0.2	0.4
Fine leaf litter	0.9	1.0
Coarse woody debris	0.4	0.6

Table 2. Combustion completeness ranges used in CASA-GFED for different biomass pools. Values are from Table 1 in van der Werf et al. 2010.

COMPARISON RESULTS

First, we compare our 2001-2010 aggregate results for GFED with those reported in Table 4 of van der Werf et al. 2010 for the TENA region.

Source	Surface	Standing (all)	Standing (burned)
GFED, van der Werf et al. 2010 Table 4 (1997-2009)	75.0%	17.0%	40.0%
GFED, this study (2001-2010)	73.3%	15.1%	??.?%

Table 3. Aggregate CONUS CC values for CASA-GFED.

Note that the *Standing (burned)* value would most closely correspond to the CC value derived from WFEIS, but we are unable to calculate this for 2001-2010 without mortality fraction data. However, given that the *Standing (all)* and *Surface* values align so closely with the equivalent CC reported for 1997-2009, we will assume that the 40% CC for *Standing (burned)* group reported in that table is also an approximate equivalent.

Thus, we can use 40% CC to back-transform the GFED available fuel values from provided combustion data to produce rough estimates that account for mortality and thus provide a more apt comparison to WFEIS values:

$$\text{Combustion}_{\text{Standing}} = \text{FuelLoading}_{\text{Standing}} \times 0.40$$

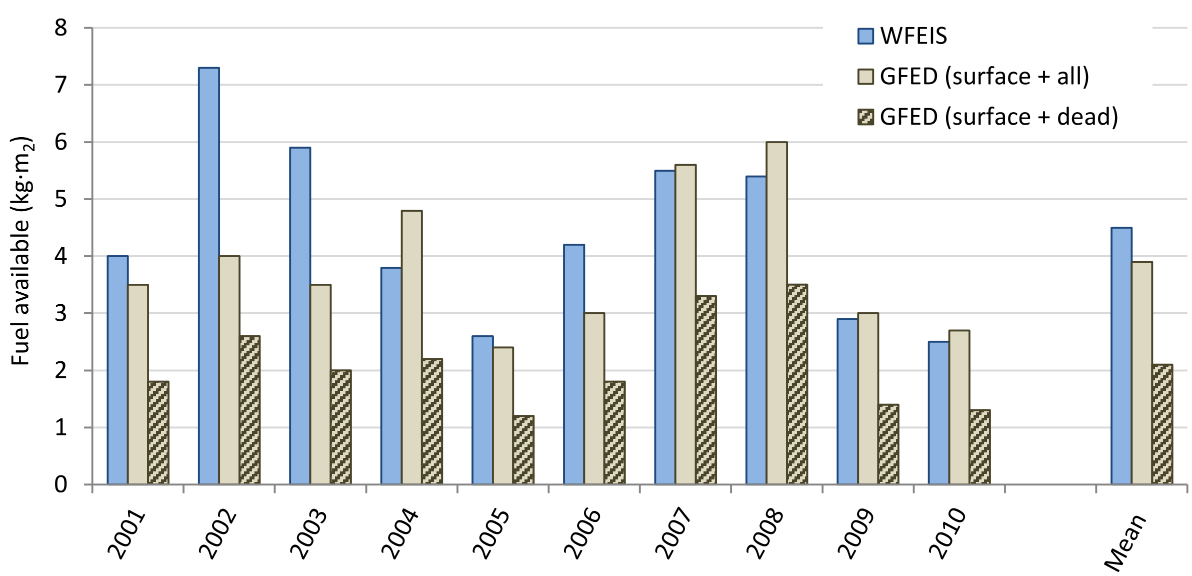
$$\text{FuelLoading}_{\text{Standing}} = \text{Combustion}_{\text{Standing}} / 0.40$$

Aggregate available fuel and consumption totals for 2001-2010 CONUS are shown in Table 4 and Figure 5. For GFED, both the original (“surface + all”) and estimates accounting for mortality (“surface + dead”) as described above are included. Figures are presented in kg·m^{-2} as opposed to total mass (Tg) to eliminate the effect of differences in burned area.

Year	**GFED**				**WFEIS**		
	FL kg·m^{-2} (surface + all)	FL kg·m^{-2} (surface + dead)	Consumption kg·m^{-2}	CC %*	FL kg·m^{-2}	Consumption kg·m^{-2}	CC %
2001	3.5	*1.8*	1.1	60.3	4.0	2.0	48.5
2002	4.0	*2.6*	1.5	57.6	7.3	3.8	50.7
2003	3.5	*2.0*	1.1	57.3	5.9	3.0	51.3
2004	4.8	*2.2*	1.3	58.3	3.8	1.6	40.9
2005	2.4	*1.2*	0.8	61.8	2.6	1.3	48.2
2006	3.0	*1.8*	1.0	58.3	4.2	2.2	53.0
2007	5.6	*3.3*	1.8	53.4	5.5	2.8	50.0
2008	6.0	*3.5*	2.0	56.0	5.4	2.9	50.5
2009	3.0	*1.4*	0.8	60.4	2.9	1.5	50.3
2010	2.7	*1.3*	0.8	60.1	2.5	1.2	48.0
All years	**3.9**	***2.1***	**1.2**	**57.2**	**4.5**	**2.3**	**50.1**

Table 4. Aggregate available fuel (FL), consumption, and combustion completeness across strata for areas that burned from 2001-2010 . FL=available fuel. For GFED FL, “surface + all” includes lives fuels not technically available for burning and “surface + dead” shows estimates that account for mortality by assuming 40% combustion completeness of *Standing* combustion totals. *GFED CC% is based on the “surface + dead” available fuel loadings as they are more appropriate for comparing with the values represented by WFEIS.

Over the entire study time period, GFED fuel available (accounting for mortality) is ~55% lower than WFEIS fuel available, but GFED CC% is ~15% higher, leading to ~45% lower overall consumption per unit of burned area than WFEIS.



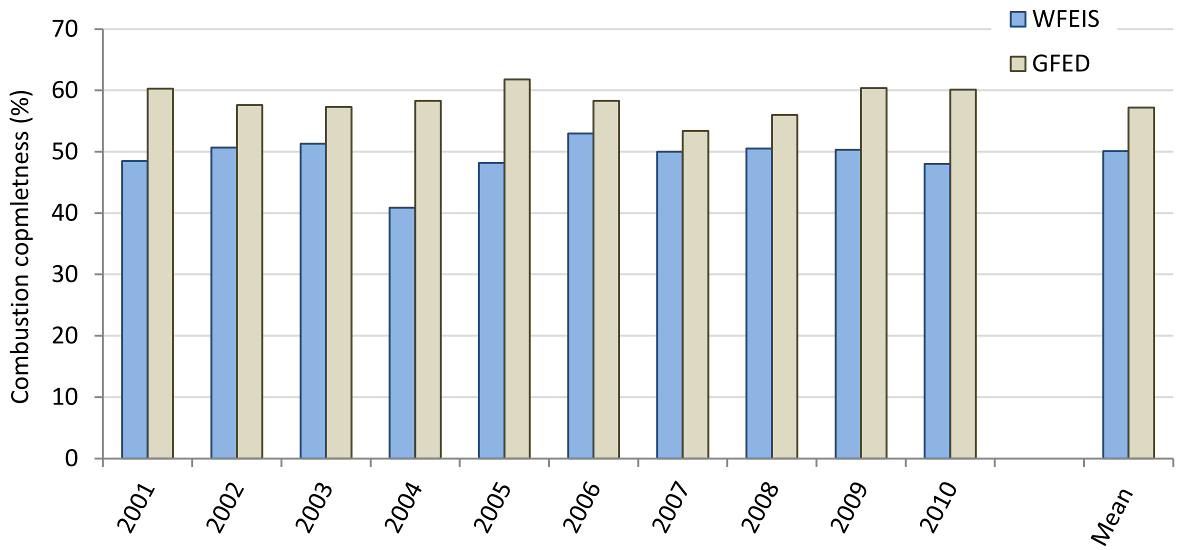


Figure 5. Fuel available (top) and combustion completeness (bottom) for CONUS 2001-2010.1.54

Table 5 shows available fuel, consumption, and CC% by general fuel/fire-type strata for the two systems.

GFED				WFEIS			
Stratum	FL kg·m^{-2}	Consumption kg·m^{-2}	CC%	**Stratum**	FL kg·m^{-2}	Consumption kg·m^{-2}	CC %
Live: Herbaceous + Woody	*1.04*	0.41	*40.0*	Canopy	1.54	0.34	21.9
				Shrub	0.35	0.19	55.7
Surface: Herbaceous	0.37	0.35	95.9	Ground	1.25	0.65	51.7
Surface: Woody	0.73	0.45	61.9	Litter-lichen-moss	0.33	0.27	81.7
				Nonwoody	0.11	0.10	92.7
				Woody	0.97	0.73	75.4

Table 5. Available fuel (FL), consumption, and CC % by strata for CONUS 2001-2010. For GFED, the “Live: Herbaceous + Woody” stratum was given an approximate CC of 40% from which the FL value was estimated.

EMISSION FACTORS

BACKGROUND: WFEIS

WFEIS uses published emission factors (see http://wfeis.mtri.org/media/img/A3-EmissionFactors.pdf) within the Consume model for appropriate fuel type, fuel strata, and combustion phase (flaming, smoldering, and residual). Combustion phase for each fuel strata is pre-defined, with more flaming in the aboveground strata and more smoldering in the ground layers. Consume includes emission factors for the following species: CO_2, CO, CH_4, NMHC, PM, PM_{10}, $PM_{2.5}$. WFEIS separately calculates carbon emissions using a static emission factor of 500 g·kg^{-1} consumed for all fuel types, strata, and combustion phases.

BACKGROUND: GFED

GFED applies fire type-specific emissions factors predominantly based on Andreae and Merlet (2001) and updated annually via personal communication with M.O. Andreae. GFED includes emission factors for the following species: Carbon, CO_2, CO, CH_4, NMHC, H_2, NO_x, N_2O, $PM_{2.5}$, TPM, TC, OC, BC, and SO_2.

COMPARISON RESULTS

Nominal values reported here (Table 6)represent the base input values by fuel type, not taking into account the amount and distribution of fuel/fire types that actually burned.

Nominal emission factors ($g \cdot kg^{-1}$ consumption) by fuel type

GFED fire type	**Carbon**	**CO_2**
Deforestation	489	1626
Savanna and grassland	476	1646
Woodland	483	1636
Extratropical forest	476	1572
Ag/waste	440	1452
Peat fires	563	1703

WFEIS (Consume)	**CO_2** flaming	**CO_2** smold/resid
Doug-fir/hemlock	1262	1143
Juniper	1701	1525
Chaparral	1663	1572
Western Pine	832	776
Minnesota Oak	855	805
Minnesota Pine	847	822
Southern Pine	840	801
Sage	795	726
Minnesota Grass	849	815

Table 6. Nominal emission factors used in GFED and WFEIS. WFEIS emission factor for carbon is 500 $g \cdot kg^{-1}$ for all fuel and combustion types.

Aggregate/effective values for CONUS are calculated for each year by taking total annual emissions divided by total annual consumed. Since GFED biomass data was not available for this analysis (just carbon), we cannot calculate aggregated values. However, since the emission factors do not vary significantly between fire types, we can assume estimated aggregate values of ~480 $g\ C \cdot kg^{-1}$ and ~1600 $g\ CO_2 \cdot kg^{-1}$ for GFED.

For WFEIS, however, the range of emissions factors depending on fuel type and combustion phase requires that aggregate/effective values be calculated. For carbon, 500 $g \cdot kg^{-1}$ is the only emission factor used and so it represents both the nominal as well as the aggregate/effective value for WFEIS. For CO_2, the yearly mean aggregate emission factor for WFEIS is **878 ± 33** $g \cdot kg^{-1}$ consumed (standard deviation of the ten annual values), but this varies considerably by ecoregion (Figure 6) with only a few southwestern ecoregions having CO_2 emissions factors comparable to those used by GFED.

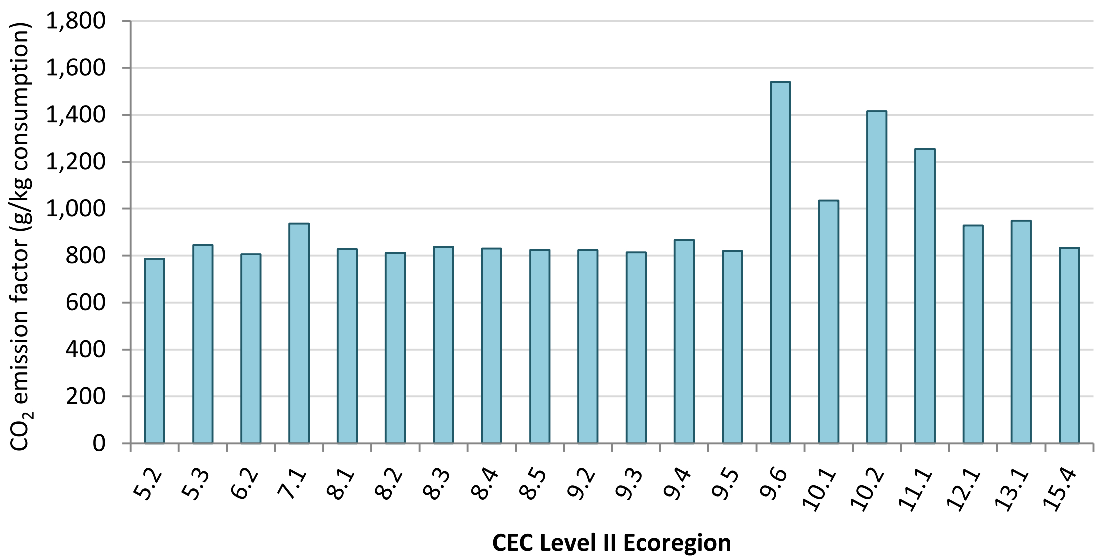


Figure 6.WFEIS aggregate CO_2 emission factors by CONUS CEC Level II ecoregion 2001-2010.

In aggregate, GFED carbon emission factors are ~5% lower than that used by WFEIS while GFED CO_2 emission factors are ~80% higher.

SUMMARY

We have compared the four major model components for fire emissions modeling for both GFED3.1 and WFEIS v0.3. The end result of the modeling- estimates of total Carbon and CO_2 emissions- are shown in Figure 7. Table 7 summarizes the degree of difference between the two systems for each model component for the study period.

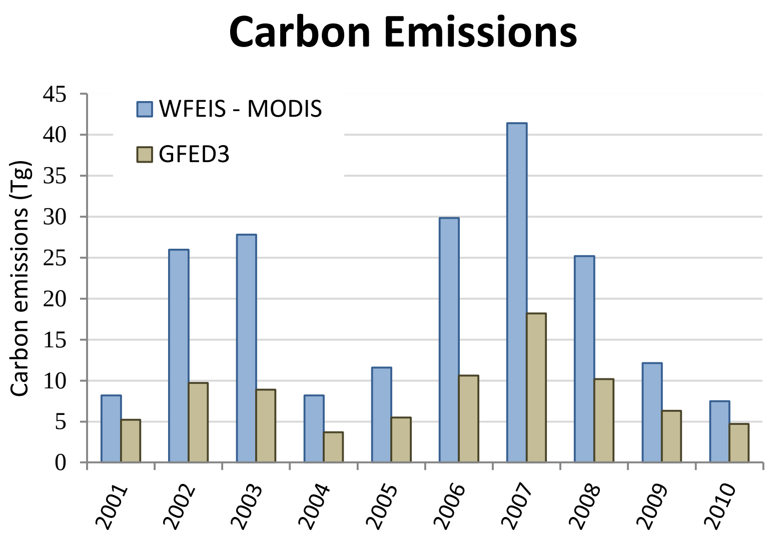
Summary of major model components	
Model component	**Difference**
Burned area	GFED 2% higher than WFEIS
Fuel available	GFED ~55% lower than WFEIS (w/ mortality effects estimated)
Combustion completeness	GFED ~15% higher than WFEIS (w/ mortality effects estimated)
Emission factors	
Carbon	GFED 5% lower than WFEIS
CO_2	GFED 80% higher than WFEIS

Table 7. Summary of differences between WFEIS and GFED for the four major fire emissions modeling components based on aggregate calculations for CONUS 2001-2010.

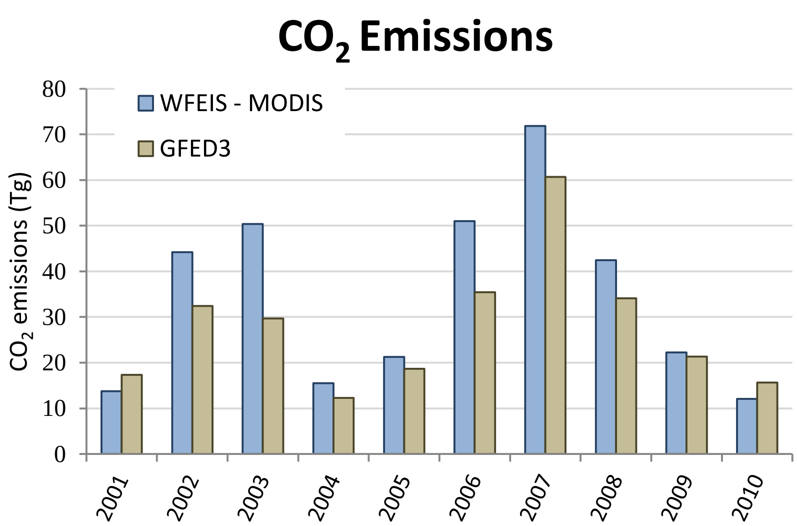
A rough calculation shows that these differences cumulatively align with modeled carbon and CO_2 totals shown in Figure 7:

GFED C =	102% * 45% * 115% * 95% =	~50% of WFEIS C
GFED CO_2 =	102% * 45% * 115% * 180% =	~95% of WFEIS CO_2

Note that the aggregate CO_2 values shown in Figure 7 are based on previously reported results published on the GFED website (http://www.globalfiredata.org/Data/index.html) whereas carbon values are modeled from combustion data provided by the GFED team. This explains why the carbon values reported here differ slightly from officially published values. According to personal communication with G.J. Collatz, this ~25% increase is likely due to higher biomass inputs relative to the standard CASA-GFED. This also explains at least partially why the published GFED3 CO_2 values shown in Figure 7 are lower than expected based on the model component analysis (i.e. they are ~80% of WFEIS estimates as opposed to the expected ~95% of WFEIS estimates).



Total Carbon emissions (Tg)		
Year	GFED	WFEIS
2001	6.3	8.2
2002	2.9	26.0
2003	10.4	27.8
2004	4.4	8.2
2005	6.6	11.6
2006	12.6	29.8
2007	22.8	41.4
2008	13.3	25.2
2009	6.8	12.1
2010	5.3	7.5
Mean	**10.2**	**19.8**



Total CO_2 emissions (Tg)		
Year	GFED	WFEIS
2001	17.4	13.8
2002	32.4	44.2
2003	29.7	50.4
2004	12.3	15.5
2005	18.7	21.2
2006	35.4	51.0
2007	60.7	71.9
2008	34.1	42.4
2009	21.3	22.2
2010	15.7	12.1
Mean	**27.8**	**34.5**

Figure 7. Aggregate carbon and CO2 totals as calculated by WFEIS and GFED systems for CONUS 2001-2010.

REFERENCES

French, N.H.F., de Groot, W.J., Jenkins, L.K., Rogers, B.M., Alvarado, E.C., Amiro, B., de Jong, B., Goetz, S., Hoy, E., Hyer, E., Keane, R., McKenzie, D., McNulty, S.G., Law, B.E., Ottmar, R., Perez-Salicrup, D.R., Randerson, J., Robertson, K.M. and Turetsky, M. (2011), "Model comparisons for estimating carbon emissions from North American wildland fire," Journal of Geophysical Research, 116, G00K05. doi:10.1029/2010JG001469.

Giglio L, Loboda T, Roy DP, Quayle B, Justice CO (2009) An active-fire based burned area mapping algorithm for the MODIS sensor. *Remote Sensing of Environment* **113**, 408-420

Giglio, L., Randerson, J. T., van der Werf, G. R., Kasibhatla, P. S., Collatz, G. J., Morton, D. C., and DeFries, R. S.: Assessing variability and long-term trends in burned area by merging multiple satellite fire products, Biogeosciences, 7, 1171-1186, doi:10.5194/bg-7-1171-2010, 2010

McKenzie, Donald, Nancy HF French, and Roger D. Ottmar. "National database for calculating fuel available to wildfires." Eos, Transactions American Geophysical Union 93, no. 6 (2012): 57-58.

Mu, M., J.T. Randerson, G.R. van der Werf, L. Giglio, P. Kasibhatla, D. Morton, G.J. Collatz, R.S. DeFries, E.J. Hyer, E.M. Prins, D.W.T. Griffith, D. Wunch, G.C. Toon, V. Sherlock, and P.O. Wennberg. Daily and 3-hourly variability in global fire emissions and consequences for atmospheric model predictions of carbon monoxide. Journal of Geophysical Research-Atmospheres.116: D24303. doi:10.1029/2011JD016245. 2010.

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707-11735, doi:10.5194/acp-10-11707-2010, 2010