Projections of Wildland Fire Emissions Corresponding to Vegetation Changes Due to Climate Change

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ABSTRACT

Available climate forecasts have typically projected significant increases in wildfire activity due at least in part to climate change. Additionally, wildfires are a significant source of PM emissions in the western states contributing to deteriorating air quality, regional haze, and health impacts. The MC1 model has been developed to provide the capacity to estimate climate change effects on vegetative growth, carbon storage, and wildfire incidence in the contiguous US.

This paper discusses the development of wildfire emission inventories (PM10, PM2.5, CO, CO2, methane and non-methane hydrocarbons), under a base and policy case that assumed global-scale GHG mitigation, using output from the MC1 model. In order to make the emission estimates, SC&A needed to first understand, and then adapt the MC1 output to derive data on fire start dates and duration using the available outputs of the MC1 model. The variability of emissions over time and emission trends during the 100-year projection period are presented. The paper also presents several recommendations to improve the MC1 model output to make the data more usable in climate and air quality modeling. The wildfire emissions developed under this project are part of a broader, multi-sector climate change impacts project called the Climate Change Impacts and Risks Analysis (CIRA), coordinated by the US EPA, for use in the climate change and air quality modeling analysis being performed by MIT as part of the CIRA project.

INTRODUCTION

Using a dynamic global vegetation model (DGVM), EPA has developed the capacity to estimate climate change effects on vegetation growth, carbon storage, and wildfire incidence in the contiguous United States. This analysis has produced projections of wildfire location and duration for the lower 48 states. The purpose of this project was to use the wildfire incidence output from the DGVM to produce emission estimates that can be used by air quality modelers to estimate the air quality concentrations associated with changes in wildfire incidence for forecast years as far in the future as 2100.

This paper explains how predictions from a DGVM, in this case the MC1 model,[1] with a fire sub model (MCFire) were used to estimate air pollution emissions from wildfires over the next 100 years. MC1 was applied by Stratus Consulting to project climate change impacts on terrestrial carbon storage and wildfire in the U.S. SC&A, Inc (under contract to Industrial Economics, Inc) was tasked to develop a time- and spatially-resolved fire emissions inventory based on Stratus' MC1 modeling results. Data files containing results of this analysis have been prepared for use by a team at Massachusetts Institute of Technology (MIT) to estimate air quality impacts of these emissions across the contiguous US.

MC1 MODEL

A thorough review of MC1's emissions estimation methodology was beyond the scope of this effort. However, several important aspects of the methodology were revealed and are worth noting.

- MC1 doesn't output the day a particular fire starts. The start days are triggered in MC1 when conditions are conducive to fire, based on climatology and conditions conducive to lightning strikes.
- A fire in a cell is completely independent of fires in any other cells; thus a fire can never be larger than the cell in which it initially ignited.
- All fires are completely "burned out" at the end of the month in which they began.
- A daily emission flux is not directly obtainable from the MC1 output because the emission flux is monthly and the duration of the fire in days is unknown.
- No information is available in the model to estimate plume rise using traditional heat release physics.

In addition to the above, the USDA-Forest Service (FS) staff has expressed reservations on using the model results in an absolute sense, recommending that the best way to interpret MC1 results is to compare future modeled values vs. present (as modeled) and interpret the trends, rather than absolute values projected by MCI. The USDA-FS also provided extensive confirmation and clarification of the MC1 documentation.[2]

SC&A used the data available from the MC1 output and developed methods to provide estimates for the fire event month and the other pollutants on a per fire per cell basis, based on the data provided from the MC1 model output.

Table 1 lists the variables SC&A used from those available from the MC1 output. This included MC1 data output for all years from 2000 through 2114, for 5 different initializations (Wind1, Wind13, Wind14, Wind26, and Wind28) for a reference case and a policy case. From these data, SC&A developed emissions data files for a 10-year base period from 2000 through 2009 and two sets of 30-year periods centered on 2050 (2035 through 2064) and 2100 (2085 through 2114).

Table 1. Variables utilized from MC1 model output.

Variable	Description
part_burn (PART_BURNyr)	fraction of cell burned
agg_vclass (AGG_VCLASSyr)	numeric indicator of combined vegetation type (see Table 2)
em_pm	particulate matter (C) produced by fire (g PM/m2)
vegc_mo (C_VEGmo)	total monthly live C

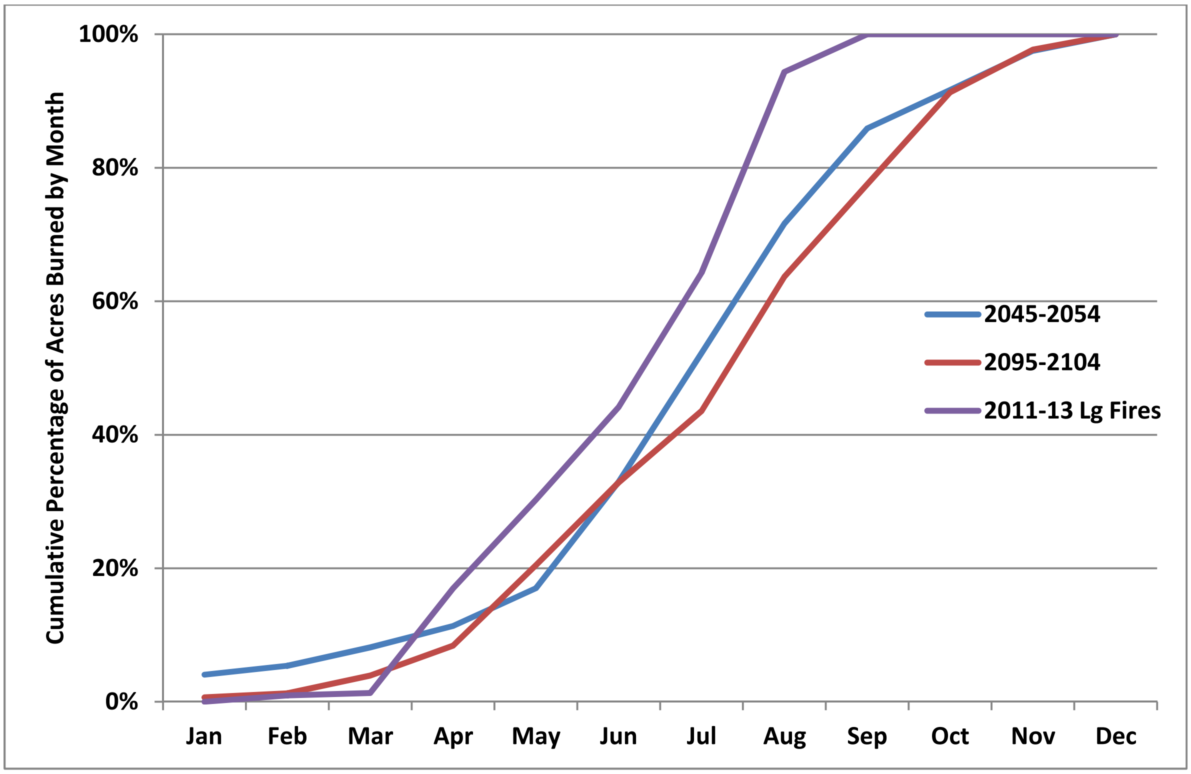
ESTIMATING THE MONTHLY DISTRIBUTION OF FIRES

The MC1 data file available to SC&A contained only annual particulate matter (PM) emissions for each year in each of MC1's 0.5 degree x 0.5 degree lat-long output cells. Many of these PM emissions are zero since fires occurred on only a small fraction of the US land area in a given year. The PM emissions available to SC&A were annual totals for each cell and did not include the MC1 output data on the month each fire occurred. Note that MC1 constrains fire ignitions, so a cell cannot have a fire more than once a year. Thus, each fire in MC1 occurs within the month it begins to burn.

SCA developed a method to indirectly infer the fire event month using other available MC1 model output. Briefly, the change in vegetation from one month to the next for a specific year (normalized over a 115 year period) was calculated by dividing the change in monthly vegetation for a given year, month, and scenario by the average change in monthly vegetation for over the 115 years (2000-2115), for that month and scenario for each cell. The resulting month in which this normalized ratio was the lowest was then identified as the month of the fire for that cell, year, and scenario. As a check, the monthly distribution of fires using the SC&A surrogate method is consistent with the current and historical monthly distribution of fires in the US.

Figure 1 shows a comparison of the cumulative distribution of the acreage burned by month from large fires over the three year historical period from 2011 to 2013 to the distributions from the two 10-year periods evaluated in this analysis. The differences were relatively minor when considered in the context of all assumptions in the MC1 model. The data plotted are for the time periods: 2045-2054 and 2095-2104 data as calculated by SC&A from the MC1 model output. Data for 2011-2013 represents large fires (40,000 acres or more) in the continental US, as reported in National Interagency Coordination Center (NICC) 2011, 2012, and 2013.

Figure 1. Cumulative distribution of acres burned from historical large fires and projected fires.



Source: 2045-2054 and 2095-2104 data as calculated by SC&A from the MC1 model output. Data for 2011-2013 represents large fires (40,000 acres or more) in the continental US.[5]

PROCESSING MC1 DATA TO CALCULATE MONTHLY EMISSIONS

The data obtained by SC&A included emissions data for only PM. Thus, SCA developed scaling factors to produce emission estimates for the other pollutants of interest to MIT and U.S. EPA. These pollutants were: PM10, PM2.5, CO, CO2, methane, and non-methane hydrocarbons. Fortunately, it was determined that the emission factors used by MC1 were the same as those used in Consume 2.1, a fire fuel consumption model available from the USDA Forest Service.[3,4]

As discussed above, the only emissions variable retained was "em_pm", the particle emissions per square meter per year in each cell. The "em_pm" data provides a basis for estimating PM2.5, PM10 and other pollutant emissions. It is worth noting that the fuel models used by MC1 and Consume are different and assumptions would need to be made to adapt the MC1 vegetation types to input to Consume or other BlueSky Framework approaches. At a minimum, we would need certain variables that were not retained during the MC1 model runs as well as information not currently produced by MC1 (but that may be available if MC1's outputs were modified). In its current state, MC1 would be difficult to adapt to provide the inputs needed to use the emissions estimation methods available in the

BlueSky Framework. Note, black carbon (BC) emissions are not estimated by Consume 2.1, and in MC1, BC emissions are computed in such a way that it appears to not be a simple scalar of PM.

First, emission factors were taken from the Consume 2.1 model for each wood/vegetation type. For each vegetation type, a scalar was calculated to estimate the emissions of PM2.5, PM10, CH4, CO and CO2 from em_pm (in $g/m^2/yr$) by dividing the Consume emission factor for each pollutant by the corresponding PM emission factor. The scalars in Table 2 were used to estimate annual emissions of these other pollutants from the "em_pm" data as follows: annual fire emissions are the product of the “em_pm” emissions, the “scalar” and the cell area (with appropriate unit conversions.

Emissions were estimated for the following pollutants: PM, PM10, PM2.5, CO, CO2, CH4, and NMHC. An annual emissions total was also produced as well as emissions of each pollutant by month. Since fires are assumed to occur in only one month of the year in a given cell, only one month for each record will have non-zero emissions data. Each cell is identified by its latitude and longitude. Cells with no fire in a given year are not included in the data file for that year.

Table 2. Scalars to develop emission estimates from MC1 output: em_pm (unitless).

agg_vclass	Description	PM	PM10	PM2.5	CO	CO2	CH4	NMHC
1	Douglas Fir	1.0	0.78	0.74	10.5	104.1	0.37	0.24
2	Hardwoods	1.0	0.67	0.60	6.8	82.1	0.35	0.29
3	Ponderosa / Lodgepole	1.0	0.63	0.56	4.5	80.9	0.21	0.16
4	Mixed Conifer	1.0	0.71	0.65	6.9	109.1	0.44	0.34
5	Juniper	1.0	0.72	0.66	5.8	114.2	0.42	0.37
	Sagebrush	1.0	0.66	0.59	4.5	69.0	0.26	0.30
7	Chaparral	1.0	0.59	0.51	4.5	95.5	0.17	0.31
8	Mean Values	1.0	0.67	0.61	6.0	91.0	0.31	0.28

Annual fire emissions were calculated using Equation 1.

Equation (1) $EMIS_{p,c} = em\_pm_c * scalar_p * Cell\_Area_c / (453.59 \text{ g/lb} * 2000 \text{ lb/ton})$

where

$EMIS_{p,c}$ = annual emissions of pollutant p in tons per year in cell c
Em_pm_c = annual particulate matter produced by fire (g PM/m^2) within cell c
$Scalar_p$ = scalar for pollutant p which yields an emission factor for pollutant p when multiplied by em_pm (unitless)
$Cell\_area_c$ = area of cell c (m^2)

Although each cell represents an area 0.5 degrees by 0.5 degrees, the actual area of each cell can differ depending on the latitude. Thus, the area of each cell differed depending upon the geographic location of the cell. Since the MC1 model assumes that a given fire burns in only one month, the annual emissions were assigned to the month in which it was determined that the fire had occurred, as discussed above, and monthly emissions for all other months were set to 0.

In addition to emissions, SC&A also calculated the acres burned within each cell, year, and scenario. Although this was not needed to estimate emissions, the acreage burned is a useful statistic for quality control and comparing to historical data. Having both the acreage burned and emissions also allows for determining some measure of the intensity of a fire. Cells with a high ratio of PM emissions per acre burned would be more intense than a cell where the same ratio is much lower. The number of acres burned in each cell, year, and scenario was calculated using Equation 2.

Equation (2) $Area\_Burned_c = Cell\_Area_c * PART\_BURNyr_c / 4046.586\ m^2/acre$

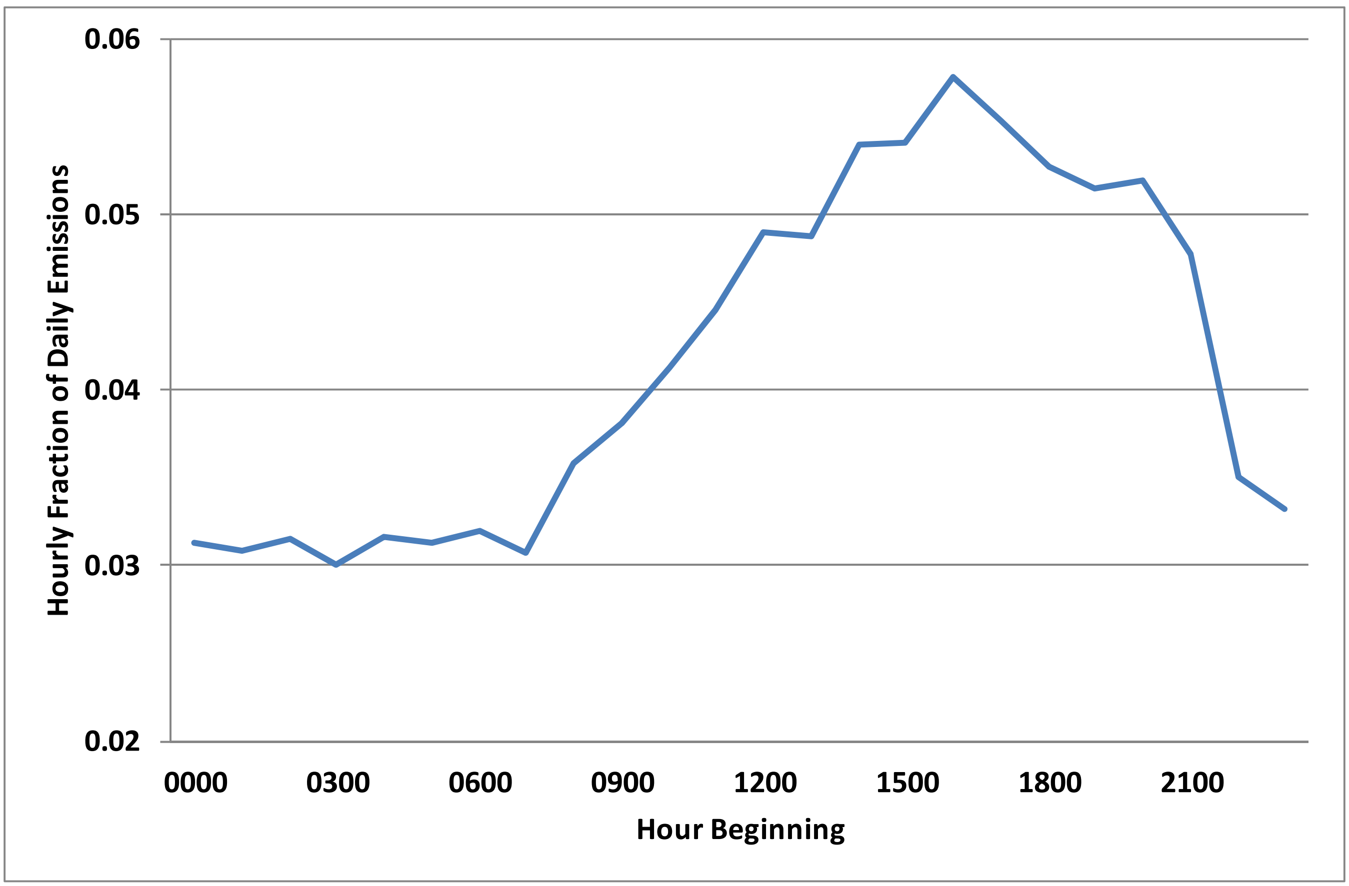
where

$Area\_Burned_c$ = total area of Cell c that burned in specified year (acres)
$Cell\_area_c$ = area of cell c (m^2)
$PART\_BURNyr_c$ = fraction of total area of Cell c that burned in specified year

Calculating Hourly Emissions

A typical diurnal profile of continental US wildfire emissions is provided in Figure 2. SC&A recommends that MIT apply these factors to the daily emissions to estimate hourly emissions. The data underlying Figure 2 were calculated as the average of the wildfire diurnal profiles for the 48 contiguous states used by EPA in its 2011 and 2018 emissions modeling platforms.[6] A review of the individual state profiles showed minimal variation from this average profile.

Figure 2. Average US wildfire diurnal profile



Source: Average of diurnal profiles for the 48 contiguous states.[6]

Calculation of Cell-Level Emission Scalars

One product of this effort was expected to be sets of monthly emission scalars between the base year period and each of the three consecutive 10-year periods. (As an example, cell-level emissions for January 2035, January 2045, January 2055, January 2085, January 2095, and January 2105 would be divided by January 2000 emissions to calculate scalars for each of these projection years.) However, because only a small fraction of cell-month combinations have a fire in any given year due to the relatively small cell size, and those combinations vary by year, it was found that the number of cell-month combinations with non-zero emissions in both the base and projection year was minimal. For example, in the Wind1 initialization for the Reference Case, only 0.87% of cell-month combinations over all of the 60 projection years had non-zero monthly projection year emissions and non-zero base year emissions for the corresponding base year, cell, and month. Thus, developing emission projection scalars at this geographic level was found to be non-productive and this effort was stopped. The recommended approach would be for MIT to develop emission scalars once the cells in these files have been aggregated, producing larger cell sizes.

RESULTING DATA

The end product of these analyses was a set of data files containing annual monthly wildfire emissions for pollutants PM, PM10, PM2.5, CO, CO2, CH4, and NMHC and annual acres burned by 0.5 degree latitude by 0.5 degree longitude cell. Each data file included data for each year from 2000-2009, 2035-2064, and 2085-2114. A separate file was prepared for each of 10 scenarios, including a reference and policy case, each modeled with five different wind initializations. The cells cover the contiguous US, and for each year, only the cells with an active fire in that year are included.

The resulting data are very variable from year to year and by scenario. Figures 3 and 4 provide a sampling of the resulting data. Figure 3 illustrates 10-year averages of the annual PM2.5 wildfire emissions under the reference and policy cases for two different wind initializations, for the entire modeled area. Figure 4 shows the monthly variation in PM2.5 emissions and acres burned for one scenario, averaged over the 10-year period from 2045 through 2054.

Figure 3. 10-year average annual PM2.5 emissions under the reference and policy scenario for two wind initializations.

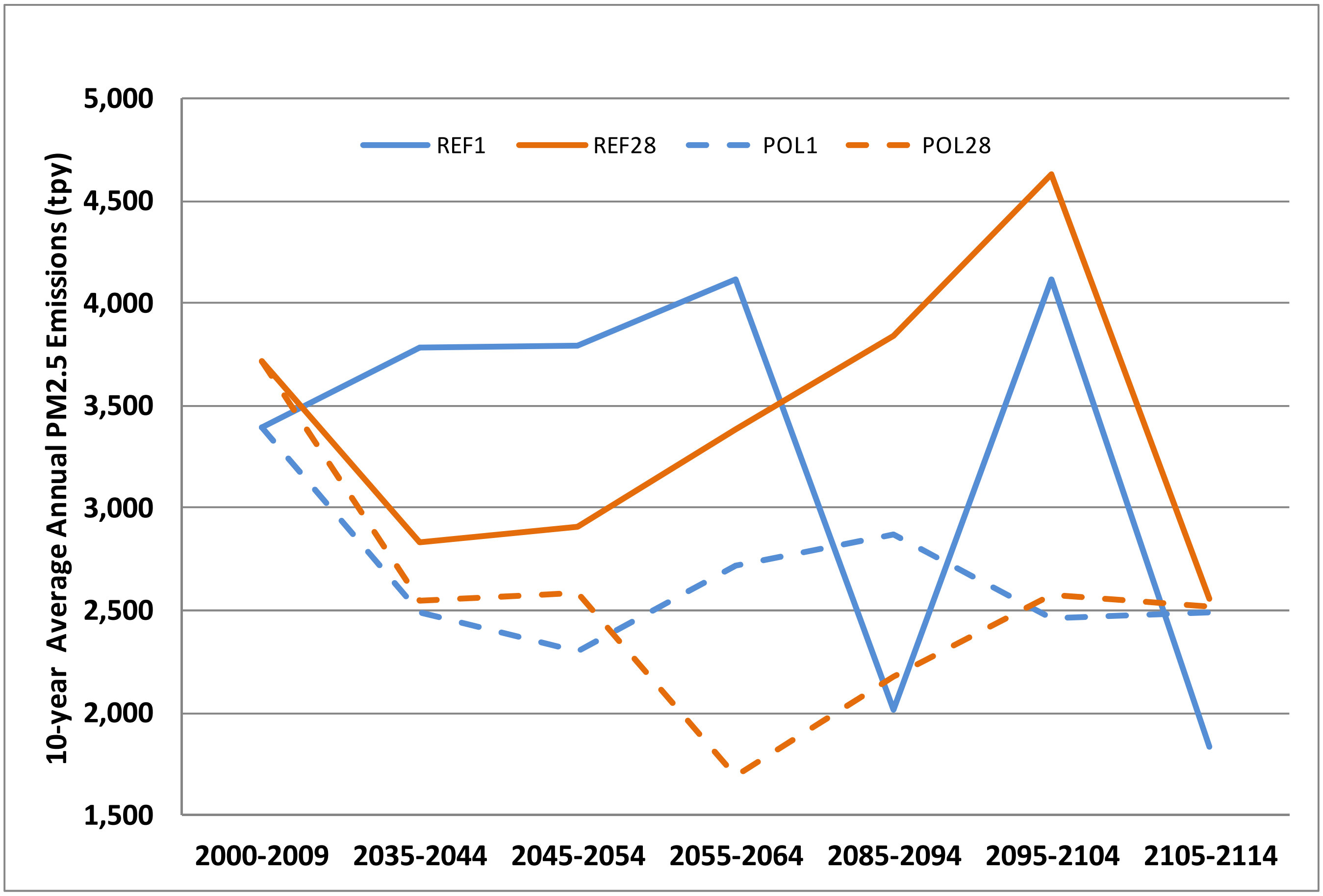
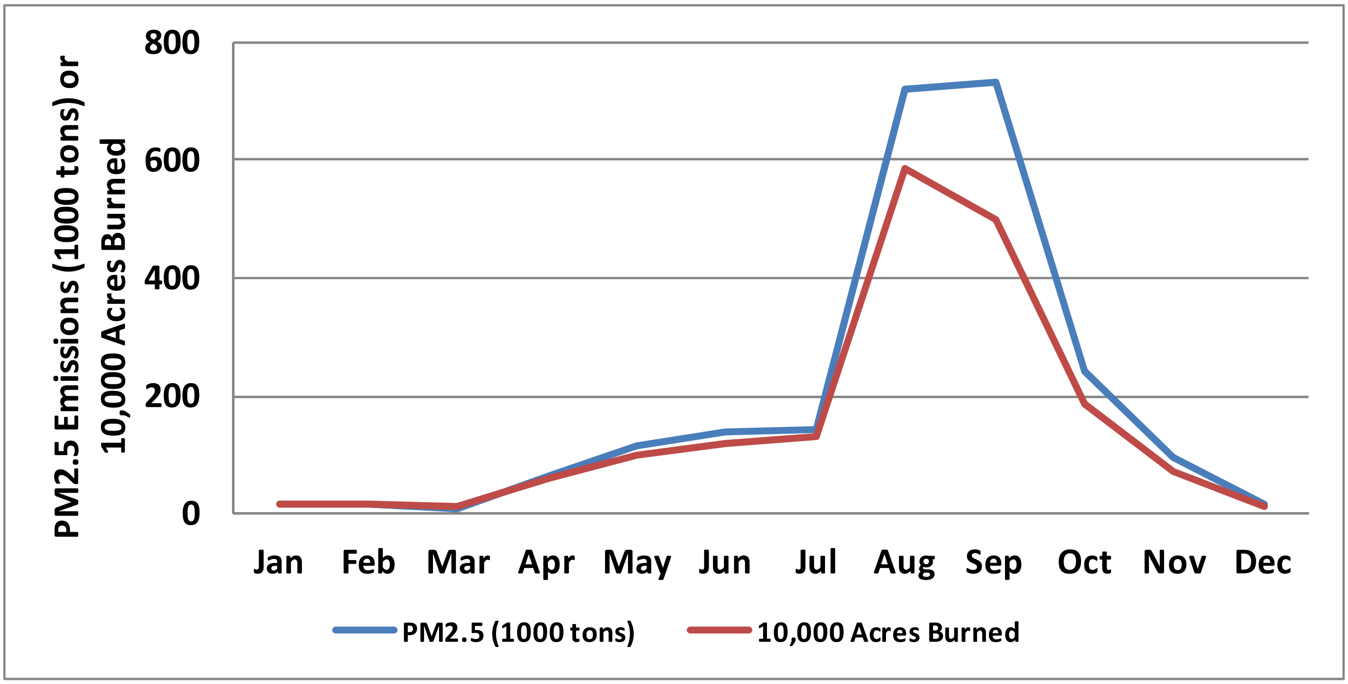


Figure 4. Sample monthly distribution of PM2.5 emissions and acres burned, average over 2045-2054 period, POL1 scenario.



CONCLUSIONS

This analysis showed an approach to calculating geographic-specific wildland fire emissions by month suitable for including in air quality modeling using output from a dynamic global vegetation model. The output from this model provided projections of vegetation growth, carbon storage, and wildfire incidence in the contiguous United States under a reference and policy case for five different wind initializations. Through the analysis conducted as described in this paper, emissions of PM, PM10, PM2.5, CO, CO2, CH4, and NMHC resulting from these projected wildland fires were calculated by month and cell for the lower US. The resulting data gives EPA the ability to perform climate change and air quality modeling based on these projected wildfire emissions. The monthly distributions of these fires, estimated using the approach described here, were found to be comparable to historical distribution of large wildfire emissions in the US. The uncertainties and limitations of this analysis and future research needs are discussed below.

UNCERTAINTIES AND LIMITATIONS

Based on the understanding of the MC1 model, the outputs of this analysis should not be interpreted as absolute values. Instead, the future modeled values should be compared to the historical modeled values, and among the modeled scenarios, to develop projected trends in wildfire emissions.

All fires were assumed to have reached burn completion within the calendar month of the fire start and emissions were calculated per fire, assigned to the month in which the fire was expected to have started. In actuality, the burn rate of the fire will vary by time of day and day of the fire, based on a number of external factors including meteorology, the spatial characteristics of the fuel loading, and the types of vegetation burned. The total number of days or hours that will be needed for the fire to burn out will also vary by fire. In addition, some fires will span more than one calendar month. These variations were not captured in this analysis.

FUTURE RESEARCH NEEDS

Over the course of this project, SC&A identified several areas where this analysis could be enhanced or expanded with additional resources. These are summarized below.

Daily Emissions

There is no objective way to convert monthly emissions into daily emissions. A daily emission flux is not directly obtainable from the MC1 output because the emission flux provided is "per fire" (i.e., monthly) and the duration of the fire in days is unknown. Our recommendation is that MIT randomly select a fire start date and duration within the specified fire month. Once this is done, parsing the daily emissions to hourly for modeling purposes is possible. SC&A recommends using the wildfire diurnal profile used by EPA in its 2011 and 2018 emissions modeling platforms for the 48 contiguous States, as shown in Figure 2. In future analyses, it may be possible to recode the MC1 model to output the fire start day information in future runs.

Plume Rise

SC&A was not able to identify any information in the model (MC1) to estimate plume rise using traditional heat release physics. For future analyses, SC&A identified satellite data sources that might be used to perform a calculation of plume rise. However, the resources that would be needed to perform this analysis were outside of the scope of the current project.

Black Carbon, Organic Carbon, and Ammonia

If estimates or emissions of these pollutants are needed, additional research would be needed in order to establish relationships between PM and these pollutants. SC&A was not able to perform this research within the project.

REFERENCES

1. MC1 Model: http://www.fsl.orst.edu/dgvm/mcgtr508.pdf and http://www.fsl.orst.edu/dgvm/publications.htm (accessed February 2014).

2. Kim, J. 2014. USDA-Forest Service, *personal communication*s to T. Pace.

3. Consume 2.1; http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume_download.shtml.

4. C. Hardy, Ward, D and Einfeld; "**Emissions from a major wildfire using a GIS: Rectification of Airborne Measurements".** Annual Meeting of Pacific Northwest International Section of the A & WMA; Maykut, Naydene, Tech. ed. Bellevue WA; November 11-13, 1992.

5. NICC 2011-2013; NICC; “Wildland Fire Summary and Statistics”; See http://www.predictiveservices.nifc.gov/intelligence/2011_statssumm/Annual_Report_2011.pdf; http://www.predictiveservices.nifc.gov/intelligence/2012_statssumm/2012Stats&Summ.html; http://www.predictiveservices.nifc.gov/intelligence/2013_Statssumm/2013Stats&Summ.html.

6. EPA 2014; EPA’s temporal profiles used for wildfires in the 2011 and 2018 modeling platforms, worksheets Tpro_2011.xlsx and tref_2011.xlsx . Accessed May 2014; See ftp://ftp.epa.gov/EmisInventory/2011v6/v1platform/reports/temporal_profiles/.

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KEY WORDS

Wildfires
Emission Inventories
PM
CO2
Climate Change