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Article in Climate Change and Environmental Sustainability - June 2019
DOI: 10.5958/2320-642X.2019.00005.X

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Estimation of Greenhouse Gas Emissions from Vegetation Fires in Central India

Tapas Ray1 • Dinesh Malasiya1 • Javid Ahmad Dar1 • P. K Khare1 • Mohammed Latif Khan1• Satyam Verma2 • Arun Dayanandan3

Abstract Interactions between biodiversity loss and climate change pose significant challenges for scientific research, policy-making, and the management of ecosystem processes. Greenhouse gases released from vegetation fires have been identified as a key environmental issue within the context of global warming and climate change due to increasing concentrations of greenhouse gases in the atmosphere. Occurring mostly during the dry season in India, the burning of vegetation causes a variety of negative environmental impacts on air and soil quality. The present study estimates greenhouse gas emissions caused by vegetation fires in Central India through the use of MODIS-based burnt area maps, Land sat-based land cover maps, biometric models, and pre-existing datasets. Greenhouse gas emissions were calculated as the product of area burnt, biomass loading per unit area, combustion factor, and emission factor. The results indicate that the number of fires and burnt areas increased significantly between 2002 and 2016, MODIS fire counts increased from 720 to 3165 between 2002 and 2016. A strong correlation between area burnt and greenhouse gas emissions allowed for accurate emissions estimates once area burnt was quantified. These variations in vegetation fire cycles have an important influence on forest composition and structure at the landscape and regional levels, and maintenance of this natural variability should be targeted by forest managers concerned with biodiversity conservation. These results indicate that continued vegetation fires will produce a greater impact on global carbon emissions and reduce forest biodiversity. Fire emissions have been increasing over the past decades and are likely to remain high due to forecasted changes in fire caused by climate change.

Keywords: Vegetation fires, Remote sensing and GIS, Greenhouse gas emission, Climate change, MODIS

1. Introduction

Forest fire cycles are a complex biophysical process with multiple direct and indirect effects on the atmosphere, the hydrosphere, and the biosphere. Moreover, in certain fire prone regions, fire disturbance is essential in maintaining a healthy ecosystem as it is a key factor in determining forest diversity and the dynamics of vegetation (Bajocco et al., 2010). An ecological conundrum, forest fires disturb flora, fauna, and man-made structures, causing wide-ranging environmental damage including shifts in the understory vegetation structure, composition, and forest splendour (Rojas-Sandoval and Acevedo-Rodríguez, 2014; Hoffmann et al., 2012; Brooks et al., 2004; Cochrane and Gerwing, 2002). Despite these negative impacts, forest fires are also beneficial for plant regeneration, nutrient recycling and natural processes initiating forest vegetation successions (Rowell and Moore, 2000).

Recognized as a major driving force of global change in terrestrial ecosystems (Rudel et al., 2005; Crutzen et al., 1979; Olson et al., 1983), burning of forest biomass is the second largest source of trace greenhouse gases (GHG) in the global atmosphere (Crutzen and Andreae, 1990; Bond et al., 2004). These forest fires strongly influence global and regional...
carbon cycles (Narayan et al., 2007), due in part to fire-induced decreases in forest carbon sequestration capacity (Van Der Werf et al., 2006; Wiedinmyer and Neff, 2007). In addition, forest fires release large amounts of greenhouse and trace gases such as carbon monoxide, methane, hydrocarbons, nitric oxide and nitrous oxide into the atmosphere (Seiler and Crutzen, 1980), of which Carbon dioxide (CO₂), Methane (CH₄), and Nitrous oxide (N₂O) are the primary greenhouse gases that contribute to global warming at 60%, 15% and 5%, respectively (Watson et al., 1996). Concentrations of these greenhouse gases in the atmosphere has been increasing at a rate of 0.4%, 3.0% and 0.22% per year, respectively (Battle et al., 1996).

While the normal forest fire season in India spans the months of February to June, most forest fires are anthropogenic in nature, caused through negligence, intentional setting, the collection of non-timber forest products such as Tenduleaves in Central India (Singh and Singh, 1987), and land clearing for shifting cultivation in the North-Eastern India (Singh and Singh, 1987). Ranjan and Upadhyay (2002) reported that 0.45 Mha of land is cleared under shifting cultivation each year, a practice which has removed 0.05 Mha of forest area every year in the North Eastern states of India, 17.22 Mt of total wood biomass, and 10.69 Mt Carbon at a rate of 1.72 Mt and 1.07 Mt C yr⁻¹, respectively (Manhas et al., 2006). To date, there are no comprehensive studies with respect to the burnt area, fire incidence rate, amount of biomass burnt, and carbon emissions in vegetation types of Madhya Pradesh, India. The present work of estimating burnt area and carbon emissions from forest vegetation fire has been undertaken to assess the amount of greenhouse gases released between 2002 and 2016, in Madhya Pradesh, India.

Most biomass burning emission studies rely on the model developed by Seiler and Crutzen (1980), combining information on above-ground biomass available for burning, burning area, combustion factors, and emission factors for a certain gas species and vegetation type to calculate pyrogenic emissions (Wooster et al., 2005).

The objectives of this study are to estimate atmospheric greenhouse gases emissions from vegetation fires in Madhya Pradesh using the latest high-resolution data available. We rely on a combination of forest burnt area maps and land cover maps derived from remote sensed data, statistical growth models for forests and shrub lands, forest inventory data, and results from the literature for combustion factors, emissions factors, and for biomass of a variety of land cover types.

2. Study Area

The study was conducted in the Central Indian state of Madhya Pradesh (MP). MP is the second largest state of the country with an area of 3,08,252 sq km, comprising 9.38% of the geographical area of the country. The state lies between 21° 17’-26° 52’ N latitudes and 78° 08’-82° 49’ E longitudes and has a subtropical climate. Madhya Pradesh can be divided into four different regions: the low-lying areas in north and north-west of Gwalior, the Malwa Plateau, the Satpura, and the Vindhyan Ranges (FSI, 2017). Average annual rainfall varies from about 654 mm to 2043 mm, and average annual temperature from about 20.8°C to 27.6°C, with the minimum temperature going as low as 6.4°C in December and January and the maximum temperature going up to 43.4°C in May and June. Elevation varies from 72 m to 1317 m. Champion and Seth (1968) classified the vegetation type in Madhya Pradesh to three forest type groups: Tropical Moist Deciduous, Tropical Dry Deciduous and Tropical Thorn Forests.

3. Material and Methods

3.1 Burnt area assessment

Burnt area data from 2002 to 2016 was derived from NASA’s Earth Observing System’s Moderate Resolution Imaging Spectroradiometer (MODIS) direct broadcast burnt area product (MCD64A1; http://modis-fire.umd.edu), which uses surface reflectance, daily active fire, and land cover products to delineate burnt areas and tag burn cells with the approximate burn date. This tool detected an approximation of burning at 500 m pixel resolution. MODIS has collected and stored image data since February 2000 and has been generating a number of land surface products to meet the goals of NASA’s Earth Science Enterprise (Justice et al., 1998). MODIS Fire Products are designed to provide information for both global change science and practical application (Justice & Korontzi, 2001; Kaufman et al., 1998a and 1998b), and provides two types of fire products: active fire products which give the location of current burning fires, and a burnt area product which gives the extent of burn scars over a specified time period.

3.2 Biomass estimation

Estimation of biomass is complex due to the high spatial heterogeneity of vegetation. For simplicity, all forest land
cover (except “Agriculture”) classes were aggregated into three main groups: Forests, Shrub lands, and Grasslands, on the basis of biomass estimation methodology given by the IPCC (2006). We used generic fuel (dead organic matter plus live biomass) biomass consumption values (tonnes dry matter ha⁻¹) for fires given by the IPCC (2006).

3.3 Combustion factors

Combustion factor, a measure of the proportion of the fuel combusted based on the size and architecture of the fuel load, the moisture content of the fuel, and the type of fire (i.e., intensity and rate of spread, which are markedly affected by climatic variability and regional differences). The ratio of fuel consumption to total available fuels is known as the combustion factor (van der Werf et al., 2006). Combustion factor is difficult to estimate as it is influenced by vegetation factors such as age, phenology, and moisture content, and also by factors related to fire behavior, namely fire line intensity, fire rate of spread, and flame residence time. Combustion factor values used in our analysis are from the IPCC guidelines for National Greenhouse Gas Inventories Volume 4 (IPCC, 2006).

3.4 Emission factors

Emission factors represent the quantity of a chemical species that is released to the atmosphere per unit biomass burnt (Andreae, 1991). Emission factors were collected from IPCC guidelines for National Greenhouse Gas Inventories volume 4 (IPCC, 2006). We used “Savanna and Grassland” emissions factors for shrub land and grasslands. “Tropical Forest” emissions factors were used for the forest land cover classes. We calculated pyrogenic emissions of the following chemical species: Carbon dioxide (CO₂), Carbon monoxide (CO), Nitrous oxide (N₂O), Methane (CH₄) and Nitric oxide (NOx) (Table 1).

Table 1. Emission factors (g kg⁻¹ Dry matter burnt) used in study (Andreae and Merlet, 2001)

<table>
<thead>
<tr>
<th>Chemical Species</th>
<th>Forests</th>
<th>Shrub land and Grassland</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1580</td>
<td>1613</td>
</tr>
<tr>
<td>CO</td>
<td>104</td>
<td>65</td>
</tr>
<tr>
<td>CH₄</td>
<td>6.8</td>
<td>2.3</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.20</td>
<td>0.21</td>
</tr>
<tr>
<td>NOx</td>
<td>1.6</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Methane (CH₄) pyrogenic emissions in Madhya Pradesh between 2002 and 2016 was calculated through the following equation:

\[ E = A \times Bm \times Cf \times Ef \]

Where \( E \) = emission of GHG (kg), \( A \) = area burnt (ha), \( Bm \) = biomass of m component on vegetation class (Mg/ha), \( Cf \) = combustion factor (%) and \( Ef \) = emission factor (gm/kg).

4. Results

4.1 Burnt area assessment

Inter-annual variability in number of fires and burnt area did not show a uniform trend and was wide-ranging during (Figure 1) the study period of 2002-2016. MODIS active fire data showed that the number of fires was low in 2002 (720), 2003 (728), 2014 (792) and 2015 (527), whereas fire incidences were high in 2008 (3,991), 2009 (5,982), 2011 (3,451), 2012 (5,435), and 2016 (3165) (Figure 2). Similarly, burnt area varied from 18,000 ha and 13,175 ha in 2002 and 2015 to 114,550 and 135,857 in 2009 and 2012 respectively.

During the fifteen-year study period, the highest burnt vegetation class was the deciduous broad leaf forest at an average 41,990 ha burnt annually. Plantations and grass lands were the lowest burnt vegetation class at 20 ha and 5 ha respectively. Shrubland burnt at an annual rate of 6,950 ha and was high in 2012 (50,275 ha) (Figure 3).

The majority of fires were clustered in the central region of Madhya Pradesh, including parts of the Satpura Tiger Reserve and Betul District (Figure 4). Fires were primarily located in regions of Madhya Pradesh with low rainfall.

4.2 Greenhouse gas emission

Total annual greenhouse gasses (GHG) emitted from vegetation fires in Madhya Pradesh for different gaseous species (CO₂, CO, N₂O, NOx, and CH₄) between 2002 and 2016 was 56.7150 Tg. The years of 2009 and 2012 showed highest greenhouse gases emissions in all greenhouse gases types, calculated at 7.9398 Tg in 2009 and 7.1091 Tg 2012. Greenhouse gas emissions was at its lowest across all greenhouse gas types in 2015 (0.7963 Tg). The highest emissions of a single GHG species in the study period was CO₂ at 53.0197 Tg, and the lowest single species emission was N₂O (Table 2).

It has been observed that Deciduous Broadleaf Forests (DBF) are contributing high emissions of GHG Gat 45.9013 Tg, followed by the Deciduous Needle leaf Forests (DNF) at
Figure 1. Study area location, land use and land cover, elevation and climate maps.

Figure 2. MODIS active fire counts between 2002 and 2016 in Madhya Pradesh, India

Figure 3. Area burnt in different vegetation classes between 2002 and 2016
Table 2. Annual greenhouse gas emissions per gas species from vegetation fire between 2002 and 2016 in Madhya Pradesh, India

<table>
<thead>
<tr>
<th>Year</th>
<th>CO₂</th>
<th>CO</th>
<th>CH₄</th>
<th>N₂O</th>
<th>NOₓ</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>0.9995</td>
<td>0.0639</td>
<td>0.0041</td>
<td>0.0001</td>
<td>0.0011</td>
<td>1.0688</td>
</tr>
<tr>
<td>2003</td>
<td>1.6338</td>
<td>0.0660</td>
<td>0.0042</td>
<td>0.0001</td>
<td>0.0011</td>
<td>1.7053</td>
</tr>
<tr>
<td>2004</td>
<td>4.4104</td>
<td>0.2886</td>
<td>0.0188</td>
<td>0.0006</td>
<td>0.0046</td>
<td>4.7229</td>
</tr>
<tr>
<td>2005</td>
<td>2.3761</td>
<td>0.1553</td>
<td>0.0101</td>
<td>0.0003</td>
<td>0.0025</td>
<td>2.5443</td>
</tr>
<tr>
<td>2006</td>
<td>2.2570</td>
<td>0.1473</td>
<td>0.0096</td>
<td>0.0003</td>
<td>0.0024</td>
<td>2.4165</td>
</tr>
<tr>
<td>2007</td>
<td>2.3529</td>
<td>0.1535</td>
<td>0.0100</td>
<td>0.0003</td>
<td>0.0025</td>
<td>2.5191</td>
</tr>
<tr>
<td>2008</td>
<td>6.4738</td>
<td>0.4235</td>
<td>0.0276</td>
<td>0.0008</td>
<td>0.0067</td>
<td>6.9324</td>
</tr>
<tr>
<td>2009</td>
<td>7.4147</td>
<td>0.4849</td>
<td>0.0316</td>
<td>0.0009</td>
<td>0.0077</td>
<td>7.9398</td>
</tr>
<tr>
<td>2010</td>
<td>4.1173</td>
<td>0.2695</td>
<td>0.0175</td>
<td>0.0005</td>
<td>0.0043</td>
<td>4.4091</td>
</tr>
<tr>
<td>2011</td>
<td>5.6750</td>
<td>0.3719</td>
<td>0.0250</td>
<td>0.0007</td>
<td>0.0058</td>
<td>6.0786</td>
</tr>
<tr>
<td>2012</td>
<td>6.6582</td>
<td>0.4169</td>
<td>0.0252</td>
<td>0.0008</td>
<td>0.0079</td>
<td>7.1091</td>
</tr>
<tr>
<td>2013</td>
<td>1.5458</td>
<td>0.1047</td>
<td>0.0068</td>
<td>0.0002</td>
<td>0.0017</td>
<td>1.6592</td>
</tr>
<tr>
<td>2014</td>
<td>1.1719</td>
<td>0.0784</td>
<td>0.0051</td>
<td>0.0002</td>
<td>0.0013</td>
<td>1.2568</td>
</tr>
<tr>
<td>2015</td>
<td>0.7446</td>
<td>0.0478</td>
<td>0.0031</td>
<td>0.0001</td>
<td>0.0008</td>
<td>0.7963</td>
</tr>
<tr>
<td>2016</td>
<td>5.1886</td>
<td>0.3399</td>
<td>0.0222</td>
<td>0.0007</td>
<td>0.0053</td>
<td>5.5567</td>
</tr>
<tr>
<td>Total</td>
<td>53.0197</td>
<td>3.4123</td>
<td>0.2207</td>
<td>0.0067</td>
<td>0.0556</td>
<td>56.7150</td>
</tr>
</tbody>
</table>

6.9925 Tg, Shrubland (SH) at 2.4166 Tg, Mixed Forest (MF) at 1.3857 Tg, Plantation (Pa) at 0.0182 Tg, and Grassland (Gr) at 0.0006 Tg (Table 3).

5. Discussion

Results of our analysis on greenhouse gas emissions per forest type based on satellite-based burnt area maps, land cover maps, and data on combustion factor, emission factor, and the amounts of trace gases in Madhya Pradesh, India, showed that tropical dry deciduous forests were the forest type most affected by fire in terms of burnt area and contribute the highest amounts of annual carbon emissions.

MODIS active fire counts between 2002 and 2016 in Madhya Pradesh indicated peaks in 2012 (5435 fires) and 2009 (4582 fires), and a positive trend from 2002 (720 fires) to 2016 (3165 fires). Area burnt and mean annual greenhouse
Table 3. Annual greenhouse gas emissions per forest type calculated between 2002 and 2016 in Madhya Pradesh, India

<table>
<thead>
<tr>
<th>Forest Types</th>
<th>CO₂</th>
<th>CO</th>
<th>CH₄</th>
<th>N₂O</th>
<th>NOₓ</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBF</td>
<td>42.8477</td>
<td>2.8204</td>
<td>0.1844</td>
<td>0.0054</td>
<td>0.0434</td>
<td>45.9013</td>
</tr>
<tr>
<td>MF</td>
<td>1.2868</td>
<td>0.0913</td>
<td>0.0060</td>
<td>0.0002</td>
<td>0.0014</td>
<td>1.3857</td>
</tr>
<tr>
<td>SH</td>
<td>2.3402</td>
<td>0.0698</td>
<td>0.0022</td>
<td>0.0002</td>
<td>0.0042</td>
<td>2.4166</td>
</tr>
<tr>
<td>Pa</td>
<td>0.0170</td>
<td>0.0011</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0182</td>
</tr>
<tr>
<td>Gr</td>
<td>0.0006</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0006</td>
<td>0.0006</td>
</tr>
<tr>
<td>DNF</td>
<td>6.5273</td>
<td>0.4296</td>
<td>0.0281</td>
<td>0.0008</td>
<td>0.0066</td>
<td>6.9925</td>
</tr>
<tr>
<td>Total</td>
<td>53.0197</td>
<td>3.4123</td>
<td>0.2207</td>
<td>0.0067</td>
<td>0.0556</td>
<td>56.7150</td>
</tr>
</tbody>
</table>

gas emissions were found be highly correlated between the years 2002 and 2016, with 2009 and 2012 showing the highest amount of both factors, as well as the highest intensity and spread of forest fires (14% and 13% of total respectively).

From emissions observations of burnt area under forest types, dry months were shown to release highest emissions across all vegetation types. Additionally, it is suggested that dense forest types emit more CO₂ than open forest types due to a high accumulation of flammable organic material in the form of litter and dry grass.

The total amount of Greenhouse Gases (GHG) emitted in Madhya Pradesh was 56.7150 (Tg). The GHG emissions in the years 2002 and 2016 increased from 1.0688 (Tg) (2%) to 5.5567 (Tg) (10%) respectively. The Deciduous Broadleaf Forests (DBF) (81% of total) and Deciduous Needle Leaf Forests (DNF) (12% of total) were responsible for the largest contribution of these greenhouse gas emissions. During the fifteen-year study period, the vegetation class most affected by fire was the deciduous broad leaf (DBF) forest at an average of 41,990 ha burned annually while the vegetation classes least affected by fire were the plantations and grasslands.

Biomass burning is a major source of many greenhouse and trace gases, such as Carbon dioxide (CO₂), Methane (CH₄), Carbon monoxide (CO), Nitrous oxide (N₂O), and Nitric oxide (NOₓ). Of all five chemical species studied, CO₂ (93% of total) and CO (6% of total) were the gases emitted in highest magnitudes across all vegetation types.

Unlike other sources of GHGs, emissions from biomass burning are strongly seasonal and heavily concentrated in the dry season/summer months. Thus, during peak fire activity periods, the public health and environmental impacts of GHG emissions may be much higher than inferred from the relatively low overall value. Biomass fires emit the same gases (CO, Hydrocarbons, NOₓ) as fossil fuel burning in industrial regions, many of which lead to the formation of photochemical smog as the hot gases from these fires rise into the atmosphere. Frequently, these smoke plumes form clouds, re-evaporating without causing rain and lead to further fire-supporting dry conditions. It must also be noted that actual annual emissions would be markedly higher than those estimated in this study as emissions from non-forest (e.g. agricultural) areas have not been considered. While there are cases of emissions from industry, agriculture, and transportation directly resulting in the production of goods and services, most GHG emissions are associated with environmental and economic damages and losses.

As the factors regulating wildfires are dynamic and continually change as the environment responds to global climatic change, we expect that fire activity will continue to increase as a result and thus policies focused on fire prevention, including the use of prescribed fire to maintain fire regime in the ecosystems, must be considered with great care. To develop practical policies for conservation effectiveness in protected areas, it is essential to integrate remotely sensed information with human population and socio-economic data. In this regard, satellite-detected fire pixels proved to be an effective surrogate for anthropogenic disturbance useful for forest fire management in Central India, particularly in protected areas.

6. Conclusion

The spatial data provided in this study can support the improvement and prioritization of management strategies for protected area monitoring in India, and the spatial database generated will be useful in studies related to the influence of fire on species regeneration and adaptability, ecological modelling, and ecological damage assessment. The results of our study show the need for improved historical and future carbon emission estimates, in addition to better estimates of post-fire analyses and reduction in
the uncertainty. Fire emissions have been increasing over the past two decades and are likely to remain high for the upcoming decades due to forecasted changes in fire regimes caused by climate change.

Acknowledgment

The authors acknowledge the financial support provided by Department of Biotechnology, Government of India (No. BT/PR12899/NDB/39/506/2015 dt. 20/06/2017). The Third Author thanks the Council of Scientific and Industrial Research, Government of India, New Delhi, for partial support provided through the Junior Research Fellowship program (No:09/150(0134)/2018-EMR-1).

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