Estimation of pyrogenic carbon emissions from forests of Sikkim Himalaya, India: a geoinformatics approach

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With a view to understanding the micro-level mechanisms and lay the future path for improved carbon emission estimations from forest fires, we estimate fire emissions in Sikkim Himalaya, India. Remote sensing and geographical information system were used for fire scar identification, by mapping the multiple strata-based carbon density and partitioning the forest carbon into multiple pools. Fraction of carbon consumed in fire was further partitioned into the processes of flaming and smouldering. The estimation of trace gases of carbon dioxide, carbon monoxide and methane was made accordingly.

Keywords: Carbon emissions, forest fire, geoinformatics approach, remote sensing.

WITH climate change gradually occupying centre stage in the global environmental governance, the forests and carbon locked in them are increasingly being seen as a commodity to be conserved. For representing forest in climate change policy at regional, national and global levels, the first step is the credible accounting of carbon stocks and changes therein emanating from anthropogenic activities[1]. By playing an important role in the global carbon balance, both as carbon sources and sinks, forests have the potential to form an important component in efforts to combat global climate change.

The pyrogenic forest carbon emissions contribute a significant amount globally though a definitive estimate is not yet available. Even though wildfires are a natural ecological process in the evolution of forests, the anthropogenic forest fires have recently assumed dimensions which have not only added to the global greenhouse gas (GHG) emissions, but have also altered the ecological and succession processes of forest species.

Trace gases, i.e. carbon dioxide, methane and non-methane hydrocarbons, carbon monoxide, nitrogen gases, carbonyl sulphide, methyl chloride emissions and aerosols from biomass burning represent a significant part of total gas emissions[2,3]. The nitrogen cycling budget is also greatly influenced by biomass burning[4]. Biomass burning also results in the production of aerosols composed of organic hygroscopic particles and graphitic carbon. The smoke particles influence the radiation budget by altering the surface albedo, and atmospheric scattering and reflectance[5].

Even though work has been done at the global and regional levels in terms of estimation of emissions and modelling their effects on the atmosphere and impacts on global climate change, local estimations are also required to understand micro-scale mechanisms[3]. With this idea in mind, the present article focuses on high-resolution estimation of pyrogenic carbon emissions from the forests of Sikkim Himalaya, India making use of ground survey, remote sensing and geographical information system (GIS).

Location of the study site

Sikkim is a mountainous state of India in the Eastern Himalaya, extending approximately 114 km from north to south and 64 km from east to west, between 27°00′46″–28°07′48″N and 88°00′58″–88°55′25″E (Figure 1). It encompasses a great altitudinal compression ranging from 300 to 8585 m amsl.

Forest fires in Sikkim

Forestry is the major land use in the state covering around 47.69% of the total geographical area[6]. From the point of view of vulnerability to forest fires, the forests of Sikkim can be grouped into two classes, i.e. the lower hill deciduous forests which shed their leaves in February–March, and the middle hill and upper hill forests.

The former ones comprising hardwood trees like *Shorea robusta*, *Tectona grandis* and *Terminalia myriocarpa* are highly prone to forest fires due to the fuel load of leaf litter during dry season. Winter precipitation dampens fires, but with winters becoming increasingly warm and dry, forest fires are continuing for longer periods and also ascending to higher altitudes.

The latter group is primarily composed of oaks, *Abies densa*, *Tsuga dumosa*, rhododendrons and high-altitude

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Figure 1. Location of the study site (Sikkim, India).

bamboos such as *Arundinaria*. This group is not as vulnerable but can be highly susceptible to fires during drought years due to large amounts of broken branches and logs on the forest floor as a result of snowfall. Oaks have high calorific value and the fire, if it takes the form of a canopy fire, can carry on for several days. Subsequently, the middle storey vegetation of dwarf bamboo thickets, *Viburnum* sp. and *Edgeworthia* sp. can aggressively colonize the burnt area and prevent the climax species from regenerating.

Fire intensity varies in a systematic way with the degree of drying of ground vegetation and weather conditions. The fire hazardness is negatively correlated with December–January rainfall, and positively correlated with the average daily temperature. The greatest fire hazard is in April–May just before the monsoon arrives. It is exacerbated by the development of more windy conditions during that period.

The year 2009 was specially dry and Sikkim recorded one of highest forest fire incidences in that year. This study estimates pyrogenic carbon emissions from the forests for the year 2009 only.

Forest fire chemistry

The chemistry of forest fuels is complex due to unpredictable arrangement of fuel load, moisture gradients and highly variable nonlinear influences of weather conditions[2]. Plant material consists of polymeric organic compounds with plant tissue having approximately 50% carbon, 44% oxygen and 5% hydrogen by weight. The complete combustion of plant fuel can be shown as follows[7]

$$4C_6H_9O_4 + 25O_2 + (0.332MH_2O + 94.0N_2)$$
$$\rightarrow 18H_2O + 24CO_2 + (0.332MH_2O + 94.0N_2)$$
$$+ 110.6 \times 10^9 J.$$

where M is per cent of moisture content of its oven dry weight.

However, the combustion of plant material from open fires is rarely 100% complete and efficient. On burning of vegetation, carbon is released in the form of carbon dioxide, carbon monoxide, hydrocarbons, particulate matter and pyrolysis products including hydrocarbons[2,8]. Two types of combustion occur during biomass burning – flaming combustion and smouldering combustion[9]. Duration and occurrences of flaming and combustion phases and combustion efficiency are highly influenced by the fuel characteristics. Smouldering combustion phase is more favourable for production of particulate matter, carbon monoxide and methane[2]. For boreal forests, field and laboratory measurements have both shown that the emission factors for smouldering combustion are much higher than those for flaming combustion[10].

Forest fire mapping methodologies

It would be worthwhile to review the forest fire mapping methodologies before selecting a suitable one for the present study. The physical mapping of forest fires, particularly in mountainous terrain was both physically and financially demanding. It was not possible to map an active fire in terms of its spread since it was still dynamically spreading. The field records based on physical manual reporting always result in an underestimation, since many small fires and those from inaccessible areas always go unreported. In such circumstances remote sensing and GIS offer suitable solution. Fire causes changes in the reflectance of surface in different wavelengths (near infrared (NIR), SWIR, visible, etc.) of the electromagnetic spectrum along with changes in the surface temperature. Due to these changes, burnt area can be mapped reasonably accurately with the help of satellite images with suitable band combinations[11]. Remote sensing operating at NIR and thermal bands offer insights which are not available to the naked eye. Typical spectral reflectance characteristics of fire scar and healthy vegetation offer capabilities of burnt area estimation. Normalized difference vegetation index (NDVI) and vegetation anomaly index can be used. For example, Landsat images have the ability to capture signals from recent burning events due to charcoal and ash accumulation just after the fire when NIR vegetation signal is reduced.

The estimated area coupled with the type and amount of fuel load can then be used for estimating emissions for a given intensity of forest fire. However, the accuracy of estimates of emissions from forest fires could be affected due to the complexity of mapping active fires and quantification of the variable levels of fuels available for burning[12].

Material and methods

Data for accounting can be gathered from a variety of sources, including existing secondary data, remotely sensed data and primary data through field surveys. The amount of data from each source depends on the quality of the source as well as the trade-offs that must be made between accounting for accuracy and costs of resources and time[13]. With this background, various parameters were collected from both primary and secondary sources for the study site of Sikkim Himalaya. For improving the accuracy of estimates, the forest area was stratified into those with similar carbon characteristics. Primary sources used in the study are the remote sensing images, digitization of the burn scars and personal observations, and the secondary sources used are published reports like forest-type maps, carbon density and forest-cover maps from the Forest Survey of India (FSI). Forest fires of the year 2009 only were considered.

Assessment of burnt area

In the present case we detected the fire scars by visual interpretation of satellite images over different combinations of bands. For this purpose we selected the IRS P6 LISS III imageries with data for three seasons – 10 January 2009, 23 March 2009 and 10 May 2009. LISS III is a multi-spectral sensor operating in four spectral bands. Three bands are in visible and NIR, and one in the SWIR region. The spectral range operational in the bands are band 1 (620–670 nm), band 2 (841–876 nm), band 3 (459–479 nm) and band 4 (1550–1700 nm). We processed the satellite data in the ERDAS Imagine 9.1 software environment. We did the training of visual interpretation by first identifying the known locations of fire occurrences in the satellite images. This was done by assigning different colours to different band combinations and finding the suitable combination which made the fire scar most conspicuous in the particular area. Contrast stretching was also done for accentuating the discrimination of burnt areas. We then digitized the fire burnt areas in the form of polygons and saved all the fire polygons as a vector layer in the form of shapefiles (Figure 2). We used GIS tools for mapping and analysis.

Pre-burn forest carbon assessment

There are large differences in the various types of vegetation carbon pools in carbon content, fuel composition (quality, moisture and other factors) and consumption during burning[14]. Due to large differences in the pools, they need to be separated. In the present study the pre-burn carbon assessment is based on carbon stock accounting done by FSI. Accounting of carbon stocks has been separated in the different carbon pools of above-ground biomass (AGB), below-ground biomass (BGB), dead organic matter (wood), dead organic matter (litter) and soil organic matter (SOM). Carbon content varies not only according to the forest type, but also with respect to forest density. Therefore, thematic layers of forest type and forest density are also prepared.

Forest types of Sikkim

Forest-type mapping has been done by FSI on the basis of extensive study in GIS framework using relevant layers like soil, rainfall and temperature along with remote sensing data, details from forest management plans and inventory information. For the purpose of carbon mapping, these forest types have been regrouped as below for the study site. Figure 3 shows their distribution. (i) Tropical moist deciduous forests; (ii) Tropical–subtropical dry evergreen and broadleaved hill forests; (iii) Montane moist temperate forests; (iv) sub-alpine and dry temperate forests; (v) Alpine scrub; (vi) Plantation/tree outside forests (TOF).

Forest cover mapping of Sikkim

Forest cover mapping is based on State of Forest Report (SFR) 2011 prepared by FSI[6]. This mapping has been done on the basis of digital image processing of IRS P6, LISS III data supported by extensive ground truthing with overall accuracy of classification being 91.97%. Forest cover as divided into the following groups has been used for the present study:

(i) Very dense forest (VDF) – all lands with tree canopy density of 70% and above.
(ii) Moderately dense forest (MDF) – all lands with tree canopy density between 40% and 70%.
(iii) Open forest (OF) – all lands with tree canopy density between 10% and 40%.

Figure 4 shows the forest cover map of Sikkim (SFR 2011).

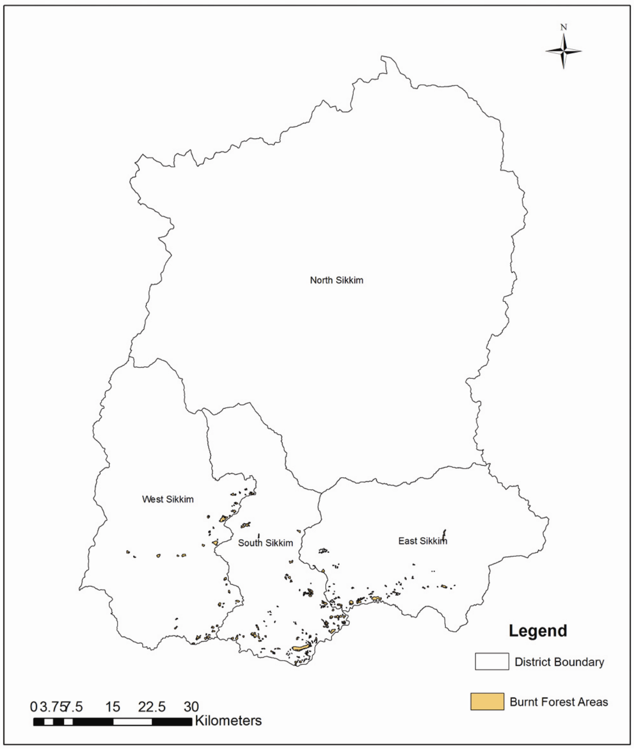

Figure 2. Forest fire map.

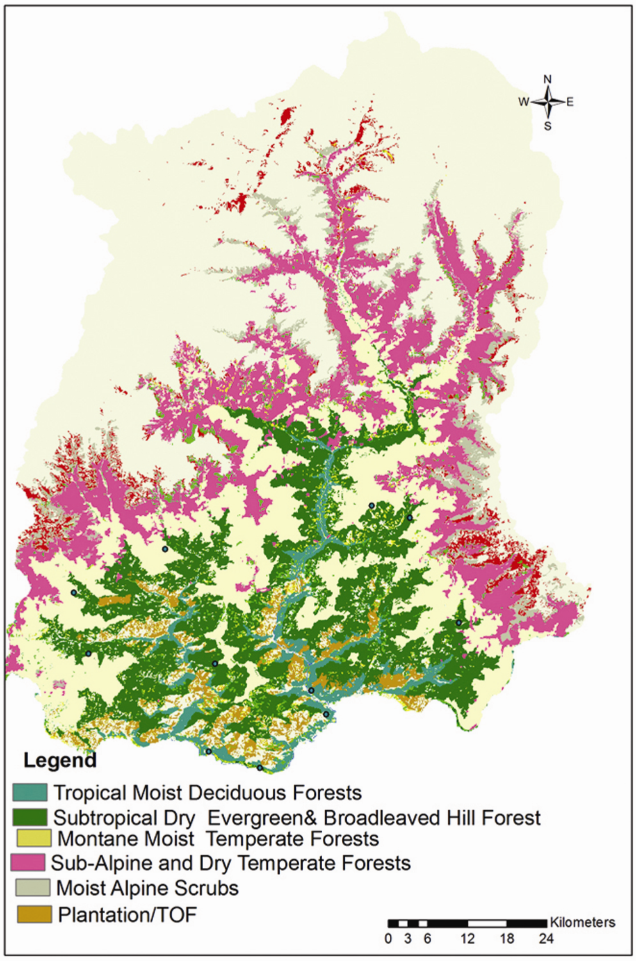

Figure 3. Forest type map of Sikkim.

Table 1. Carbon density in different carbon pools

Forest type	Forest cover density	Total carbon stock density (tonnes/ha)	AGB	BGB	Dead wood	Litter	SOM
Tropical moist deciduous forest	VDF	96.9	20.00	4.00	1.00	4.00	63.00
Tropical moist deciduous forest	MDF	90.53	20.08	4.13	0.82	2.71	62.79
Tropical moist deciduous forest	OF	60.6	18.33	3.77	0.40	1.47	36.58
Tropical, subtropical dry evergreen and broadleaved hill forest	VDF	152.78	40.34	15.84	1.24	0.22	95.73
Tropical, subtropical dry evergreen and broadleaved hill forest	MDF	128.38	30.93	12.14	0.37	0.81	84.14
Tropical, subtropical dry evergreen and broadleaved hill forest	OF	39.57	13.54	5.32	0.20	0.49	20.02
Montane moist temperate forests	VDF	197.72	63.77	16.10	1.36	3.34	113.14
Montane moist temperate forests	MDF	132.99	33.06	8.34	0.37	1.54	89.69
Montane moist temperate forests	OF	93.99	10.27	2.59	0.20	1.39	79.52
Plantation/tree outside forests (TOF)	MDF	102.35	25.21	5.18	0.36	2.81	68.74
Plantation/TOF	OF	73.4	11.91	2.45	0.00	1.18	58.24

VDF, Very dense forest; MDF, Moderately dense forest; OF, Open forest; AGB, Above-ground biomass; BGB, Below-ground biomass; SOM, Soil organic matter.

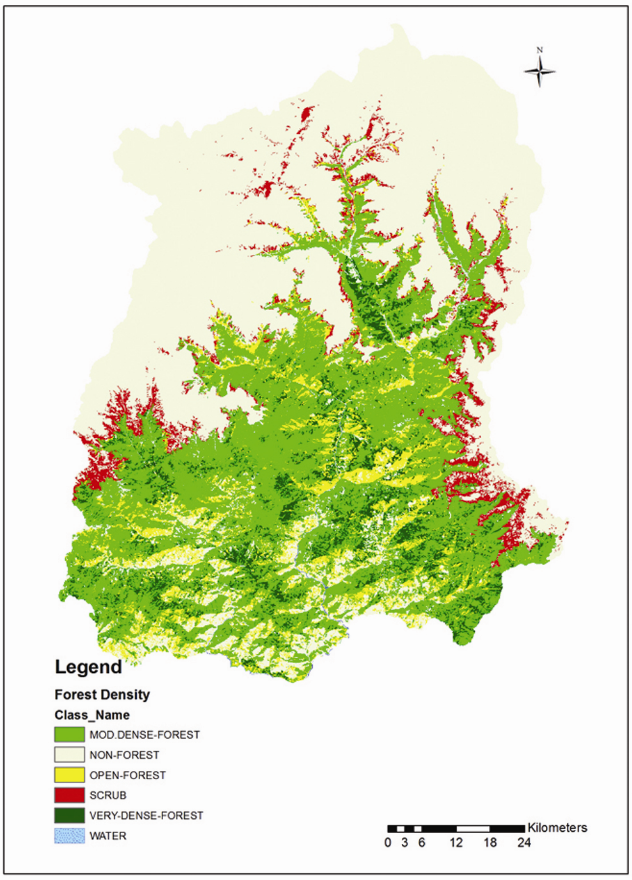

Figure 4. Forest density map of Sikkim.

GIS analysis

Forest type map and forest density maps were vectorized and then overlaid (with intersection functionality) in Arc GIS 10.2 environment to obtain a composite type density map having 18 type-density classes.

Table 1 shows the carbon density (tonnes/ha) against different carbon pools[15].

The composite forest type-density classified areas having 18 classes were then overlaid with forest fire polygons. This allowed the extraction of burnt area of the forests having a combination of particular density and class. The areas of the respective polygons with particular type-density classes were then added to get the area burnt in a particular forest type-density class. This was done for all the forest type-density classes where forest fire occurred.

Estimation of carbon emissions

In simplest terms, according to the IPCC methodology[16], the GHGs directly released from the forest fires can be summarized as follows

$$L_{\text{fire}} = A \times B \times C \times D \times 10^{-6},$$

where L_{fire} is the amount of GHG released due to fire (tonnes), A the area burnt (ha), B the mass of 'available' fuel (kg dry matter ha^{-1}), C the combustion efficiency (or fraction of the biomass combusted; dimensionless) and D is the emission factor g (kg dry matter)$^{-1}$.

For the purpose of estimating carbon release from biomass burning (C_t), Seiler and Crutzen[17] have used the following equation

$$C_t = A \times B \times f_c \times \beta,$$

where A is the total area burned (ha), B the biomass density (tonnes/ha), f_c the fraction of biomass that is carbon, and β is the fraction of carbon consumed during burning.

Here we use this standard equation that also includes other below-ground components like deadwood, leaf litter and SOM. There are many species present in a single burnt area with multiple values of f_c according to the species. Therefore, rather than using biomass density, carbon density has been used so that multiple values of f_c can be integrated in any burnt area. The carbon emitted from a particular pool has been obtained by multiplying carbon density, area burnt and fraction of carbon consumed.

The emissions from flaming combustion and smouldering combustion have been estimated separately. Based on the fire behaviour in different forest types and our own observations, the allocation of forest fire in flaming and combustion in different forest types and different carbon pools has been done. These factors vary from year to year depending on the intensity of fires.

Several trace gases are also released during forest fire. The amount of any specific trace gas released during fires (E_s) can be estimated as

$$E_s = C_t + E_{fs},$$

where E_{fs} is the emission factor (in weight of gas released per weight of carbon burned) for a specific gas species[18].

In order to increase the granularity and improve the estimates, the above equation can be further split into the flaming combustion and smouldering combustion components[19]

$$E_s = C_{t-f}\ E_{fs-f} + C_{t-s} E_{fs-s},$$

where subscripts f and s refer to flaming and smouldering combustion components respectively. Based on the previous studies of trace gas emissions from the forests[19,20], it is assumed that 80% of the carbon in above-ground biomass and deadwood is consumed in flaming combustion and 20% in smouldering combustion, whereas 20% of the carbon in below-ground biomass and litter is consumed in flaming fires and 80% in smouldering fires.

Emission factor averages are defined by IPCC LUCF Sector Good Practice Guidance, but they are not available separately for flaming and combustion. The emission factors as shown in Table 2 have been adopted for the present study[19].

SOM contributes a major portion of the carbon pool. Only a part of heat is radiated to the soil and its effect is variable over the depth of the soil because of the temperature gradient, soil composition (including moisture) and structure (porosity), etc.[21]. These effects may range from destruction of SOM to even its increase due to piling up of burnt material[22]. In the present study, based on the results of Campbell *et al.*[23], the combustion factor for soil organic carbon has been taken as 0.04 for a soil burning depth of 2.0–4.0 cm. According to the type of forest fires in Sikkim and edaphic profile, it has been assumed that SOM is consumed only through the smouldering.

Table 2. Emission factors for trace gases

	Emission factor, *g* (gas/kg total carbon)		
Combustion type	CO_2	CO	CH_4
Flaming	3145	190	5.5
Smouldering	2590	460	15.2

Results

The pyrogenic carbon emissions and emissions of trace gases vary according to the carbon pool. From the burnt forest area of 1287.62 ha, the carbon emitted from the forests is to the tune of 7512.2 tonnes. Table 3 provides the forest type-wise, forest density-wise, carbon pool-wise and combustion type-wise detailed emission analysis. There are wide variations in the proportional contributions from different forest types across different carbon pools (Figure 5). Forest type category-wise tropical moist deciduous forest fires emit maximum carbon amounting to 3521.29 tonnes, of which maximum share of 2513.40 tonnes (i.e. 71.38%) is contributed by moderately dense forests (Tables 3 and 4). Montane moist temperate forests contribute a meagre 5.36% of the total emissions (Figure 6). Among the trace gases, maximum contribution (88.72%), i.e. 21,194 tonnes is from CO_2 and minimum contribution (0.4%), i.e. 84 tonnes is from CH_4. CO contributes 10.93%, i.e. 2610 tonnes (Table 5). Carbon pool-wise emission analysis reveals that maximum emissions to the tune of 3351.18 tonnes (44.6%) are contributed by above-ground biomass, followed by those from SOM. Below-ground biomass contributes the minimum in the total share of emissions (Figure 7).

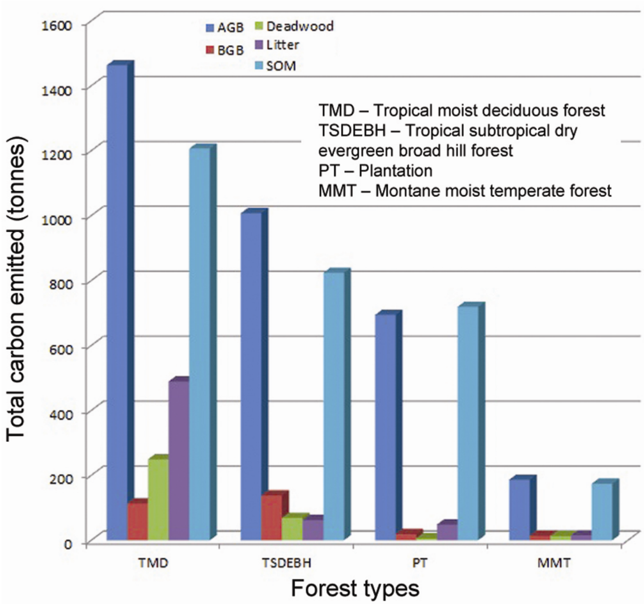

Figure 5. Forest type-wise and pool-wise carbon emissions.

Table 3. Emissions from different carbon pools

Forest type	Forest cover density	Burnt area (ha)	Carbon density (tonnes/ha)					Fraction of carbon consumed in					Total carbon emitted (tonnes)	Allocation of carbon in flaming and smouldering (tonnes)		Gases released (tonnes)		
			AGB	BGB	Deadwood	Litter	SOM	AGB	BGB	Deadwood	Litter	SOM	Sum of (area burnt × carbon density × fraction)	Flaming	Smouldering	CO_2	CO	CH_4
Tropical moist deciduous forest	VDF	17.23	20.00	4.00	1.00	4.00	63.00	0.15	0.05	0.70	0.40	0.04	138.18	57.20	80.98	390	48	2
Tropical moist deciduous forest	MDF	340.29	20.08	4.13	0.82	2.71	62.79	0.15	0.05	0.70	0.40	0.04	2513.40	1063.90	1449.50	7100	869	28
Tropical moist deciduous forest	OF	210.84	18.33	3.77	0.40	1.47	36.58	0.10	0.05	0.50	0.30	0.04	869.71	369.41	500.30	2458	300	10
Tropical, subtropical dry evergreen and broadleaved hill forest	VDF	20.67	40.34	15.84	1.24	0.22	95.73	0.12	0.04	0.70	0.30	0.04	211.58	97.25	114.33	602	71	2
Tropical, subtropical dry evergreen and broadleaved hill forest	MDF	177.77	30.93	12.14	0.37	0.81	84.14	0.12	0.04	0.50	0.30	0.04	1420.01	579.72	840.29	4000	497	16
Tropical, subtropical dry evergreen and broadleaved hill forest	OF	182.97	13.54	5.32	0.20	0.49	20.02	0.10	0.04	0.50	0.20	0.04	469.59	224.33	245.26	1341	155	5
Montane moist temperate forests	VDF	18.557	63.77	16.10	1.36	3.34	113.14	0.10	0.03	0.40	0.15	0.04	230.68	106.41	124.27	657	77	2
Montane moist temperate forest	MDF	18.135	33.06	8.34	0.37	1.54	89.69	0.10	0.03	0.40	0.15	0.04	136.39	51.83	84.56	382	49	2
Montane moist temperate forest	OF	7.9091	10.27	2.59	0.20	1.39	79.52	0.10	0.03	0.30	0.15	0.04	36.03	7.34	28.69	97	15	0.5
Plantation/TOF	MDF	85.298	25.21	5.18	0.36	2.81	68.74	0.15	0.02	0.20	0.10	0.04	595.99	269.49	326.50	1693	201	6
Plantation/TOF	OF	207.94	11.91	2.45	0.00	1.18	58.24	0.15	0.02	0.20	0.10	0.04	890.67	304.12	586.55	2476	328	11
	Total	1287.62											7512.23	3131.00	4381.23	21196	2610	84

Table 4. Forest type-wise carbon emissions

Forest type	Carbon emitted due to forest fires (tonnes)
Montane moist temperate forest	403.1
Plantation/TOF	1486.66
Tropical, subtropical dry evergreen and broadleaved hill forest	2101.18
Tropical moist deciduous forest	3521.29
Total	7512.23

Table 5. Forest type-wise trace gas emissions

Forest type	CO_2 emitted (tonnes)	CO emitted (tonnes)	CH_4 emitted (tonnes)
Montane moist temperate forest	1136	141	4.5
Plantation/TOF	4169	529	17
Tropical, subtropical dry evergreen and broadleaved hill forest	5943	723	23
Tropical moist deciduous forest	9948	1217	40
Grand total	21,196	2610	84.5

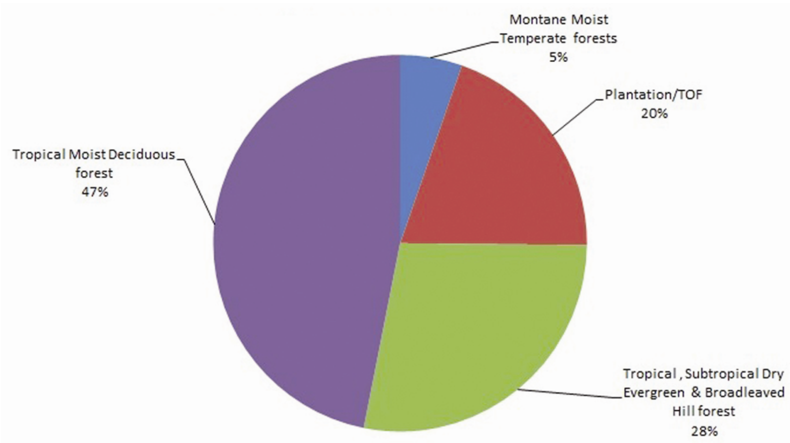

Figure 6. Forest type-wise carbon emissions.

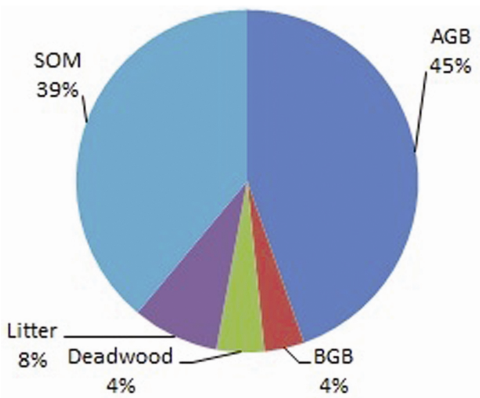

Figure 7. Carbon pool-wise emissions.

Discussion

Forest fire chemistry is complex and so are the carbon emission contributions from different forest types and different carbon pools coupled with the processes of burning like combustion and smouldering[7,10]. During forest fires what is mostly visible is the flaming combustion. However, more carbon (4381.23 tonnes) is released from smouldering than from the visible flaming combustion, which amounts to 3131.00 tonnes. In case of trace gases emission, it may be noted that the percentage contribution of trace gases is in tonnage terms; however, their individual radiative forcing potential will be totally different[24]. The tropical moist deciduous forests are the ones most affected by the fire in terms of burnt area and they contribute maximum pyrogenic carbon emissions. In order to minimize emissions, the maximum efforts should be concentrated in these forests.

Several fires have occurred outside the forest area and they have not been considered here. The actual annual emissions would certainly be more than those estimated in this study, since emissions from the non-forest areas have not been considered. Since the burnt area polygons have been digitized through visual interpretation, there could be some subjectivities involved in the digitization of burnt area polygon. Due to the complexity of the processes, there are inherent uncertainties in the emission estimates[11,25]. The emission estimates can be further improved by grouping fire occurrences in to burn severities (e.g. high, moderate, low or unburned/very low). Over a period of time, the annual emissions cannot just be added to get the total emissions in any specified period, because forest regrowth after burn events and consequent carbon capture will have to be accounted for. The amount of trace gases released depends on the allocation of combustion to flaming and smouldering, and the emission factors. The emission factors should be chosen judiciously for arriving at any credible estimate. The values presented here can work as indicative figures, as there could be substantial variations in the fractions of biomass consumed each year[19].

To the best of our knowledge, there are no previous estimates of pyrogenic carbon emissions from the forests of Sikkim Himalaya. With the use of remote sensing, the burnt areas can be estimated reasonably accurately, but the estimates of fraction of carbon consumed in different pools will need to be refined further[25]. There is also scope for refinement in the percentage allocation of carbon consumed to flaming and smouldering[8,10]. This can be done by establishing a network of experimental fire plots and long-term observations. Further improvements can be made in different variables and constants used here adopted and a deeper study into these aspects can lay the roadmap for future research in this direction. Due to inaccessibility of terrain in the mountains and complexity of calculations, geoinformatics will hold the key for solution.

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